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SUMMARY TECHNICAL REPORT
OF THE
NATIONAL DEFENSE RESEARCH COMMITTEE

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SUMMARY TECHNICAL REPORT OF DIVISION 6, NDRC

VOLUME 1

A SURVEY OF SUBSURFACE WARFARE IN WORLD WAR II

OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT
VANNEVAR BUSH, DIRECTOR

NATIONAL DEFENSE RESEARCH COMMITTEE
JAMES B. CONANT, CHAIRMAN

DIVISION 6
JOHN T. TATE, CHIEF

WASHINGTON, D. C., 1946

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NOTES ON THE ORGANIZATION OF NDRC

The duties of the National Defense Research Committee were (1) to recommend to the Director of OSRD suitable projects and research programs on the instrumentalities of warfare, together with contract facilities for carrying out these projects and programs, and (2) to administer the technical and scientific work of the contracts. More specifically, NDRC functioned by initiating research projects on requests from the Army or the Navy, or on requests from an allied government transmitted through the Liaison Office of OSRD, or on its own considered initiative as a result of the experience of its members. Proposals prepared by the Division, Panel, or Committee for research contracts for performance of the work involved in such projects were first reviewed by NDRC, and if approved, recommended to the Director of OSRD. Upon approval of a proposal by the Director, a contract permitting maximum flexibility of scientific effort was arranged. The business aspects of the contract, including such matters as materials, clearances, vouchers, patents, priorities, legal matters, and administration of patent matters were handled by the Executive Secretary of OSRD.

Originally NDRC administered its work through five divisions, each headed by one of the NDRC members. These were:

Division A—Armor and Ordnance
Division B—Bombs, Fuels, Gases, & Chemical Problems
Division C—Communication and Transportation
Division D—Detection, Controls, and Instruments
Division E—Patents and Inventions

In a reorganization in the fall of 1942, twenty-three administrative divisions, panels, or committees were created, each with a chief selected on the basis of his outstanding work in the particular field. The NDRC members then became a reviewing and advisory group to the Director of OSRD. The final organization was as follows:

Division 1—Ballistic Research
Division 2—Effects of Impact and Explosion
Division 3—Rocket Ordnance
Division 4—Ordnance Accessories
Division 5—New Missiles
Division 6—Sub-Surface Warfare
Division 7—Fire Control
Division 8—Explosives
Division 9—Chemistry
Division 10—Absorbents and Aerosols
Division 11—Chemical Engineering
Division 12—Transportation
Division 13—Electrical Communication
Division 14—Radar
Division 15—Radio Coordination
Division 16—Optics and Camouflage
Division 17—Physics
Division 18—War Metallurgy
Division 19—Miscellaneous
Applied Mathematics Panel
Applied Psychology Panel
Committee on Propagation
Tropical Deterioration Administrative Committee

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NDRC FOREWORD

As events of the years preceding 1940 revealed more and more clearly the seriousness of the world situation, many scientists in this country came to realize the need of organizing scientific research for service in a national emergency. Recommendations which they made to the White House were given careful and sympathetic attention, and as a result the National Defense Research Committee [NDRC] was formed by Executive Order of the President in the summer of 1940. The members of NDRC, appointed by the President, were instructed to supplement the work of the Army and the Navy in the development of the instrumentalities of war. A year later, upon the establishment of the Office of Scientific Research and Development [OSRD], NDRC became one of its units.

The Summary Technical Report of NDRC is a conscientious effort on the part of NDRC to summarize and evaluate its work and to present it in a useful and permanent form. It comprises some seventy volumes broken into groups corresponding to the NDRC Divisions, Panels, and Committees.

The Summary Technical Report of each Division, Panel, or Committee is an integral survey of the work of that group. The first volume of each group's report contains a summary of the report, stating the problems presented and the philosophy of attacking them and summarizing the results of the research, development, and training activities undertaken. Some volumes may be "state of the art" treatises covering subjects to which various research groups have contributed information. Others may contain descriptions of devices developed in the laboratories. A master index of all these divisional, panel, and committee reports which together constitute the Summary Technical Report of NDRC is contained in a separate volume, which also includes the index of a microfilm record of pertinent technical laboratory reports and reference material.

Some of the NDRC-sponsored researches which had been declassified by the end of 1945 were of sufficient popular interest that it was found desirable to report them in the form of monographs, such as the series on radar by Division 14 and the monograph on sampling inspection by the Applied Mathematics Panel. Since the material treated in them is not duplicated in the Summary Technical Report of NDRC, the monographs are an important part of the story of these aspects of NDRC research.

In contrast to the information on radar, which is of widespread interest and much of which is released to the public, the research on subsurface warfare is largely classified and is of general interest to a more restricted group. As a consequence, the report of Division 6 is found almost entirely in its Summary Technical Report, which runs to over twenty volumes. The extent of the work of a Division cannot therefore be judged solely by the number of volumes devoted to it in the Summary Technical Report of NDRC: account must be taken of the monographs and available reports published elsewhere.

Any great cooperative endeavor must stand or fall with the will and integrity of the men engaged in it. This fact held true for NDRC from its inception, and for Division 6 under the leadership of Dr. John T. Tate. To Dr. Tate and the men who worked with him—some as members of Division 6, some as representatives of the Division's contractors—belongs the sincere gratitude of the Nation for a difficult and often dangerous job well done. Their efforts contributed significantly to the outcome of our naval operations during the war and richly deserved the warm response they received from the Navy. In addition, their contributions to the knowledge of the ocean and to the art of oceanographic research will assuredly speed peacetime investigations in this field and bring rich benefits to all mankind.

The Summary Technical Report of Division 6, prepared under the direction of the Division Chief and authorized by him for publication, not only presents the methods and results of widely varied research and development programs but is essentially a record of the unstinted loyal cooperation of able men linked in a common effort to contribute to the defense of their Nation. To them all we extend our deep appreciation.

VANNEVAR BUSH, Director
Office of Scientific Research and Development
J. B. CONANT, Chairman
National Defense Research Committee

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PREFACE

THIS FIRST volume of the Summary Technical Report of Division 6, NDRC is an overall account of the Division's activities. It is written for those whose chief interest lies not so much in the technical details of the program as in the general philosophy which determined the form of organization, the nature of the services undertaken, and how these were integrated with the bureaus and operating forces of the Navy.

The unique feature of Division 6 was that its responsibility was not to develop a particular instrumentality of war or to exploit a particular field of science for military purposes, but was to assist the Navy in all ways in which men of scientific and engineering experience and skill could significantly contribute to the prosecution of subsurface warfare. In the restricted fields of submarine and antisubmarine warfare, therefore, the problem facing the Navy and Division 6 was the general one: through what plan of organization might the scientific and technological resources of the country be made available to the military services for the prosecution of the war and for the maintenance of national security through continued technological preparedness?

As the reader will note, this volume is a compendium of contributions by a number of authors, all former members of Division 6 or its contractors' laboratories. This method of presentation was chosen in the full knowledge that the volume would lack that uniformity of style to be expected were the writing done by a single author and that some repetitiousness was bound to result from the fact that two or more contributors would choose to discuss aspects of subsurface warfare common to more than one field of specialization. But it was felt that these disadvantages were minor as compared with the great advantage of having the parts and chapters and sections which compose the volume each written by the one author best qualified by first-hand experience to deal with the subject under consideration.

The authors who contributed to the writing of this volume are John T. Tate, Chief of Division 6; Philip M. Morse, Director of the Operations Research Group under first NDRC and later the Navy; Elmer Hutchisson, Chief Technical Aide of the Division; Edwin H. Colpitts, Chief of Section 6.1; Carl Eckart, Associate Director of the San Diego Laboratory; Frederick V. Hunt, Director of the Harvard Underwater Sound Laboratory; Franz N. D. Kurie, Associate Director of the San Diego Laboratory; Robert S. Shankland, Director of the Underwater Sound Reference Laboratory; Robert T. Knapp, Head of the Fluid Dynamics Research Group; William V. Houston, Director of the Columbia University Special Studies Group; Timothy E. Shea, who, as Director of Research for the Columbia University Division of War Research, organized and guided the activities of the Field Engineering Group; Gaylord P. Harnwell, Director of the San Diego Laboratory and Chairman of the Committee on Selection and Training; and the editor. The Division and the Summary Reports Group are extremely grateful to these men for their contributions to both this and the other volumes of the Division 6 Summary Technical Report.

It is hoped that the reader will keep in mind that this volume, as its title indicates, reviews the activities in subsurface warfare of Division 6 only; and only insofar as they concern or impinge on the program of Division 6 is any attempt made to discuss the manifold activities of the Navy, our Allies, other Divisions of NDRC, and many other agencies, governmental and private, which contributed to the development and use of the equipment and tactics which won final victory in subsurface warfare.

JOHN S. COLEMAN,
Editor, Division 6

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INTRODUCTION

By *John T. Tate*

IN TWO WORLD WARS the submarine has demonstrated its deadly effectiveness. It cannot be repeated too often nor with too great emphasis that the margin of Allied victory over the U-boat in both wars was narrow and precarious and that the U-boat emerged from the recent war potentially more dangerous than at the beginning. Had the Nazis been a little more imaginative, had their leaders better exploited the scientific and technical skills at their command so as to anticipate by six months or a year the service use of new submarine types which were under development or just completed when the war was already lost, the outcome might well have been different. For these new type submarines would have rendered obsolete much of the Allied antisubmarine equipment and tactics. Lest we be lulled into a false sense of security the stark fact should be emphasized that today we are technologically unprepared to cope with the U-boats which the Nazis had on the point of readiness for operational use in 1945 when the war was already lost by them.

Fortunately the Allies did win the upper hand in the battle of the Atlantic and were able to hold it long enough to win the war with Germany, but only after a staggering loss of millions of tons of shipping and of vital matériel and with the knowledge that had the war continued for another year they might again have lost control.

On the other hand, the Japanese lost the battle with our own submarines in the Pacific, and the consequences of that loss are an object lesson to those who may doubt the necessity for continuing into peacetime the research and development necessary to keep abreast in the contest of wits which is subsurface warfare.

The balance of power in submarine and antisubmarine warfare is peculiarly sensitive to scientific and technological developments rather than to the brute force of numbers. In two world wars the U-boat almost singlehanded narrowly missed victory over the two most powerful navies in the world.

Another consideration of particular concern to a militarily nonaggressive country such as ours is that continental isolation is meaningless to the submarine. An aggressive enemy could strike against our vital shipping lanes at once and with full strength, and press the attack up to our home ports. Distance would give us no time for preparation.

It is sometimes argued that developments such as radar, guided missiles, and the atomic bomb, will so change the pattern of naval warfare that the submarine will be obsolete. On the contrary there is every reason to believe that in a future war the submarine will be called upon to play a much more vital part than in the past. The operational reports of the last few months of World War II indicate a widening differential between the safety of the submarine and that of surface craft. The naval losses at Okinawa due to suicide planes indicate the future danger to concentrations of surface forces from various types of guided missiles—a danger made more intense by the possibilities of the atomic bomb. On the other hand the great difficulty encountered in detecting and attacking U-boats equipped with *Schnorchel* emphasizes again the great difficulty in locating and destroying a submerged vessel. It is likely therefore that in the event of World War III greater reliance and greater responsibility will be placed on submersibles than in the past. In a technological sense the submarine as an instrument of war is in its infancy.

Although later on we shall indicate certain lines of investigation and development which at present appear fruitful it is with no thought that such suggestions have more than transient value. As already noted, there is every likelihood that the pattern of subsurface warfare will be radically changed in the event of a future conflict. This may come about because of the particular nature of the resources and geographical location of the opposing nations. It will almost certainly come about because of scientific and technical advances—most of which will have originated with no specific ref-

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erence to subsurface warfare. If there is anything of permanent value in the present discussion it is that which relates to the manner in which we may at all times be aware of our state of preparedness or lack of it and be assured that our research and development program is relevant to the needs of the situation.

Apart from the explosiveness of the action and the violence and deadliness of the competition, warfare resembles a huge, technical, competitive service enterprise involving millions of men and their coordinated use of an immense and complex variety of technical equipment. There are three principal activities of this enterprise—each distinct in function but each vital to success. They are operations, production, and research. The inherent differences in function, in viewpoint, in skills, and in mode of procedure inevitably requires that these three divisions of the enterprise be distinct with respect to organization and lines of authority and responsibility.

Each is a specialized field which demands of its leaders long experience and breadth of knowledge and understanding in these specialties. The director of research, for example, should have the qualities demanded of the director of research of a great industrial research laboratory and a place in the overall enterprise of equal prestige and responsibility.

The distinctness of organization of these three divisions—so necessary for their individual functioning—does not imply any lack of necessity for complete cross correlation and liaison all down the line in each. There is but a single measure of success of the entire enterprise and that is success in the operating division. For this reason the top policy and programming level of each division must join together for planning and for mutual understanding.

In reaching conclusions, this combined planning body must have before them the results of a continuing, thoroughgoing analysis of operations (actual operations in time of war, simulated operations in time of peace)—an analysis of the performance of men and equipment not only as individuals but as elements in the overall system. Such a system demands teamwork among men and coordinated functioning of equipment to accomplish the final objective.

No type of warfare lends itself better to illustrate the force of the above conclusions than subsurface warfare; antisubmarine warfare, for example, and in particular, the attack on a submerged submarine by a surface vessel. Although, as already noted, the Naval Research Laboratory had developed an efficient detection and location device, we entered this war with the same crude ordnance, the depth charge, which was used in World War I. What was more serious we had an unrealistic notion of the effectiveness of this combination of equipment. No really scientific analysis of the operation had been made or the glaring ineffectiveness of the "ash can" depth charge would have been so obvious that research to develop more effective ordnance would have been undertaken long since. Not until our Navy so wisely centralized control of A/S warfare operations in the Tenth Fleet, attached to it the Operations Research Group, and established ASDevLant to simulate operations, to study and develop tactics in the use of equipment, and brought the leaders of research groups into their full confidence was there assurance that research programs were kept relevant to operational needs and that first things were being put first.

These matters of organization and function are stressed because they are vital to future preparedness. There can be no substitute for exact knowledge of the state of our preparedness as the first step in any program to assure the future security of the nation. This knowledge cannot be gained through casual observation and opinion but only by the cold-blooded objective methods of science.

As to the foreseeable needs for research and development in subsurface warfare, only major aspects can here be discussed.

As already noted, the development of radar, guided missiles, and the atomic bomb are likely to call upon the submarine to play an even more important role as an offensive weapon in the event of a future war. One of the most important development tasks facing the Navy is the perfecting of a high-speed (both on the surface and submerged) submarine capable of long endurance at high speed under water. It must be made to be as silent as possible at high under-

water speed and as "dead" as possible to radar or sonar reflection. Because of the desirability of silent operation and for other safety reasons it should be capable of submergence to a depth of 1,000 ft or more. Submersibles capable of carrying guided missiles and launching facilities should be developed.

These foreseeable possibilities for the development of the submarine make necessary the perfection of antisubmarine measures to counter them. Antisubmarine ships must be developed capable of a speed superior to that of the submarine and equipped with detection and locating gear which will operate reliably at these speeds. This gear should be continuously and automatically alert in all directions and be capable of revealing not only the range but the depth of the submarine. Ordnance must be devised for the certain destruction of the submarine when detected. This will probably take the form of homing torpedoes which are self-guided to the submarine by the same means as that used by the surface ship for detecting it. There is every reason to believe that the submarine can be developed to the point where in battle with surface craft the submarine will have every advantage. For this reason great emphasis should be placed on the full development of aircraft for antisubmarine use. This will involve the perfection of means for detecting and locating submerged submarines from aircraft, and ordnance which when dropped from aircraft will seek out and overtake the submarine.

These foreseeable countermeasures to the submarine suggest counter-countermeasures for submarine equipment among which are early warning equipment to detect radar or sonar search, homing torpedoes to destroy an attacking surface craft, coating of hull to reduce reflecting power for radar and sonar, devices for jamming radar and sonar; devices for decoying homing torpedoes away from the submarine, and devices for detecting torpedoes.

The engineering research and development necessary to accomplish these ends are sufficiently obvious to require little comment. They involve among many other matters the following: studies of hull design for submersibles to achieve strength for deep submergence, resistance to shock, streamlining for high underwater speed and silence; an intensive study of means for reducing machinery noises; studies of methods of propulsion and of fuels to make possible long submergence (6 hours or more) at high speeds (25 knots or more). It is not too early to give great attention to the development of atomic energy as a power source for submersibles.

In addition to engineering research there are certain fields of basic research of particular importance to subsurface warfare which should be continued energetically.

1. Oceanography. The medium in which the submarine moves is the ocean. Both the design and tactical use of submarines require as complete knowledge as possible of the physical character of this medium—the temperature, salinity, and density gradients; the currents; the bottom characteristics—all as they depend on locality and time of year.

2. Underwater acoustics. At present the only form of energy known to science which can be used for detection of submerged objects at ranges greater than a few hundred feet is sound energy. For this reason the basic study of all aspects of sound transmission, reflection, refraction, reverberation, scattering, should be intensively continued.

3. Hydrodynamics. It is obvious that the study of the motion of objects through water—the stability, the resistance to motion, cavitation, manner of propulsion—is vital to the design of submarine hulls and types of ordnance. In the case of torpedoes dropped from aircraft the problems of water entry need further basic study.

Let it be emphasized again that perfection in the operation of entire systems of men and equipment is the sole criterion of success in a research and development program for subsurface warfare; that the performance of these systems must be continually subject to critical analysis; and that the research leaders must study this analysis. On the other hand those in charge of the research program must be in touch with, and professionally a part of, the general scientific life of the country. In no other way will they be able intelligently to direct and to keep relevant a program of research

which will assure the continued readiness of our Navy in subsurface warfare.

Few aspects, therefore, of continuing preparedness for national defense deserve more careful consideration than those concerned with submarine and antisubmarine warfare. It is to aid in such consideration that Division 6, the subsurface warfare division of NDRC, has prepared the present series of technical reports. During World War II, Division 6 joined with the Navy and with other agencies in an intensive effort to mobilize the scientific and technical talent of the country to assist in the defeat of the U-boat and in strengthening the striking power and safety of our own submarines. The division sponsored a broad program of research in those aspects of physical oceanography, of underwater acoustics, and of fluid dynamics which must form the basis of the proper design of submarine and antisubmarine equipment and ordnance. The results of this program have permanent value.

The division organized and trained groups of scientists and engineers to join with the Navy in the performance of special services essential to the effective use of men and equipment in the conduct of subsurface warfare. The form of organization, the methods and techniques developed for these services—for operational analysis, for field engineering, for the selection and training of personnel—have permanent value.

The division developed many new and improved devices for offense and defense in subsurface warfare. Although most of these, even those which proved so effective in World War II are, or soon will become obsolete, many are capable of further development and refinement to meet new requirements. In any case the lessons learned in this development program are of future value.

It is to preserve the permanent values of this extensive wartime program of Division 6, to present them in coherent form for the use of those agencies which may continue to be concerned with readiness for defense in this type of warfare that this series of summary technical reports has been prepared. At the same time, of course, these reports form a record of accomplishment in a joint Navy-NDRC enterprise in which both agencies may take pride. For in a very real sense it was a joint enterprise and the manner and extent of the coordination of the division's organization and activities with those of the Navy deserve special emphasis.

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PART I

ORGANIZATION AND ACTIVITIES OF DIVISION 6

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Chapter 1

THE ANTISUBMARINE PROBLEM

By *Philip M. Morse*

THE SUBMARINE WAS still impractical in 1890 when Mahan's *The Influence of Sea Power upon History* was published. True, Bushnell had traveled some thousands of feet under water during the American Revolution, but his endeavors were abortive; Fulton poured a great deal of his inventive genius and enthusiasm into the design of a submersible, but the results were disappointing. The necessary power plants had yet to be perfected. Not until a few years after 1900 could the internal combustion engine for surface running be used with the electric battery motor for submerged running to create a practicable combination. During the first decade of the twentieth century the American inventors, Holland, Lake, and others, rapidly developed the submarine into a practicable naval vessel—ready for effective use by the Germans in World War I.

Though the introduction of the submarine changed the tactical picture, it did not change the rules of grand strategy outlined by Mahan. As was so well stated by Brodie in 1944 in *A Guide to Naval Strategy*:

> Sea power has never meant merely war ships. It has always meant the sum total of those weapons, installations, and geographical circumstances which enable a nation to *control transportation* over the seas during wartime. If the airplane (or submarine) plays an important part in such a control, it is functioning as an instrument of sea power. All naval enterprise—with the exception of bombardment of land objectives from the sea, which is only an incidental use of sea power—is directed toward the single aim of affecting the movement of the lowly freighter or transport in which are carried nearly all the commodities and the men that move across the sea.

Control of the sea has usually gone to that side which had the greatest number of warships. The weaker naval powers have always tried to break down this control by the use of vessels which could sink the enemy's merchant shipping in spite of his predominating battle fleet, the so-called *guerre de course*. In Napoleonic wars the privateer was tried against the English naval power and failed. As used by the Allies' enemies in both World Wars, the submarine played the role of a modern privateer, which was expected to sink Allied merchant shipping despite the Allies' greater naval power.

The submarines of the enemy almost succeeded in both World Wars—but they did not succeed. This story of the activities and achievements of NDRC's subsurface warfare group includes a partial list of the technical reasons why submarines have not yet broken Allied sea power, and will indicate, it is hoped, the narrowness of the present margin of safety.

1.1 THE LOGISTICAL PROBLEM

For the past 40 years Great Britain has maintained afloat approximately 20,000,000 gross tons[a] of merchant shipping: about 2,500 ocean-going vessels of 6,500 gross tons average, and about 2,500 coastal ships of 1,200 gross tons average. Her allies in the two wars have had about another 20,000,000 gross tons available. A sizable part of this fleet is needed to keep England fed and supplied in a war when no supplies can be obtained from Europe.

In 1943 the total imports to the United Kingdom averaged about 3,600,000 long tons a month, more than 80 per cent of this being carried by the North Atlantic convoy system. To make a round trip, the average ship in the North Atlantic convoy system took about 70 days, half of which were spent at sea and the other half in port. Therefore, a flow of 10 ships a month, of 6,500 gross tons apiece, would require a fleet of about 24 ships in commission. A ship of this size carries about 8,000 long tons per trip. From these figures, we see that in 1943 the United Kingdom needed a fleet of between 7,000,000 and 10,000,000 gross tons just to keep fed and supplied.

[a] A gross ton is a measure of total internal *cubic capacity* of the ship, expressed in *tons* of 100 cu ft to the *ton*. A ship of 1,000 gross tons capacity will, as a rule, be able to carry more than 1,000 long tons of freight.

But the United States and other Allied nations in World War II sent great expeditionary forces overseas, eventually into continental Europe. These immense armies had to be supplied by sea. The average soldier was accompanied by about 5 tons of equipment and supplies when he went, and after his arrival he needed an additional ton per month. Since complete replacements were needed once a year on the average, each soldier maintained in Europe needed between 16 and 20 long tons shipped across each year to keep him fighting. Again utilizing the previous figures, we see that each soldier needed on the average between 3 and 5 gross tons of shipping to keep him steadily supplied, or an army of 5 million men in Europe required a fleet of 20 million gross tons total continually plying the Atlantic to keep it going.

These figures simply serve to illustrate the obvious fact that the sinking of merchant vessels reduces our ability to fight overseas and that the Allied margin of safety in this respect is extremely small. In World War I and World War II the U-boats of Germany plus the submarines of Italy and Japan reduced Allied shipping strength to a level close to the danger mark. In addition it disrupted the naval building program and in World War II it delayed the building of vitally needed landing craft. There is no reason to believe that the threat will be any less should there be a next time.

In World War II, of course, the United States also sent a great force to the Pacific theater. The Japanese never used their submarines a fraction so effectively as the Germans, but the problem of supply over ocean routes far longer than those of the Atlantic was one that required more millions of tons of shipping.

1.2 CONVOYS

It is not 30 times easier to find 30 ships together than to find one ship. Consequently it is harder for a privateer to find a convoy of 30 ships than it is to find *some* ships if the 30 are spread over the ocean in independent routings. This advantage of concentration, however, would be more than counterbalanced if the privateer, once the convoy is found, could maintain the attack long enough to sink the same percentage of ships no matter how large the convoy. In Napoleonic times the exigencies of sailing-vessel tactics made it difficult to continue the attack for long, so that usually a smaller percentage of ships were destroyed out of a large convoy than out of a small convoy. Consequently, convoying was a useful defense against privateers in Napoleonic times, even when no naval escort vessels accompanied the convoy.

In the latter part of the nineteenth century, with the development of the dreadnought-type warship, it was believed that the advantages of convoying had disappeared. This belief carried over into the planning of antisubmarine warfare in World War I and nearly lost the battle for England. Finally the suggestions of Admirals Sims and Jellicoe and others prevailed, and convoying was tried, even though the number of escort vessels was considered to be inadequate. The introduction of convoying in 1917 immediately cut the monthly toll of sinkings to approximately half its previous value. As the number of escort vessels accompanying the convoys was increased, the sinkings dropped still further.

Thus, the introduction of convoying defeated the submarine in World War I and maintained Allied control of the sea, although precariously. The North Sea mine barrage solidified this control though the barrage was completed so late in the war that it was not possible to determine exactly how efficacious it was. In World War II convoying again proved its value. The mine barrage could not be used, but a new element effective against the submarine entered into the picture—the airplane.

1.3 EXPERIENCE OF WORLD WAR I

The German blueprint for World War I did not contemplate use of the submarine as a means of denying the British freedom of the seas. The German plan, as was to be true also in the case of World War II, was for a short war where overseas supply could be ignored. Surface raiders were tried sporadically during the first year. The results were not promising. But the Germans' few submarines immediately showed profitable returns. Crude as the World War I U-boats were, compared to their World War II successors, and undeveloped as were their tactics, the first two years' figures indi-

cated to the Germans that in this modern, submersible version of the privateer they had a potent weapon. During those years, on the average, each U-boat sank about 13,000 gross tons of shipping a month. The mean life of the U-boat at that time was about 10 months, so that each U-boat sank approximately 1 per cent of England's total shipping before it itself was sunk. The Germans became convinced that if they could build up their submarine fleet to 100 or 200 U-boats, they might inflict decisive damage on British shipping. The results showed that the German strategists were correct. If the English antisubmarine defenses had not been improved after 1916, the submarines would have blockaded the British Isles.

In the latter part of 1916, the Germans started a large U-boat construction and training program. In February 1917 they began a large scale campaign of unrestricted submarine warfare on merchant shipping, which almost proved successful. Allied shipping losses rose steadily to a peak of about 900,000 gross tons sunk by U-boats in April 1917; nearly one-twentieth of Britain's shipping was sunk in a month. The British Fleet was confined to its bases, for at one time there was only 8 weeks' supply of fuel oil in England.

In the face of such a crisis, the British at last decided to try reviving the ancient expedient of convoying. On the part of many in the Admiralty, the decision was a reluctant one. They expected to gain little advantage. At that time only a few destroyers and other antisubmarine craft were available for protecting shipping in the vicinity of England. These craft were distributed evenly along the shipping lanes on protective patrol, and the merchant shipping was routed independently as in peacetime. If all transatlantic shipping was to be put into convoy, it was felt that each convoy should be heavily protected, and there simply were not enough escort vessels available. It was, however, a desperate case of do the best one could and a few convoys were experimentally allotted such escorts as could be gotten together. The results showed promise. Consequently, in April 1917, convoying was generally introduced, and escort vessels were added as fast as they were built. By October 1917, 1,500 ships in 99 convoys had been brought into port with a loss of only ten ships sunk while in convoy, a rate of loss considerably smaller than that for independent shipping.

The results of convoying in World War I, and also in World War II, have shown that on the average the *number* of ships sunk in a convoy which is attacked by submarines is no greater for a large convoy than for a small one. Large convoys, therefore, have a smaller *percentage* of ships sunk per attack. The percentage diminishes slightly as the number of escort vessels is increased: for instance, a convoy with ten escort vessels is about twice as safe as a convoy with three escort vessels. Careful analysis of the results of both wars indicates that in the case of escorted convoys the average number of vessels sunk per attack is independent of the size of the convoy, is proportional to the number of U-boats participating in the attack, and is inversely proportional to the square root of the number of escort vessels. The size of the proportionality factor depends on tactical details, and is different for different periods.

The introduction of convoying eased the situation for the Allies but did not solve the antisubmarine problem. After the start of unrestricted U-boat warfare early in 1917, the Germans maintained an average of about 40 U-boats at sea at any one time. During this period the average number of U-boats sunk each month was only about 7, the maximum number of U-boats sunk in any month being 14 in May 1918. Therefore, the average life of a U-boat at sea during the last year of World War I was still about 6 months. In the last 4 months of World War I each U-boat was still sinking about 45,000 gross tons before it itself was sunk. The submarine weapon had been dulled somewhat, but it remained an extremely dangerous threat to the Allied control of the seas.

1.4 THE TECHNICAL PROBLEM

Obviously the problem was technical and extremely difficult, involving elements quite different from other naval technical problems. The most difficult part was that of detecting the position of the submarine at a great enough distance so that the threatened vessel might

do something about it, either run away or attack before the submarine launched its torpedo.

Salt water is a good medium for concealment. It is opaque enough to visual light so that only rarely can a submerged submarine be seen. Submarines sometimes leak small quantities of oil which come to the surface and form a "slick" which can be seen for some distance. It was soon found, however, that an oil slick was a very unreliable means of detection, for it could be confused with similar slicks left by surface vessels, and there was no sure way of determining how far ahead of the leading edge of the slick the submarine was located. The magnetic field of the submarine could be used as a means of detecting its presence, but this field was imperceptible beyond a few hundred feet. Salt water is practically impenetrable by electromagnetic waves over wide ranges of wavelengths from a few centimeters to a number of meters. The only practicable means of detecting the submerged submarine seemed to be through the use of underwater sound.

Sound waves in water travel considerable distances, although they are diffracted by temperature and salinity gradients, and are scattered and reflected from the ocean bottom. Except under unusual conditions, a submarine has to be under way to maintain its equilibrium while submerged. While it is moving, even very slowly, it produces low-frequency noise from the machinery and movements inside the hull. At higher speeds, it produces high-frequency noise from cavitation about the propellers. The low-frequency sounds are the louder, but the direction of motion of the waves is difficult to determine accurately and background noise in the low-frequency range may mask the wanted sounds entirely. The supersonic waves are more directional and less susceptible to masking, but they disappear if the submarine slows down.

Toward the end of World War I, submarine chasers were equipped with hydrophones capable of hearing the low-frequency sound put out by submarines and capable of determining the approximate direction of the source by means of the binaural effect. The equipment was difficult to use successfully. The range of the sound source could not be determined; and the detecting vessel had to come nearly to rest in order that its own noise might not drown out that of the submarine. The majority of the submarines which were detected in World War I were spotted on the surface or their periscopes were seen.

The difficulties of detecting a submerged submarine are reflected in the data on U-boat losses in World War I. In this first struggle, 178 U-boats were sunk, about 30 per cent being sunk by mines before they were able to get out of the North Sea. Ten per cent of the U-boat losses were due to Allied submarines which spotted them on the surface and sank them by torpedoes. About 25 per cent were sunk by surface vessels which caught them on the surface and sank them by gunfire or by ramming. Only about 20 per cent of the U-boats lost were caught and sunk while they were submerged. (The other 15 per cent of the losses was not due to Allied action.) The detection problem was far from being solved, nor is it solved yet.

In September 1918 a committee was formed in England called the Allied Submarine Devices Investigation Committee to study the problem of improving the range of detection of submerged U-boats. A method of echo ranging using supersonic pulses was proposed which would give not only bearing but range. This type of gear (called ASDIC, after the initials of the proposing committee) was still in the experimental stage when World War I ended. Work was continued between wars, however, and by 1930 both England and the United States had practicable supersonic echo-ranging detection gear which could be installed on destroyers and other submarine chasers. The advantages and limitations of this type of gear are considered in great detail in the Division 6 volumes.

Another problem in antisubmarine warfare, nearly as difficult as the detection problem, is that of ordnance. After the submerged submarine has been located, unless one elects to run away, the U-boat must be rendered incapable of launching its torpedo. The problem here is twofold: the choice of ordnance which will damage a submerged submarine and the design of fire control equipment which will enable the ordnance to be projected close enough to the submarine to do damage. World War I saw

the development of depth charges, cans full of TNT which could be projected from the deck of a destroyer and which were provided with fuzes detonating at a predetermined depth. The "ash cans" were not streamlined to ensure an accurate path through the water, and fire control equipment was almost nonexistent. The destroyer would drop astern a few depth charges at the point estimated to be above the submarine, and if these charges exploded within approximately 20 ft of the submarine's hull, damage usually resulted. The method of location was so inaccurate that several hundred depth charges had to be dropped before any damage might be expected to result, and a great number of submarines escaped unscathed.

The beginning of World War II found both sides relatively unprepared for the resumption of submarine warfare. England had only about 200 ASDIC-fitted antisubmarine craft (compared to more than 3,000 such craft at the end of World War I). The Germans, probably again expecting a short war, had only about 60 U-boats, of which 30 were of the small 250-ton type of limited endurance. Of the 30 larger U-boats, 20 were of 500 tons, and 10 were of 750 tons. These last two classes were faster than the U-boats used in World War I and were also considerably stronger, being able to dive deeper and to withstand more depth-charge punishment. The Germans had also developed an electric torpedo which did not leave any visible wake. Nevertheless, 30 ocean-going submarines were not sufficient to constitute a threat to England's shipping. Neither side had appreciated the usefulness of aircraft in antisubmarine warfare, and the Germans either had not heard about the supersonic echo-ranging gear of the English or else had underestimated its effectiveness in locating U-boats.

1.5 ANTISUBMARINE WARFARE IN WORLD WAR II

1.5.1 Period I—September 1939 to June 1940

By September 1, 1939, when Germany invaded Poland, there were already six U-boats at sea. This time England immediately instituted convoying, and the first convoy sailed on September 6. Since most of the ASDIC-equipped destroyers were needed to protect the Fleet, there were very few escort vessels available. Nevertheless, convoying immediately showed its value; for during September, while convoying still was only partial, more than 900 ships were convoyed without the loss of a single ship while in convoy. By contrast, during the month 39 unconvoyed ships of 151,000 gross tons were sunk by U-boats.

The U-boat tactics at the beginning of World War II paralleled closely those of World War I, and took little or no account of the development of the British ASDIC gear. The U-boats preferred attacking their targets during daylight, believing themselves relatively invisible because of their powers of submergence, while they could observe the targets through their periscopes. The attacks often were made by torpedoes from periscope depth, but if the target were an unarmed merchant vessel, U-boats would generally surface and attempt to sink the ship by gunfire. Gunfire from surfaced U-boats sank 10 of the 39 ships sunk during September 1939. This led the British to take steps immediately to arm defensively as many merchant ships as possible.

At first, aircraft carriers were used on antisubmarine escort, but after HMS *Courageous* was sunk by a U-boat on September 17 the carriers were withdrawn. Shore-based aircraft of the Coastal Command, however, helped considerably by flying more than 100,000 miles in September, sighting some 50 U-boats (or supposed U-boats) and attacking more than 30 of them. Few of the aircraft attacks were very effective because aircraft antisubmarine armament was undeveloped. But they did cause U-boats to submerge and thereby reduced the submarines' effective operating period.

The September U-boat campaign was followed by a lull during the first 10 days of October, during which hardly any ships were attacked, although U-boats were at sea. This probably reflected the current political situation, as it was accompanied by Hitler's offer of peace on October 6. U-boat activity flared up again on October 12, and by the end of the

month 28 ships of 136,000 gross tons had been sunk by U-boats. In addition, the U-boat ace, Prien, the commander of U-47, penetrated the harbor of Scapa Flow in the middle of October and sank the battleship HMS *Royal Oak*. This served to direct British attention to the necessity of protecting harbors against U-boats.

During November and December the main effort seems to have centered on a mine-laying campaign off the east coast of England, particularly in the Thames estuary. Mines laid were both the old-type contact mines and also a new type of magnetic mine, which at first proved difficult to sweep. Monthly losses due to U-boats fell to 18 ships of about 65,000 gross tons and were exceeded by the 100,000 gross tons of shipping sunk by mines during each of these months.

U-boat activity began increasing again in the second week of January 1940 and by the end of the month there were as many U-boats at sea as at the start of the war. In February the U-boat effort was greater than during any previous period and 35 ships of 153,000 gross tons were sunk. The U-boats continued to follow a policy of attacking without warning either neutral single ships or stragglers from convoys, thus making it difficult for the antisubmarine ships to make an effective search and counterattack. The respect U-boats had been showing for the British convoys is indicated by the fact that although roughly about half the shipping had been sailing in convoys during this time, only 7 of the 169 ships sunk by U-boats during the first 6 months of the war were in convoy when sunk.

There was a marked lull in U-boat activity throughout March, featured by the complete absence of submarines from Atlantic waters after about March 12. Early in April every available U-boat left Germany to take up patrol positions in the North Sea to help in the impending military operations against Norway. The average number of U-boats in this region reached a peak of about 15 during the second week of April when Germany invaded Norway. Despite the large concentration of U-boats, the damage done by them was remarkably small. No British capital ship was even attacked by a U-boat, and only six ships of 31,000 gross tons were sunk during the whole month of April. Germany, on the other hand, lost six U-boats during the month, a new high for the war.

There was very little activity during the first half of May as Germany started her invasion of Holland and Belgium. It is believed that no U-boat proceeded to the western approaches until May 21, and only ten ships of 48,000 gross tons were sunk during the month. Shipping losses to U-boats were exceeded for the first time during the war by the 154,000 gross tons of shipping sunk by aircraft. These losses were incurred largely in connection with the evacuation of the British Expeditionary Force from Dunkirk at the end of May.

In June, Germany recommenced her submarine campaign with increased vigor. Convoys were attacked with greater boldness than in earlier months, advantage being taken of the paucity of escorts, rendered inevitable by the demands of the military evacuation and by an urgent phase of surface warfare. The losses for June were the highest of the war with 56 ships of 267,000 gross tons being sunk by U-boats. By the end of June, France was out of the war and Italy had entered it against the Allies with more than 100 submarines, about 60 of which were ocean-going.

In this first period, the convoy system was by far the most effective countermeasure in keeping down shipping losses, just as it had been during World War I. The data indicate that shipping was four times more likely to be sunk if it was not in convoy than if it was. This advantage of the convoy was all the more remarkable because most convoys at that time were poorly protected by escort vessels. The British tried to make up for the scarcity of escorts by keeping their convoy system flexible, changing the number of escorts and the distances for which convoys were escorted in accordance with U-boat activity. For their part, the Germans made the problem more difficult by sending the U-boats out in waves, so that peaks of U-boat activity occurred in September 1939 and in February and June of 1940.

Aircraft began to show their value in antisubmarine warfare in this first period, although their value was mainly defensive, since the ordnance they carried was ineffective or even

nonexistent. Coastal Command aircraft flew an average of about 5,400 hours monthly on antisubmarine work. About 20 U-boats were sighted monthly and of these 12 were attacked, with about 10 per cent of the attacks resulting in some damage to the U-boat. This effort reached a peak of 9,500 hours during June 1940 when about 2,800 hours were spent on antisubmarine patrol and 6,700 hours on convoy escort duty.

The main value of this flying was in causing the U-boats to submerge. This prevented U-boats from shadowing or approaching convoys on the surface. It also helped to discourage them from operating close to the shores of England where the flying was heaviest. U-boats at this time were under orders to submerge as soon as they sighted a plane, and the British took advantage of this by starting to use, in November 1939, light aircraft of the moth type in patrol around the coast. These aircraft were known as "scarecrows." They carried no bombs and were used solely to sight and report U-boats, making them submerge. Their reports on sightings helped considerably in keeping an accurate plot of submarine locations.

Surface craft equipped with ASDIC and depth charges were the most potent enemy of the U-boats during the first phase. Twenty-one German submarines are known to have been sunk as a result of Allied action during this 10-month period. Fifteen were sunk by surface craft, one by the coordinated action of two ships and one plane, one by a plane from a British battleship, two by torpedoes from English submarines, and two by mines while attempting to pass through the Dover mine barrage. In addition, ten Italian submarines were sunk in the Mediterranean, Red Sea, and Indian Ocean between June 10 when Italy entered the war and the end of the month.

The submarine war had not reached its full intensity during this first period. The average number of U-boats at sea in the Atlantic during this time was about 6. The average number of ships sunk monthly by U-boats was 26, representing a loss of about 100,000 gross tons. Therefore, during Period I about four ships of about 18,000 gross tons were being sunk by each U-boat each month at sea. At the same time, however, about two out of the six U-boats at sea were being sunk each month, so that the average life of a U-boat at sea was only about three months. Since each U-boat spent about one month out of three at sea, this represented a total commissioned life of about nine months, which was not bad for a naval vessel constantly in action against the enemy. Nevertheless the rate of loss was quite high, much higher than at any stage of World War I.

Though the overall exchange rate of 13 ships of about 53,000 gross tons sunk for each U-boat sunk represented a fairly satisfactory bargain from the German point of view, the rate of loss of the limited number of U-boats had become greater than the Germans could stand. By the end of June 1940 despite the fact that the U-boats had concentrated against unescorted ships rather than against escorted convoys, 18 of the original 30 ocean-going U-boats had been sunk, whereas only about 15 new ones had been commissioned, representing a net loss of 3 commissioned units. This high rate of loss caused the Germans to change their submarine tactics during the next phase of the U-boat war.

At the end of June 1940 England was left alone in the war against Germany, and her ability to carry on the struggle was dependent on her being able to keep open the sea lanes between herself and America. Shipping losses of the Allied and neutral nations were about 280,000 gross tons monthly as compared to a building rate of only about 90,000 gross tons monthly, representing a total net loss of 1,900,000 gross tons for the 10-month period, or about 5 per cent of the total Allied shipping available at the beginning of the war. Shipping losses promised to remain on the upgrade for some time to come. And since no method had yet been devised to counter the U-boat effectively, the only hope of keeping the rate of net loss down was to expand and accelerate the building of merchant vessels. This, of course, reduced England's capacity to build warships, and later reduced the Allied capacity to build landing craft.

The U-boat was definitely the main threat to Allied shipping, being responsible for at least half of the sinkings due to enemy action. Mines sank one-fourth of the total, aircraft one-eighth of the total, and surface craft and other causes

were responsible for the remaining eighth. The convoy system had been the main factor in keeping the shipping losses to submarines down to a moderate level. The British had nearly doubled their ASDIC-equipped antisubmarine vessels in this 10-month period, but even so the number of these ships that could be spared for escort duty was still insufficient to provide adequate protection. The British had been fortunate during the first period in that the enemy had only a small number of U-boats available, and these had operated in a limited area, almost all of the sinkings of ships occurring in the northeast Atlantic east of 20 degrees west longitude, and north of 30 degrees latitude. This had helped to make the escort problem easier during this first period. But to those who had fought the U-boat in the First World War, the signs were reminiscently ominous. If Germany could build submarines faster than England was sinking them, the problem would become serious indeed.

1.5.2 Period II—July 1940 to March 1941

The second phase of the U-boat war was marked by a complete change in submarine tactics. The U-boats, having discovered as a result of their high rate of loss that they could be located by ASDIC when submerged, decided to make use of the hours of darkness to regain their relative invisibility. At night, trimmed down on the surface, a U-boat offers a very small target to the human eye and is also rather difficult to detect by ASDIC. Acting on this principle and encouraged by the results achieved by the few attacks at night during the first period, the Germans began in July 1940 the general practice of attacking convoys at night from a surfaced position and then using their high surface speed to escape. Occasional daylight attacks were still made on ships sailing independently and on stragglers from convoys.

Accompanying this change in the enemy tactics came the occupation of the French ports and their establishment as submarine bases. The use of these bases served to cut down the transit time of the U-boats and enabled them to extend their area of operation further westward in the Atlantic. From air bases in France the enemy was also able to send out long-range reconnaissance aircraft to pick up transatlantic convoys. Many British destroyers and aircraft had to be concentrated along the east and south coasts of England in order to repel a possible invasion. Consequently, just at a time when Germany was able to make more efficient use of her submarines, the English were compelled to reduce the protection of their convoys. In addition, all the convoys had to be routed around the north of England, which increased their time at sea.

Increased U-boat activity, which had commenced in June 1940, continued through July and August with more than 200,000 gross tons of shipping being sunk in each of these months. Up to the middle of July, the most active area was still in the western approaches between the latitudes of 48° N and 51° N. After the British convoys had been rerouted around the north of England, the U-boats lost no time in shifting their area of activity to the northwestern approaches. This activity was marked by increased attacks on convoys while antisubmarine escorts were present. But these attacks at first were only on those convoys which were scantily guarded by only one or two ASDIC-fitted ships.

The attacks increased in intensity after August 15 when Germany proclaimed a complete blockade of the British Isles. The shipping losses continued to increase with about 300,000 gross tons being sunk in September and 346,000 gross tons in October, a new high for the U-boat up to that date. The scene of greatest activity during these months was still the northwestern approaches, with night attacks on convoys being the most favored method. Of the 59 ships attacked in this area in September, 40 were in convoy; 70 per cent of the total were night attacks. The concentration of attacks into the period of, and immediately following, the full moon was especially noticeable during October, when 31 ships were attacked on October 18 and 19.

The losses resulting from this increased activity were a vindication of the new tactics, since during these 3 months the average number of U-boats at sea was still only about six. This meant that ten ships of about 60,000 gross

tons were sunk by the average U-boat at sea during October 1940, probably an all-time high in general effectiveness for submarines. In addition to inflicting these heavy losses, U-boats were almost invariably escaping undamaged. In October, for instance, only one U-boat was sunk in the Atlantic. It is no wonder that the antisubmarine problem was rated high on the priority list of the newly formed National Defense Research Committee in the United States.

The new tactics, which were proving so successful for the Germans, involved shadowing and night attack. The individual U-boat would usually gain contact with the convoy during the day, either as a result of reports from long-range German reconnaissance aircraft or from reports from other U-boats or by direct sighting. It would then shadow the convoy at visibility distance on the bow or beam until darkness. The U-boat, trimmed down on the surface, would then close on the convoy and endeavor to reach a position broad on its bow. It would try to come in astern of the forward escorts and approach as close as possible to the merchant vessels themselves. Having reached a firing position on the beam of the convoy, most U-boats would increase to full speed, fire a salvo of four torpedoes, turn away still at full speed, firing the stern tubes if possible, and would then retire as rapidly as possible on the surface in the direction considered safest. If their retreat was undetected, they sometimes reloaded their torpedo tubes on the surface and attacked again later in the night.

The serious damage inflicted on British convoys by these new U-boat tactics caused a number of changes to be made in the convoy disposition. The spacing of the columns of the convoy was opened up to reduce the chance of more than one ship being hit by a salvo. Escorts were stationed farther away from the convoy, and new plans were developed for searching for the U-boats with illumination after an attack had taken place. In order to improve the tactical efficiency of the escorts, these ships were formed into groups and, as far as possible, ships of one group were to work together. Admiralty took over the responsibility for the routing of all ocean-going convoys, thus enabling emergency changes to be made without delay. In addition, great efforts were made to equip all convoy escorts with radar, which would enable them to locate the U-boats on the surface at night beyond visibility distance; if possible, before they could attack the convoy.

Since the new U-boat tactics involved a great deal of wireless communication to and from the submarines, *high-frequency direction finders* [HF/DF] or "Huff-Duff" were developed and installed on some escort vessels. In time, after experience had been gained, the HF/DF was often capable of warning the escorts of an approaching attack. This proved to be exceedingly valuable, for it was then possible to bring in aircraft if the convoy was close enough to an air base, and to strengthen the escort in the direction from which the attack would most likely come. Land-based HF/DF stations could fix the location of the various U-boats by triangulation, and it was not long before the Admiralty U-boat plot provided a fairly accurate day-by-day location of nearly all the German submarines on patrol. This plot proved of great value in deciding the routing of convoys and in sending additional escort strength to convoys which might be threatened with attack. The U-boat plot, with its necessarily complex system of news gathering, proved to be an immensely valuable facility in the antisubmarine war. With its aid, more protective forces could be concentrated to meet the enemy at his point of greatest concentration, so that the inadequate number of escort vessels could be used as efficiently as possible.

With the fall of France, the Germans made the ports in the Bay of Biscay into bases for the repair and refitting of operative submarines. By November 1940, Lorient had become the principal U-boat base, with St. Nazaire, Bordeaux, and other ports as subsidiary bases. Possession of the Bay of Biscay ports was a great advantage to the U-boats, since it not only shortened the transit time between base and patrol area, but also ruled out an effective Allied mine barrage. It might be barely feasible to close the exits to the North Sea by mines, but to blockade the Bay of Biscay was practically impossible. The U-boat bases in the Bay of Biscay were subjected to a gradually increasing number of bombing attacks which

seem to have been annoying to the Germans, but not too serious in their effects. The repair facilities and the U-boat docks were all put underground beneath huge thicknesses of concrete. After the capture of these ports in 1945, it was discovered that only one or two bombs had ever penetrated the concrete defenses into the U-boat docks.

For the time being, all the British could do to counter these new and serious attacks on convoys was to improve the use of the antisubmarine gear they had on their escort vessels by continuous refresher training and to perfect their counterattack tactics. In November 1940, three U-boats were sunk while they were attacking convoys. This minor success might account in part for the reduced number of attacks on escorted convoys in November and December 1940. Heavy winter weather in the North Atlantic was more probably a factor in accounting for the decrease in shipping losses to U-boats. Only 150,000 gross tons were sunk by U-boats in November, and 200,000 gross tons in December. Parenthetically, it might be noted how serious the matter had become when the word "only" can be used in connection with these tonnages lost.

The Coastal Command increased its antisubmarine flying out from England, and the aircraft attacks on submarines became somewhat more lethal. Partly on this account, early in December, a westerly movement of the U-boats became noticeable, with most of them patrolling as far out as 20° W longitude. This westerly movement may also have been due to an attempt to intercept incoming convoys before the heavy antisubmarine escorts joined them. As a matter of fact, however, patrolling so far from the focal points of convoy routes made it considerably more difficult for the U-boat to find the convoys and considerably easier for the English to route their convoys evasively. The advantages of a complete and accurate U-boat plot became more apparent to the English.

In December 1940, maximum evasive routing of convoys was tried by the British. The routes of convoys were spread between 64° and 57° N latitude, and the cycles of convoys were also opened out with the object of reducing the strain on escorting forces. This thorough spreading of convoy routes seems to have been a main factor in the reduction of shipping losses, just as it had been in World War I. No attacks were made on escorted convoys from December 2, 1940 until January 29, 1941, and the losses due to U-boats in January dropped to 21 ships of 127,000 gross tons, the lowest figure since May 1940. This occurred despite the fact that the average number of U-boats at sea in the Atlantic had increased to about 12. Most of the ships lost were not in convoy, since the U-boats went back to the much easier task of picking off stragglers or independents.

The month of February 1941 opened with a continuation of the comparative lull in U-boat activity. This lull, however, was due to the Germans' preparation for new tactics, the "wolf pack." The obvious answer to wide evasive routing of convoys was increased cooperation between U-boats, utilizing high-frequency wireless intercommunication, and handling the submarines more and more as surface raiders which submerged only when under attack. The U-boats began operating in groups of three to five, each U-boat being given a limited patrol area within the wider area covered by the group. The first U-boat to gain contact shadowed the convoy, while other U-boats were ordered to close in, homing on the radio signals given out by the shadowing U-boat. At times, aircraft were used to home U-boats on a convoy.

Cooperation between U-boats, aircraft, and surface craft is well illustrated by the attack on the convoy, HG-53, consisting of 21 ships escorted by one sloop and one destroyer. The convoy was attacked by a U-boat early on February 9, two ships being sunk. The U-boat continued to shadow the convoy and probably homed six Focke-Wulf aircraft to it during the afternoon of February 9. Five ships were bombed and sunk while one plane was shot down. The U-boat continued to shadow the convoy and again attacked successfully, sinking one ship. After this she maintained touch with the convoy, reporting its position. Her reports were evidently intended for a German *Hipper* class cruiser. While closing HG-53, however, this cruiser came upon the unescorted slow portion of another convoy and attacked this target instead, sinking seven ships.

Three other convoys were attacked by U-boats in the last week of February, and as the month drew to an end, with the losses to U-boats amounting to 36 ships of 190,000 gross tons, it was evident that the expected spring offensive had commenced. The average number of U-boats at sea in the Atlantic rose to 16 in March. Their tactics included a repetition of the concentrated night attack upon convoys, and six convoys were attacked during the month. Losses were still higher in March, being 40 ships of 240,000 gross tons. These losses, however, were considerably less than those during the previous September and October, and since there were twice as many U-boats at sea in March as in September, the situation was not yet regarded as critical.

As a matter of fact, the antisubmarine escort vessels were becoming increasingly efficient at using their supersonic echo-ranging gear and in conducting antisubmarine attacks. One after the other of the outstanding "U-boat aces" of the early part of the war was sunk or captured about this time. This seems to have made the Germans somewhat more cautious, for, during the last week in March, activity slackened somewhat.

During this second period of the U-boat war, the British were learning how to use aircraft against submarines. They were learning that the plane is extremely valuable in finding submarines, as long as the U-boat tactics are to stay on the surface most of the time. A U-boat on the surface is fairly certain of seeing an enemy ship before she herself is seen. This is not true of aircraft and a fairly large number of U-boats were unpleasantly surprised by having aircraft swoop down and drop depth charges before they had had any warning at all. This was an unsettling experience, even though it was not at first very dangerous.

It had already been realized that ordinary general-purpose bombs were of very little use against submarines, and Coastal Command had begun using naval depth charges modified for use from aircraft. They began in July 1940, and on August 16 their first success was scored when a U-boat was severely damaged as a result of a depth-bomb attack. On the first run-in, the U-boat, which was submerging rapidly, was blown to the surface to be further damaged by subsequent run-ins. In view of this success, steps were taken to modify all Coastal Command aircraft in order to enable them to carry depth charges. A considerable amount of study was made to determine the best depth setting for these charges. At first the setting was 50 to 75 ft or deeper. It was realized later, however, that most of the attacks were being made on submarines surfaced or near the surface, so that a 25-ft setting would be more lethal. This was subsequently adopted.

By the fall of 1940 a few Coastal Command aircraft were being fitted with radar of the long-wave type. It was hoped that this would eventually enable the aircraft to be used against submarines at night as well as on days of poor visibility. With the developing U-boat tactics of shadowing by day and running in to attack by night, it was important that the rear and flanks of the convoy be searched thoroughly at evening. It was hoped that radar-equipped aircraft could help in this task.

After the evasive routing of shipping had led to the start of wolf-pack tactics in February 1941, the early detection of the shadowing U-boat became the main problem. Having gained contact with the convoy, the U-boat took great care not to reveal its presence by attacking in daylight, but shadowed the convoy at some distance. There was, therefore, only a small chance of the surface escort discovering or attacking these U-boats, and the task fell more and more on the escorting aircraft. Consequently the number of Coastal Command aircraft available for escort duty was increased. The average number of hours flown monthly by Coastal Command aircraft on antisubmarine duty increased to about 6,300 hours per month, 5,100 hours being on convoy escort and 1,200 hours on general patrol. The number of flying hours on antisubmarine work dropped to about 4,000 hours during the winter months of December 1940 and January 1941, because of the poorer weather. By March 1941, however, it was back up to about 8,000 hours per month. This increased amount of flying was partly the cause of the U-boats' leaving the near shores of the British Isles and extending their activities farther westward. As a result of the move-

ment of the U-boats, the antisubmarine flying of Coastal Command became less productive of submarine sightings and attacks. By March 1941 the number of sightings made monthly was only about 14, and the number of attacks was about 8. As before, only about 10 per cent of the attacks resulted in some damage to the U-boat, but now that depth charges were being used about 2 per cent of the 10 per cent represented probable sinkings of U-boats. The lethality of the aircraft against the submarine was slowly increasing.

To help in locating the shadowing submarine, which was sending out radio signals to allow the other U-boats to home on it, the HF/DF sets mentioned earlier were rapidly developed and installed on escort vessels. A carefully constructed and continually manned land-based network indicated the location of every radio transmission from the Atlantic. The combination of shore- and ship-based HF/DF was soon so good that it was possible to estimate the danger of attack on a convoy with some accuracy. Thus it was possible to send Coastal Command aircraft only to threatened convoys, thereby providing an immense saving in effort.

The chief scientific improvement in antisubmarine defenses introduced during this period was the radar set for ships and aircraft. The sets were crude according to present standards, and their efficient use was not yet well understood. Nevertheless these sets enabled attacks to be made on submarines which could not have been carried out otherwise. They were particularly valuable during this phase when the U-boat attacks were mostly at night, although the results from the first installations on escort vessels were disappointing to their designers. The effective ranges on submarines were very much less than had been expected, and a great deal of interference was encountered because of the presence of the convoy. Nevertheless, the sets gave a measure of protection during the night, and immediate steps were taken to improve the range by increasing the directionality of the antennas.

During this second period, surface craft continued to be the most effective weapon in attacking and sinking U-boats, making about 25 attacks a month. Of the 23 U-boats sunk, or probably sunk, in the Atlantic during this period, surface craft could be credited with 13. Allied submarines continued to be highly effective early in the period, patrolling close to the French bases and torpedoing five U-boats in September 1940 and one in December. These submarine attacks made it necessary for the U-boats to enter and leave their bases submerged. Two U-boats were probably sunk as a result of aircraft attacks and one was sunk as a result of a combined attack by ship and plane. One submarine was lost to a mine.

In the Mediterranean, 11 Italian U-boats were sunk in Period II, with surface craft accounting for 6 of them. Italian submarines, in all, had very little success against Allied shipping. Only 5 ships of 28,000 gross tons were sunk in the Mediterranean and the Indian Ocean during the first two years of the war.

When all the returns were in, it could be seen that this second period had resulted in somewhat of a draw between convoys and submarines. The new U-boat tactics adopted had accomplished their primary objective of reducing the high rate of loss of U-boats. The average number of German submarines at sea in the Atlantic during the period rose to about 10, while only about 2½ of these were lost monthly. The average life of a U-boat at sea, therefore, increased from three to four months. In addition, the efficiency of U-boats in sinking ships had increased slightly, since the average U-boat sank four ships of 22,000 gross tons per month at sea. This resulted in an increase in the overall exchange rate for submarines to 16 ships of about 88,000 gross tons sunk for each U-boat sunk or probably sunk; representing a fairly profitable transaction for the Germans.

On the other hand, the Germans had suffered considerable losses early in the period, losing many of their ablest and most experienced U-boat captains and crews, who were not so easily replaced as the U-boats themselves. The necessity of sending out relatively inexperienced U-boat captains was probably a factor influencing the Germans in February 1941 to inaugurate wolf-pack tactics, so that several inexperienced U-boat captains could operate with a more experienced one.

Total Allied shipping losses during Period II

were about 456,000 gross tons a month, more than 60 per cent higher than during the first period. Meanwhile the building rate had increased only slightly to about 114,000 gross tons a month. Total shipping available had been reduced from about 38,000,000 gross tons at the start of the second period to about 35,000,000 gross tons at the end. Of the 456,000 gross tons of shipping lost monthly, the U-boat accounted for 42 ships of 224,000 gross tons a month on the average, more than twice the monthly tonnage sunk by U-boats during the first period. Losses due to enemy surface craft and to enemy aircraft increased somewhat, and losses due to mines dropped to a negligible amount.

There is no doubt that the U-boats had inflicted a serious loss to the Allies during this second period; but the situation was beginning to look more promising toward the end. One favorable element was the increasing number of antisubmarine ships and aircraft becoming available for convoy escort. New ships and planes were being built and since the threat of invasion to England was decreasing, other ships could be assigned to fight the U-boat. The number of antisubmarine ships suitable for ocean escort had increased from about 235 at the start of the second period to about 375 at the end. A new type of escort vessel, the corvette, was coming into use, and the United States transferred to the British 50 old-type destroyers which were of considerable value. All these destroyers were equipped with U.S. echo-ranging gear. Ships and planes were being fitted with radar as fast as possible.

1.5.3 The Situation in the Spring of 1941

This was the situation in the spring of 1941 when NDRC commenced its work on the development of antisubmarine equipment. The U-boats, with their newly developed pack tactics, were showing themselves to be even more dangerous than in World War I. In 1940, Germany had begun to realize that this was not to be a short war and had considerably increased the program of U-boat building. These new U-boats were beginning to become operational in 1941; and by the end of the year they had about 200 ocean-going submarines, and new units were being commissioned at the rate of about 20 a month. Many of the veteran crews and commanders had been killed, but the group tactics enabled comparatively inexperienced U-boat crews to be used fairly effectively. Successful attacks were being made on convoys, although the submarines still preferred attacking independent shipping, as the United States discovered to its considerable cost in the next year.

The most important protection against U-boats was still the convoy. During the summer of 1941, the submarines' wider distribution over the Atlantic forced the British to escort their convoys clear across the Atlantic, and by the end of 1943 complete escorting of all Atlantic convoys, including coastal shipping along the eastern seaboard of the United States, had been adopted. By the middle of 1941, all shipping of less than 15 knots speed, which was crossing the Atlantic, was required to sail in convoy.

An analysis of the convoys during the summer of 1941 gives information about the "average attacked convoy." On the average the convoy was attacked by 4.2 U-boats of which 2.6 succeeded in delivering effective attacks. A total of 4.6 ships in the convoy were torpedoed, 1.7 ships being torpedoed in each effective attack. Of the 4.2 U-boats engaging the convoy, 3.2 were attacked by the air and surface escort, and 0.7 were sunk or probably sunk.

The value of aircraft in antisubmarine work was beginning to be realized. Aircraft had primarily been responsible for forcing these U-boats away from the British shores. In the summer of 1941, the effective lethality of aircraft attacks on U-boats was considerably improved by changing the attack tactics to conform to the fact that most of the effective attacks were against surfaced submarines. By the end of the summer the lethality of aircraft attacks had increased considerably, about 25 per cent of the U-boats attacked by aircraft being damaged. During the summer and fall of 1941, a determined air campaign was begun against the U-boats moving in and out of the Bay of Biscay. By September 1941, each U-boat

was being attacked in the bay on one of every three transits of this area. This was a sufficient menace to force them to remain submerged in the bay during daytime, which increased their transit time considerably.

By the end of 1941, Coastal Command had commenced the experiment of using aircraft at night against U-boats. These aircraft, fitted with radar and searchlights, were to prove a greater and greater menace later in the war.

Attempts were also being made to improve the antisubmarine ordnance for surface vessels. The "hedgehog" device for throwing a number of small contact charges ahead of the vessel was being introduced. This did not immediately prove successful, but it represented a realization that surface craft antisubmarine ordnance must be improved.

A complete discussion of antisubmarine warfare during World War II is given in another volume.[b] Enough is included here to make it apparent why the study of antisubmarine measures was considered by NDRC to be of top priority. Allied shipping was being lost at a dangerous rate. If the losses were not reduced quickly, the whole progress of the war in Europe would be endangered; and Allied shipyards, instead of being able to add importantly to the force of warships, would be compelled to devote most of their facilities to making up, or trying to make up the losses in merchant ships. It was time for the trying out of all sorts of defensive weapons and measures, to see whether some new or improved detection gear or weapon might not be the answer. A re-evaluation was urgently needed.

[b] Division 6, Volume 3.

Chapter 2

SCOPE OF DIVISION ACTIVITIES

By *Edwin H. Colpitts*

WHEN SCIENTIFIC AID in preparing for and conducting subsurface warfare was first envisaged through NDRC, it was felt that this aid should take the form of improving and devising equipment and methods for detecting submerged enemy submarines from surface ships. But the group (later to be identified as Division 6) had scarcely been organized when it was realized that the field of its responsibility as first defined was too narrow.

The unique feature of Division 6 was that its ultimate responsibility was not to develop a particular instrumentality of war or to exploit a particular field of science for military purposes but was to assist the Navy in all ways in which men of scientific and engineering experience and skill could significantly contribute to the prosecution of subsurface warfare. Thus, as the subsurface warfare group began to work, it began to grow and assume added responsibilities. To detection from surface craft was added detection of submarines from aircraft. The development of equipment and devices, first confined to instruments of detection and location, came to include ordnance and decoys. The program of physical research quickly reached out in numerous directions to acquire information basic to the development and use of better gear. The need for operational analysis and research soon led to the establishment of a specialized unit; similar needs for aid to the Navy in the selection and training of personnel and the installation and maintenance of equipment led to the formation of other special divisional groups. As the character of subsurface war changed, the division turned more and more from a program designed to further the antisubmarine effort to one aimed at aiding our own submarines.

2.1 FORMATION OF SECTION C-4

The serious situation facing the Navy and NDRC in the spring of 1941 has been outlined in the previous chapter. It was a situation which had grave implications for the United States which once again was confronted with a tremendous problem of sea logistics.

Certain steps had already been taken. In December 1940 a subcommittee of the Naval Advisory Committee of the National Academy of Sciences was organized to analyze this country's ability to fight a successful submarine war with existing equipment and tactics and to make recommendations how best to employ the scientific and technical talent available to improve our preparedness.

This preliminary analysis, concerned only with the detection and location of submarines from surface craft, pointed out that although the supersonic echo-ranging gear developed by the Naval Research Laboratory in cooperation with the Submarine Signal Company was capable of good performance, the quality and training of Navy sound operators left much to be desired. Also, the lack of understanding of irregularities in the performance of the equipment urged the formation of a broad program of research in the fundamentals of underwater acoustics.

Shortly thereafter the Navy formally requested NDRC to set up a special group to undertake further studies and developments. This request was promptly acted upon and Section C-4 was created to develop new and improved means for detecting submerged submarines. The group continued its activities as Section C-4 until the creation of OSRD after which it became Division 6.

2.2 FORMULATION OF A PROGRAM

EQUIPMENT

Enough of the NRL echo-ranging equipment had been produced and installed on ships to enable some determination of its capabilities as well as its limitations. This was supported and

amplified by data covering British experience with quite similar ASDIC gear under actual combat conditions. This background of information indicated definite steps which should be taken to improve the performance of the equipment and to secure its more effective use.

Some of these steps had already been taken. Both the British and American Navies were experimenting with new projector housing or "dome" designs to permit echo ranging at higher ship speeds. The British had also developed an improved range recorder which could be adopted with very little change. However, other modifications were suggested which appeared likely to improve the overall performance by reducing the level of operator skill necessary for satisfactory operation and increasing the speed and ease of operation.

Because of the time elements involved in the development, design, production, and introduction into Service use of any radically new equipment it was apparent that if war came it must be fought, possibly through its most decisive period, with instrumentalities already available. The matter of greatest urgency, therefore, was to improve the effectiveness of existing designs.

For this reason only, all proposals for modifications were carefully examined and rejected unless they appeared to have a good chance of meeting these requirements of time and applicability.

A more basic attack was made on the echo-ranging problem by two of the division laboratories which led to the development of two scanning sonar systems. It was realized when undertaken that these were long-term projects which might not find actual employment unless the war was very much prolonged. Both systems, however, including the XQHA and the QLA, reached the stage of prototype construction during the course of the war. As a matter of interest it is understood that a number of sets employing one of these methods were installed on fleet-type submarines and very effectively employed late in the war for a critical operation in the Sea of Japan.

Further development of these systems to provide increased range, depth angle determination, and increased flexibility of application was under way when the laboratory programs were terminated. These projects are being continued by permanent naval laboratories, and it is anticipated they will ultimately result in the production of highly useful systems for both surface and subsurface service.

Aircraft were obviously destined to play a most important role in the war against the submarine. It soon came to be realized that, to make aircraft fully effective, their ability to detect and attack surfaced submarines should be supplemented by means for detecting and attacking submarines after submergence or when submerged. As will be described in this report, most energetic efforts were made by the division to render aircraft more effective both with respect to means for detecting or locating the submarine, and with respect to ordnance for its destruction. These endeavors resulted in the development of the *magnetic airborne detector* [MAD], the *radio sono buoy* [DRSB and ERSB], and of a highly secret mine, all of which found effective employment in combat.

Fundamental Research

It was fully realized that any basic improvement in either equipment design or operating doctrine must be based upon a clearer understanding of the physical principles involved. The fundamental importance of such knowledge to the entire effort of the division warranted the establishment of a broad research program in underwater acoustics and oceanography. Included in the scope of this activity were theoretical and experimental investigations of sound transmission, reverberation, reflection, and refraction.

Data made available by these studies not only provide information for equipment design but also apply directly to operations. Echo-ranging efficiency is peculiarly dependent upon water conditions. To employ echo ranging most effectively, therefore, these varying water conditions must be thoroughly understood by those who would attempt to lay down operating doctrine or prescribe operating practice. The same knowledge of underwater sound transmission is required in formulating and operating the training program for sound personnel, in order

that operators and officers may appreciate the possibilities and limitations of their equipment and be trained to meet the various sound conditions they will surely encounter.

Closely related to the above research effort was the immediate effort devoted to developing and standardizing means and methods for sound measurements. This latter program, among other results, enabled those designing and producing sound gear for the Navy to determine in a common language the efficiency of their product and often indicated permissible modifications by which its performance could be improved.

As the scope of the division increased, further important researches were undertaken in the fields of piezoelectricity and magnetostriction theory and practice which yielded greatly improved transducers. Also, fundamental studies in fluid dynamics led the way to improved torpedoes and other projectiles.

Operations Research

A step most important to securing effective use of gear and methods was the establishment of the Operations Research Group. The activities of this group concerned all operational aspects of antisubmarine warfare including methods not otherwise the concern of Division 6. Not only did the studies of the Operations Research Group enable available gear to be used more effectively, but these studies were also important in indicating deficiencies in the operation or design of equipment under actual conditions of war. With this information, intelligent action could be taken in accurately specifying desirable functions to be provided by modified or new gear.

Selection and Training of Personnel

The British had already found that the effectiveness of sound personnel under combat conditions was very dependent upon the amount and adequacy of their training. This fact was also fully recognized by the U. S. Navy. As another step toward effective use of already available gear, the division complied with the Navy's request for assistance in selecting and training sound operators. Later on the program was broadened to include other personnel as well.

Under the general supervision of a special committee appointed by the division, direct assistance was given in Navy schools, operating bases, and other establishments in the selection and training of sonar operators, officers, and attack teams. A large number of training aids and classroom demonstrators constructed by the several laboratories supplemented this program effectively.

The division feels that the contribution it was able to make in assisting the Navy with its task of selecting and training operating personnel significantly aided the final success achieved in both the Atlantic and Pacific areas.

Torpedo Program

The division's program for torpedo research included the study and development of sound-controlled underwater missiles, power plants for electrically propelled torpedoes, and basic design considerations relative to a torpedo capable of being dropped from a high-speed plane.

Most of the division's subsurface ordnance research was directed towards modifying and improving existing torpedoes. Although the application of acoustic homing control was undertaken with considerable skepticism, the division was successful in developing sound controls for both slow-speed and high-speed torpedoes. The air-launched, acoustically controlled antisubmarine Mark 24 played a very real role in controlling and eliminating the U-boat menace. The submarine-launched Mark 27 was designed as a prosubmarine weapon for use during evasion maneuvers, but it was actually used as an effective offensive weapon. The division also developed echo-ranging homing control for both ship-launched and air-launched torpedoes which performed satisfactorily in field tests.

The fundamental studies and design work relative to a torpedo capable of being dropped from a high-speed plane were embodied in experimental structures, but the war ended before actual production was begun.

Important projects relating to power plants for electrically propelled torpedoes included the development of high-capacity sea-water batteries and an efficient counterrotating motor. These are expected to make possible much

quieter operation which is significant in the application of acoustic homing control. Also included was the provision of a maximum range and speed equivalent to the present steam turbine torpedo. These developments produced promising results, but they were not applied to torpedoes in combat use.

Prosubmarine Activities

Although the division's effort for perhaps the first year and a half was almost wholly related to antisubmarine warfare, it became increasingly clear that there were possibilities of assisting our own submarines in their operations both by development of certain gear and in training of personnel.

A prosubmarine committee was organized which established and maintained close contact with the submarine forces in both the Atlantic and the Pacific, supplementing the established liaison with COMINCH and the Bureaus. Upon their recommendations a major effort was devoted to an increasing number of prosubmarine activities.

Results of this quite comprehensive program made available to the submarine forces improved listening and echo-ranging gear, new instruments to assist escape from depth-charge attack, special noisemakers and submarine-simulating decoys designed to distract or mislead enemy efforts at detection, as well as certain ordnance devices and assistance in training and maintenance.

Field Engineering

A step which perhaps should have been taken earlier in order to secure the optimum performance possible with existing or new equipment was assistance to the Navy in maintenance. Although certain maintenance work had been done earlier, the opportunity to provide direct assistance to the Navy only became evident when new types of gear were being introduced. As a result of the large number of ships being fitted for ASW duty and the scarcity of adequately trained and experienced personnel, the ASW gear was frequently found to be faultily installed or in poor adjustment. To solve these problems, the Bureau of Ships requested the division to organize and train a group of experienced engineers to be assigned for duty at Navy yards and bases and with the forces afloat to assist in the setting up of proper maintenance procedures. The scope of the Field Engineering Group's work was eventually broadened to include assistance to the Navy in installing and operating new gear, training personnel, and exchanging information between Navy personnel and the laboratories.

Facilities

To implement the broad program objectives undertaken, the division found it necessary to set up a number of special laboratories and groups in addition to the existing facilities. These were both academic and commercial and were secured by contract. Although fullest recognition should be given to the numerous contributions made by these organizations, their very number prohibits their inclusion in this chapter. An attempt is made in the next chapter, however, to list and describe the principal organizations and groups that participated in the division programs.

2.3 CONCLUSION

The OSRD and NDRC were established to meet a war emergency and consequently it was always understood that their operations would terminate as the end of the war approached. The termination involved the transfer of activities from Division 6 support and direction to Navy support and direction. Plans which operated very effectively were worked out cooperatively among the Navy, the division, and the division's contractors. In a substantial number of cases the Navy was able to take over either completely or in large part the going organization which the division had built up, thus assuring continuity of work in these cases. These transfers, made during 1945, adequately provided for any activities which seemingly should be continued longer, and it is believed that they were accomplished at a wisely chosen time.

In large measure, the very serious losses to U-boats sustained during the early years of the war were due to the lack of ships, equipment,

and trained personnel, rather than to a lack of technical preparedness. In many cases, however, serious deficiencies in equipment and tactics were uncovered by the application of the principles of objective analysis. Perhaps the division's greatest contribution was its assistance in organizing and supporting an effective Operations Research Group to study scientifically the operational requirements of the Navy. On the basis of knowledge thus gained and because of the close cooperation given by the Navy in providing facilities and helpful liaison, it became possible to plan a realistic and directly useful program of equipment development. Experience shows that if this close cooperation of the Navy and civilian scientists realized during World War II had been possible between the wars, both the Navy and its civilian assistants would have been better prepared to meet the emergency when it arose.

Although it is very clear that certain basic physical research and possibly certain equipment development should be continued, the experience of the division suggests that an increased emphasis should be placed upon processes which can lead to more clearly defined program objectives.

To achieve future preparedness and perfection in the operation of a system of men and equipment, such as in subsurface warfare, performance must be continually analyzed in the light of new requirements of the Navy and new developments in science. Those in charge of the program must continually study the analysis and apply information thus gained to the perfection of the system. This kind of work requires the closest cooperation between Navy staffs and civilian scientists in industry and academic life. The men in charge of the planning program must be closely in touch not only with Navy operations but also the scientific life of the nation. Only in this way will they be able to direct a balanced program of research, development, and improvement which will assure continued readiness for future subsurface warfare.

Chapter 3

ORGANIZATION OF THE SUBSURFACE WARFARE GROUP

By *Elmer Hutchisson*

3.1 EARLY ORGANIZATION AND GENERAL PROGRAM

3.1.1 Introduction

ALTHOUGH THE FIRST official act in connection with the formation of a section of NDRC on antisubmarine warfare was a letter[a] dated April 10, 1941, from Rear Admiral S. M. Robinson to Dr. V. Bush, Chairman of NDRC, requesting that NDRC undertake a study of the problem of submarine detection, there were several preliminary steps which deserve mention.

THE "COLPITTS COMMITTEE"

Some six months previous to this letter, the National Academy of Sciences, at the request of the Navy, had appointed a committee,[b] under the chairmanship of Dr. E. H. Colpitts, "to study the scientific aspects of protection against submarine warfare," and to "ascertain the degree and adequacy of the present effort." This committee recommended that an immediate and intensive program of investigation of all phases of the problem of submarine warfare be undertaken. Following the submission of this report, several discussions were held by various officers of the Navy, with Dr. Bush, Chairman of the National Defense Research Committee, and with Dr. F. B. Jewett, President of the National Academy of Sciences. Both Dr. Bush and Dr. Jewett had been asked to appear before the general board of the Navy to make recommendations regarding the best type of organization for such a comprehensive study of the submarine problem.

Dr. Bush and Dr. Jewett assured the Navy that both NDRC and the National Academy of Sciences were prepared to do everything that was necessary to get under way, as soon as possible, a broad program of research in the antisubmarine field.

COORDINATION WITH BRITISH EFFORT

In 1940, at the time that the National Academy report to the Navy was being made, a British Commission in this country under the leadership of Sir Henry Tizard, recommended the sending of one or two civilian scientists to England to confer directly with scientists of the Admiralty on the work which was being done in Great Britain on the detection of submarines. In January 1941, this recommendation was repeated by Dr. R. H. Fowler of the British Central Scientific Office. The proposal was discussed with high-ranking naval officers and it seemed best that two men be sent under NDRC auspices. Accordingly, Dr. Bush requested Dean John T. Tate of the University of Minnesota, and Professor Slichter of the Massachusetts Institute of Technology to visit Great Britain to confer with the British scientific people on what they were doing in submarine detection, with a view to supplementing the information which our Navy had obtained through their contacts. Doctors Tate and Slichter left for England on April 7, 1941.

3.1.2 Plan of Organization

Thus, when Admiral Robinson, on April 10, 1941, requested NDRC to undertake an investigation of the problem of submarine detection, preliminary negotiations had already been made. It was clear that this work in NDRC should be undertaken in Division C, which was under the chairmanship of Dr. Jewett. It was clear also that a vice-chairman should be appointed to correlate all work in this field. It seemed desirable not to disturb any of the work already going on in other NDRC divisions that

[a] See Appendix A.

[b] Members of this committee were: W. D. Coolidge, V. O. Knudsen, L. B. Slichter, H. G. Knox, Secretary, and E. H. Colpitts, Chairman.

might be applicable to the detection of surfaced submarines, and to confine the work of the new subdivision to the detection of submerged submarines.

Dr. Jewett, in consultation with Dr. Bush, prepared a memorandum[c] proposing a definite form of organization which would have the following objectives.

1. The most complete investigation possible of all the factors and phenomena involved in the accurate detection of submerged or partially submerged submarines and in antisubmarine devices.
2. The development of equipment and methods for use of promising means for detection to the point where their final embodiment in form satisfactory for naval operation can be undertaken by the regular bureaus of the Navy.

This plan further outlined the facilities which would be required.

In Dr. Jewett's proposed plan, he stated that NDRC could assist primarily in organizing the scientific work, in locating personnel, and in making necessary contracts with academic, industrial, and other institutions. To be successful, however, the Navy should provide special laboratory facilities, marine facilities, and necessary personnel for operating them and for policing the establishment, and, in general, take complete responsibility for the nonscientific operation of the laboratory.

It was recommended that two central laboratories should be provided, one on the Atlantic coast, which, because of the close liaison that could be maintained with Washington, would be concerned primarily with the final stages of research and development; and the other on the Pacific coast, charged primarily with carrying to completion fundamental research work in fields applicable to antisubmarine warfare. For the scientific work of the Atlantic coast laboratory, NDRC would provide a director who had had long industrial experience. For the scientific work at the Pacific coast laboratory, NDRC would provide a director who had had wide experience in fundamental research in the fields involved. It was proposed that the Atlantic coast laboratory be located at New London, Connecticut, and that the Pacific coast laboratory be located at San Diego, California.

[c] See Appendix B.

This proposal was submitted to NDRC and was approved at its meeting of April 18, 1941. On this same date, Dr. Bush submitted to Admiral Robinson a memorandum[d] embodying the proposal and suggested that if Admiral Robinson concurred, NDRC would proceed to organize the special committees or sections contemplated, and to put the plan in operation as promptly as possible. Admiral Robinson replied[e] stating that the suggested setup seemed satisfactory and that he would initiate the necessary Navy arrangements for carrying it out.

3.1.3 Early Stages of Organization

Following the receipt of Admiral Robinson's letter, Dr. Bush[f] immediately asked Dr. Jewett to proceed to put the plan into effect. Dr. Tate, who was still in England, had been appointed vice-chairman of Division C, NDRC in December 1940. He was now designated Chairman of Section C-4 which was to be concerned with submarine detection.

Dr. Jewett, on April 23, 1941, called a conference with Doctors W. D. Coolidge, E. H. Colpitts, O. E. Buckley, and C. O'D. Iselin to discuss the detailed organization of the submarine detection program. Subject to approval of the contracting universities, Mr. T. E. Shea, Vice-President of the Electrical Research Products Company, was asked to assume the directorship of the New London laboratory and Dr. Vern O. Knudsen, Dean of the Graduate Division, University of California at Los Angeles, was asked to assume the directorship of the San Diego laboratory.

Proposed Contracts

On April 29, 1941, Dr. Jewett called a conference with Messrs. Colpitts, Shea, and G. B. Pegram, Dean of the Graduate School, Columbia University, to discuss contractual arrangements which would be made to staff and operate the east coast and west coast laboratories. Dean Pegram was asked if Columbia University would become the contracting agent for the

[d] See Appendix C for letter of transmittal.
[e] See Appendix D.
[f] See Appendix E for letter to NDRC.

east coast laboratory, and Dr. Knudsen was asked to determine whether or not the University of California would be the contracting agent for the west coast laboratory.

On May 1, a conference was held at the National Academy of Sciences' Building in Washington, which was attended by Messrs. Jewett, Colpitts, Coolidge, Shea, Pegram, R. W. King, Iselin, and Knudsen. Representing the Navy at this meeting were Admiral Robinson and Lieutenant Commander M. K. Kirkpatrick, who were concerned with the providing of facilities at New London and San Diego by the Navy. Commander Kirkpatrick was appointed liaison officer to consult with Mr. Shea regarding the principal requirements of the proposed NDRC laboratory at New London. Dr. Knudsen was asked to consult with Captain W. J. Ruble, Director of the U. S. Navy Radio and Sound Laboratory at Point Loma, San Diego. Because Dr. Tate had not yet returned from England, Dr. Jewett asked Dr. Colpitts and Dean Pegram to take preliminary steps in setting up an organization.

On May 19, 1941, Doctors Tate and Slichter returned from England, and on June 5, the following Section C-4 members were officially appointed: Carl D. Anderson, E. H. Colpitts, W. D. Coolidge, E. O. Lawrence, Max Mason, and G. B. Pegram.

As a first step in setting up a central headquarters, space was rented on the 11th floor at 172 Fulton Street, New York City. Dr. Elmer Hutchisson was appointed Technical Aide and was asked to set up the New York office. On July 1, Miss Fern Sullivan was appointed to the staff and began to organize secretarial facilities.

3.1.4 Formulation of a Technical Program

Considerably before the formal request for NDRC to undertake an investigation of the field of antisubmarine warfare, Dr. Tate and others had given much thought to a program of work which might be conducted if authorization were given. In March 1941, conferences were held at the Bell Telephone Laboratories [BTL] in New York and at the Submarine Signal Company in Boston to discuss possible projects.

On March 28, 1941, a conference was held at BTL at which a memorandum[g] prepared by Dr. Fletcher, entitled "An Outline of Fundamental Research Work on Underwater Acoustics," was presented.

Also discussed at this meeting was a memorandum[h] prepared by Mr. W. H. Martin, entitled "Suggested Program on Measurement Means and Technique for Underwater Work."

Magnetic Detection

In addition to these discussions on underwater acoustics, Dr. Slichter had been giving considerable thought to the feasibility of detecting submarines by magnetic methods.

For some time, the Gulf Research and Development Corporation laboratories had been working to develop a magnetic method of locating mineral deposits, and it seemed possible that some of the results of the Gulf research might be adapted to the detection of a magnetic mass under the sea as well as one under the earth.

As early as November 20, 1940, Dr. Slichter had proposed to Dr. Jewett a scheme[i] for magnetic detection which he thought might have a range of hundreds of feet, possibly as much as 2,000 feet. Dr. Slichter believed that the sweeping rate could be made to compare favorably with supersonic gear on surface craft in which the greater detection range was offset by the comparatively slow speed of a surface vessel. It was primarily to learn of the progress being made by the British in this field that Dr. Slichter went to England with Dr. Tate in April 1941.

Oceanographic Studies

Early thinking had taken other directions. In August 1940, C. O'D. Iselin, Director of the Woods Hole Oceanographic Institution [WHOI] sent to Dr. Jewett a memorandum concerning the research facilities applicable to submarine warfare available at WHOI. He indicated the possibility of studying the impor-

[g] See Appendix F.
[h] See Appendix G.
[i] See Appendix H.

tance of the thermal structure of the ocean as a factor in submarine detection methods. After considerable discussion with the Navy, a detailed outline[j] of the proposed study of the oceanographic aspects of the sound-ranging problem was prepared on September 19, 1940. There was outlined, in order to carry out the study, field work, laboratory work, and instrumental developments which would be necessary. The *Atlantis*, the research vessel of WHOI, could be employed approximately half-time on this project, and could, in cooperation with a vessel such as the destroyer USS *Semmes*, obtain a great amount of information in this field.

The program of work outlined by WHOI seemed so important that NDRC on September 27, 1940, decided to set up a contract with this institution for an amount of $100,000 to carry on this program over a period of two years. It was recognized that this work was basic to any broader program which might be undertaken and that there was no reason for not beginning that work early. If and when a more comprehensive antisubmarine program were started, the work being done at Woods Hole would fit into the general program. Dr. Tate, therefore, kept in close touch with this work.

3.1.5 Central Laboratories

As soon as it became evident that two central laboratories were to be organized, detailed programs for these laboratories were formulated. The immediate program contemplated for the New London laboratory involved (1) study of the possibilities of magnetic detection methods; (2) study of the possibilities of optical detection methods; (3) further development of supersonic detection methods and equipment; (4) study of types of sonic detection equipment, other than supersonic; (5) in cooperation with WHOI, study of correlations between oceanographic conditions in the Atlantic with the performance of various types of detection equipment; (6) study of background noises and methods of reducing them; and (7) development of improved acoustical measuring equipment.

[j] See Appendix I.

The San Diego laboratory was assigned primary responsibility for carrying out fundamental investigations. At a meeting of an advisory group at Pasadena on June 7, 1941, it was agreed that immediate work should be begun on the following projects.

1. Study of the reflections of impulse sounds from boundaries in typical areas of the ocean near San Diego, in which the sound conditions vary from exceptionally good to average and decidedly poor.
2. Investigation of the sound transmission properties of typical ocean areas, using low-, medium-, and high-frequency sound in the audible range, and low, medium, and high frequencies in the supersonic range.
3. Immediate work on the development of a "predictor," or attack meter.

As a result of this preliminary planning, a rather complete program in the field of antisubmarine warfare was prepared and presented to NDRC at its meeting of June 12, 1941.

The work of the central laboratories is described in detail in later sections of this chapter.

In June 1941, a research and development program was established under contract at Harvard University. During its life, the program included the developments of important improvements to existing sonar gear and the development of one of the two principal types of scanning sonar, basic research on transducers, and highly significant work in the development of acoustic torpedoes. In addition, valuable work was done to devise sonar testing and training equipment. Under the leadership of Director Frederick V. Hunt, of Cruft (formerly Associate Professor of Physics and Communications Engineering at Harvard), the Harvard Underwater Sound Laboratory, with the central laboratories at New London and San Diego, was one of the three principal laboratories engaged in sonar research and development work.

3.1.6 Initiation of Formal Section Meetings

The first formal meeting of Section C-4 occurred in New York on June 11, 1941. Messrs. Tate, Colpitts, Coolidge, Iselin, King, Pegram,

Shea, and Slichter were present. The principal items of business presented to the meeting were the technical programs at the New London and San Diego laboratories and the budget both for the fiscal year ending June 30, 1941, and the fiscal year ending June 30, 1942. The members of the section approved the programs and the following budget was set up.

Estimate of Expenditures

	Through June 30, 1941	July 1, 1941-June 30, 1942
For the New London laboratory	$ 45,000	$1,000,000
For the San Diego laboratory	30,000	900,000
For the contract with industrial laboratories	60,000	800,000
For university or other non-profit laboratories	5,000	300,000
For administration	2,000	100,000
	$142,000	$3,100,000

Immediately after the meeting on June 11, 1941, Dr. Tate submitted to Dr. Jewett the budget which had been approved at the section meeting. This was for presentation at the meeting of NDRC to be held the next day. At the meeting of NDRC, authorization was given to enter into the following contracts.

For Operations Through June 30, 1941

Columbia University for the operation of the New London laboratory	$ 45,000
University of California for the operation of the San Diego laboratory	30,000
Harvard University for preliminary studies of submarine noises	5,000
Western Electric Company for development of magnetic detection methods	5,000
General Electric Company for development of magnetic detection methods	5,000
For Operations for the Fiscal Year Beginning July 1, 1941 from 1941-42 Funds when Available	
Columbia University for initial operations of the New London laboratory	$300,000
University of California for initial operations of the San Diego laboratory	300,000
Western Electric Company for study of hydrophonic calibration and measurement	20,000
Western Electric Company for development of standard projectors	15,000
Western Electric Company for development of standard pickup units	15,000

The scope of the division's program expanded rapidly necessitating corresponding expansions in facilities, staffs, and expenditures of the laboratories established to undertake work for the division. Also, the number of contracts with industrial organizations was increased. As some measure of the activity involved, the annual expenditures under the division's contracts quite promptly rose to, in round figures, $14,000,000. This, of course, takes no account of cost of ship facilities, ship personnel, and buildings furnished by the Navy, which was a very substantial item.

In the following sections certain of the facilities organized under Division 6 will be described.

3.2 FACILITIES ORGANIZED UNDER DIVISION 6

3.2.1 Central Headquarters

In June 1941, a headquarters office was set up at 172 Fulton Street, New York. The staff of this office included Dr. Tate, then Vice-Chairman of Division C and Chairman of Section C-4, Dr. Colpitts, then Consultant to Division C, several technical aides, and a secretarial staff. As the work of the group expanded, more space was needed and in July 1943, the headquarters office moved to the Empire State Building, first on the 50th floor and later on the 64th floor.

It was the responsibility of this administrative group to establish the general program of work and after examining and sifting out the various suggestions of specialists in the fields to be covered, to propose to Section C-4 contracts with academic and industrial institutions to carry out the work required. The section met several times a year to consider critically the proposals submitted and, if satisfactory, to recommend them for action by NDRC. Originally, the section consisted of Dr. Tate as chairman and Doctors Anderson, Colpitts, Coolidge, Lawrence, Mason, and Pegram. In August 1941, Messrs. Paul D. Foote, Philip M. Morse, and T. E. Shea were added to the section.

An important adjunct to the central administrative office was a group of scientists, at first designated the Program Analysis Group but later the Special Studies Group, employed un-

der a contract with Columbia University. This group, which will be described later, carried on a continuous analysis of the program of the section as related to its fundamental objectives.

To assist the Navy in keeping in touch with the progress of the work of the section, comprehensive reviews were held from time to time which were attended by a large and representative group of naval personnel. Rear Admiral Robinson had appointed Rear Admiral A. H. Van Keuren, Assistant Chief of the Bureau of Ships, as the chief liaison officer with the Navy and the first of these reviews was held in his office on September 5, 1941.

On July 1, 1941, the Office of Scientific Research and Development had been established by Executive Order. Dr. Bush was made director, and NDRC as well as CMR (Committee on Medical Research) became advisory committees to the director. In the reorganization, Sections C-4a and C-4b were merged as Division 6 of NDRC. Dr. Tate was made chief of the division and Dr. Colpitts became Chief of Section 6.1, which was the only section in the division. The organization of the work under way remained unchanged. The section and division headquarters were the same and the functions of the headquarters group remained essentially the same.

Following a period of growth and organization, work proceeded in the following divisional units:

New London Laboratory, contractor, Columbia University
Airborne Instruments Laboratory, contractor, Columbia University
Special Studies Group, contractor, Columbia University
Underwater Sound Reference Laboratory, contractor, Columbia University
Operations Research Group, contractor, Columbia University
Field Engineering Group, contractor, Columbia University
San Diego Laboratory, contractor, University of California
Underwater Sound Laboratory, contractor, Harvard University
Hydrodynamic Laboratory, contractor, California Institute of Technology
Torpedo Power Plant Laboratory, contractor, Massachusetts Institute of Technology
Torpedo Fuel Laboratory, contractor, Massachusetts Institute of Technology

In addition, already established facilities were employed under contract such as those of WHOI and of many industrial organizations. Detailed descriptions of certain of these organizations will be given in later sections of this chapter.

An important part of the work of the division staff was the editing and distribution of reports of work going on in the laboratories. In coordinating a program having such a wide subject matter diversification as well as such wide geographical distribution as that of Division 6, it was essential that accurate and up-to-date progress reports be distributed at regular intervals to all of those working in this field in Division 6 laboratories and in Navy laboratories. It was important that the reports reach those who were authorized to receive them and yet there were many parts of the program which were so secret that the distribution had to be very limited. During the later stages of the work, a bimonthly printed bulletin of some 50 to 100 pages which covered progress in all of the research work that had a rather general interest and could be given a wide distribution was prepared by the division. As each individual project was finished a final report was prepared by the laboratory and, after approval by the division chief, was distributed to an authorized list. Finally Division 6 contracted with Columbia University to assemble, edit, and print a summary report of the work of Division 6, of which this chapter is a small section.

The remaining sections of this chapter will describe the separate research and laboratory facilities organized under sponsorship of Division 6. Little will be said in this chapter about the technical programs since these are the subject of the several volumes which make up this final report.

3.2.2 Special Studies Group

The Special Studies Group, first termed the Program Analysis Group, was set up during the summer of 1941 under a contract with

Columbia University (OEMsr-20) to make studies and analyses of various problems associated with subsurface warfare under the direction of Section C-4 and later under Division 6. The studies requested and undertaken may be roughly classified into three groups.

1. Study of the physical factors underlying the work carried on at various laboratories operating under Section C-4.

2. Theoretical studies of both an analytical and a statistical nature of certain basic problems connected with the methods, the instruments, and the tactics of subsurface warfare.

3. Design of a torpedo capable of being dropped from a high-speed plane.

The group expanded considerably after its inception. At one time, there were two subgroups, A and B, under the direction of Dr. Slichter and Dr. W. V. Houston, respectively. Dr. Slichter transferred to other work on December 31, 1942, and the two groups were combined. On August 31, 1943, the personnel of the group included the director, Dr. Houston, a full-time staff of 12 scientists, 2 part-time scientists, a group of computers, and an office force of 5 secretaries. A section of the Special Studies Group which became known as the Sonar Analysis Group performed the important function of analyzing the data on underwater sound transmission collected by Woods Hole and the San Diego laboratory. The results of their analyses of these data were furnished to the Navy in a form to enable that Service to employ its conclusions effectively. The work of the Sonar Analysis Group was carried on in close liaison with the Navy groups interested.

The more important projects to which the Special Studies Group contributed, and on which reports were issued, are as follows.

1. Tactics of A/S Attack. (Studies in cooperation with Operations Research Group.)
2. Ordnance Probability Studies.
3. Mines and Torpedoes.
4. A/S Rocket Projectile (Mousetrap).
5. Transmission of Underwater Sound.
6. Prediction of Maximum Sound Ranges.
7. Underwater Explosion Studies.
8. Study of the Nature and Properties of Wakes.

In addition, various members of the group assisted in the following programs.

9. Directional Radio Sono Buoy.
10. Practice Echo-Ranging Targets.
11. Small Boat Listening Equipment.
12. Improvement of WEA-1 Echo-Ranging Gear.
13. Project MERCHANT—Study of Sound Gear for Protection of Fast Merchant Ships.
14. Oceanographic Program.

Also, the group operating in conjunction with the NDRC Transition Office assisted the laboratories in preparing projects for small-scale or quantity production, analyzing possible methods of cutting down the time between the completion of research and the actual introduction of the device to Service use.

Finally, this group was frequently called on to analyze various new suggestions for attacking and destroying enemy submarines and for protecting our own submarines.

3.2.3 Underwater Sound Reference Laboratories

It was clearly recognized that it would be necessary to establish accurate primary and secondary reference standards. Without such standards it would be impossible to compare results obtained in the east coast laboratories with those obtained in Great Britain or even on our west coast. Consequently, on July 1, 1941, a contract was arranged with the Western Electric Company, authorizing the Bell Telephone Laboratories to develop standard instruments and testing equipment and to study testing and calibrating methods for use in underwater sound measurements. They were also authorized to set up test stations in locations suitable for carrying on this work in close relation to the general subsurface warfare program of the NDRC for the Armed Services, principally the Navy. Test stations were set up under this contract at Mountain Lakes, New Jersey, and at Orlando, Florida.

On April 15, 1942, at a meeting called by Admiral J. A. Furer, Coordinator of Research and Development for the Navy, it was decided

that these laboratories, in view of their importance to other groups working on underwater sound, should be operated by an independent organization not having a direct interest in the development or manufacture of any underwater sound devices. Accordingly, on the recommendation of Division 6 the laboratories were transferred by OSRD to Columbia University, Division of War Research, to be operated under contract OEMsr-20 beginning May 1, 1942. Dr. Robert S. Shankland, Professor of Physics, Case School of Applied Science was appointed Director. At the same time Admiral Furer appointed a committee for the standardization of hydrophones to help correlate the work of the laboratories, and to advise on units and reference standards to be used generally in underwater sound measurements.

The first meeting of the committee was held on April 24, 1942. Dr. Shankland was elected chairman. The members were P. N. Arnold, representing the Naval Research Laboratory; A. H. Inglis, Bell Telephone Laboratory; J. M. Kendall, Naval Ordnance Laboratory; Frank Massa, Brush Development Company; P. M. Morse, Massachusetts Institute of Technology; H. F. Olsen, Radio Corporation of America; and Lt. (j.g.) J. T. Burwell, Office of Coordinator of Research.

Arrangements were also made with the Bell Telephone Laboratories for the transfer to the laboratory staff on a leave of absence basis of six people, who had been associated with the work: E. Dietze, F. H. Graham, E. Hartmann, R. J. Tillman, M. E. Quinn, G. D. Weldon.

In addition to the skeleton staff obtained from the Bell Telephone Laboratories, a group of physicists, engineers, technicians, and an office force were engaged to make the necessary tests and calibrations at the two test stations, to carry out the necessary design work of mechanical and electrical devices needed for the calibration and test programs, and to make analyses and theoretical studies of the data obtained to be submitted in the form of reports for distribution by the division.

The original equipment which the Bell Telephone Laboratories turned over to Columbia University comprised at each of the two test stations a laboratory building, testing pier

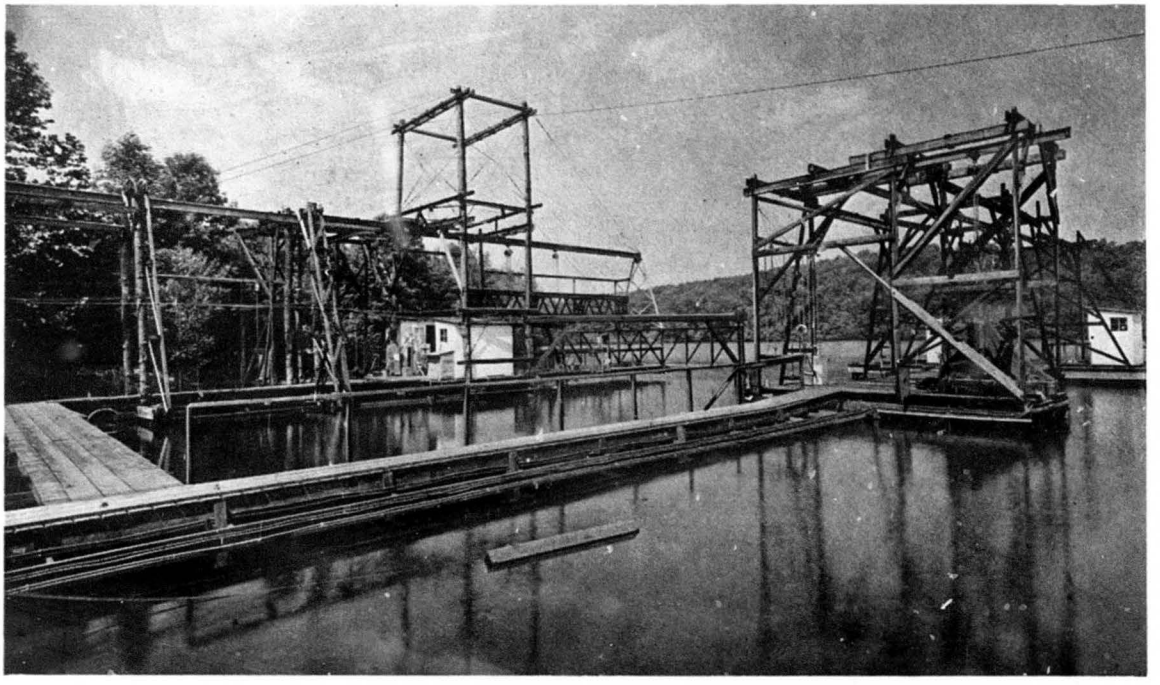


FIGURE 1. Testing piers at the Mountain Lakes Station. The booths housing terminal equipment and the overhead monorail systems are visible.

and handling equipment, electrical measuring equipment, and hydrophone and projector standards suitable for making tests and calibrations in the frequency range of about 40 c to about 100 kc. The testing equipment was continuously improved and expanded so that facilities eventually were arranged for calibrations over a frequency range from 2 c to

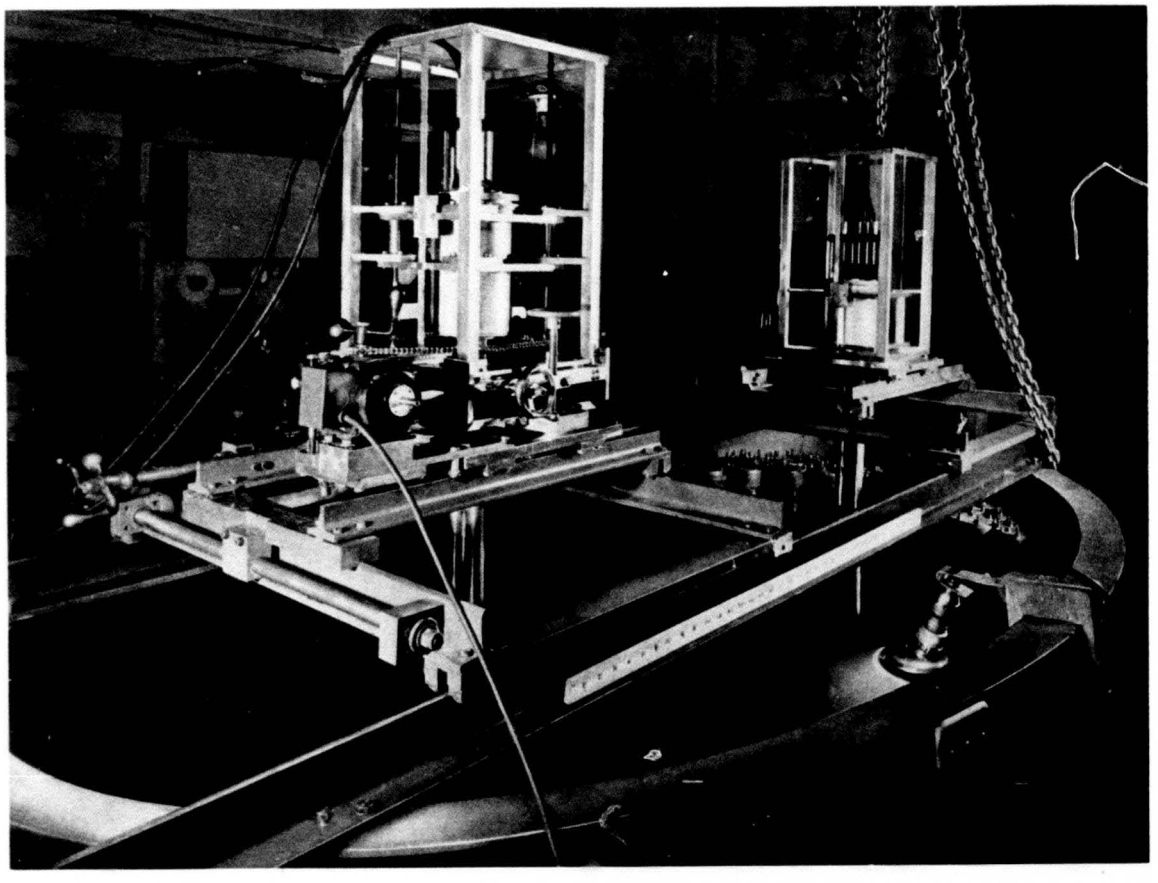


FIGURE 2. View of high-frequency calibration tank, showing mechanical equipment for holding and positioning the instruments.

2½ mc, and for permitting measurements at powers up to 1,500 watts, hydrostatic pressures up to 150 psi, and temperatures ranging from 0 to 100 C. Among the steps in the improvement were the complete replacement in the fall of 1942 of the original testing equipment at Orlando with BTL equipment of improved design, and the rebuilding of the testing pier at Orlando so that devices weighing up to 2 tons could be accommodated. In the spring of 1943, a second pier and what was essentially a duplicate set of electrical testing equipment were provided for Mountain Lakes under contract OEMsr-212 between OSRD and the Western Electric Company.

Only work of direct value to the war effort was undertaken by USRL. Tests for commercial concerns were made only when they were developing apparatus for the Navy (or in rare instances for the Army) and all such tests were made either at the request of the Navy or with its approval. No charges were ever made for tests or calibrations carried out by USRL, since none of its work could be classed as "commercial" in the usual sense of this term.

The data and log sheets taken at the test stations were sent to the New York office of USRL where they were analyzed and final reports on the work were prepared.

During the war period USRL made tests and

calibrations for more than 25 organizations that were developing and using underwater sound devices in the war effort. These included: the National Research Council of Canada; the British Admiralty Delegation at Washington; Naval Ordnance Laboratory; Naval Research Laboratory; U. S. Signal Corps Laboratory; Bureau of Ships, Navy Department; USS Corporation; Astatic Corporation; General Electric Company; Edward G. Budd Manufacturing Company; Aircraft Radio Laboratory, Wright Field; Radio Corporation of America; Submarine Signal Company; Bell Telephone Laboratories, Murray Hill, N. J.; and the Brush Development Company.

In order to complete the record of the division's calibration activities it should be added that after the transfer of the two sound reference laboratories, as above indicated, provision was made for continuing certain work at BTL. Under one contract assistance was rendered to USRL in further development and expansion of its test facilities, while under a second contract BTL produced a substantial number of standard instruments which were distributed to Navy and NDRC agencies.

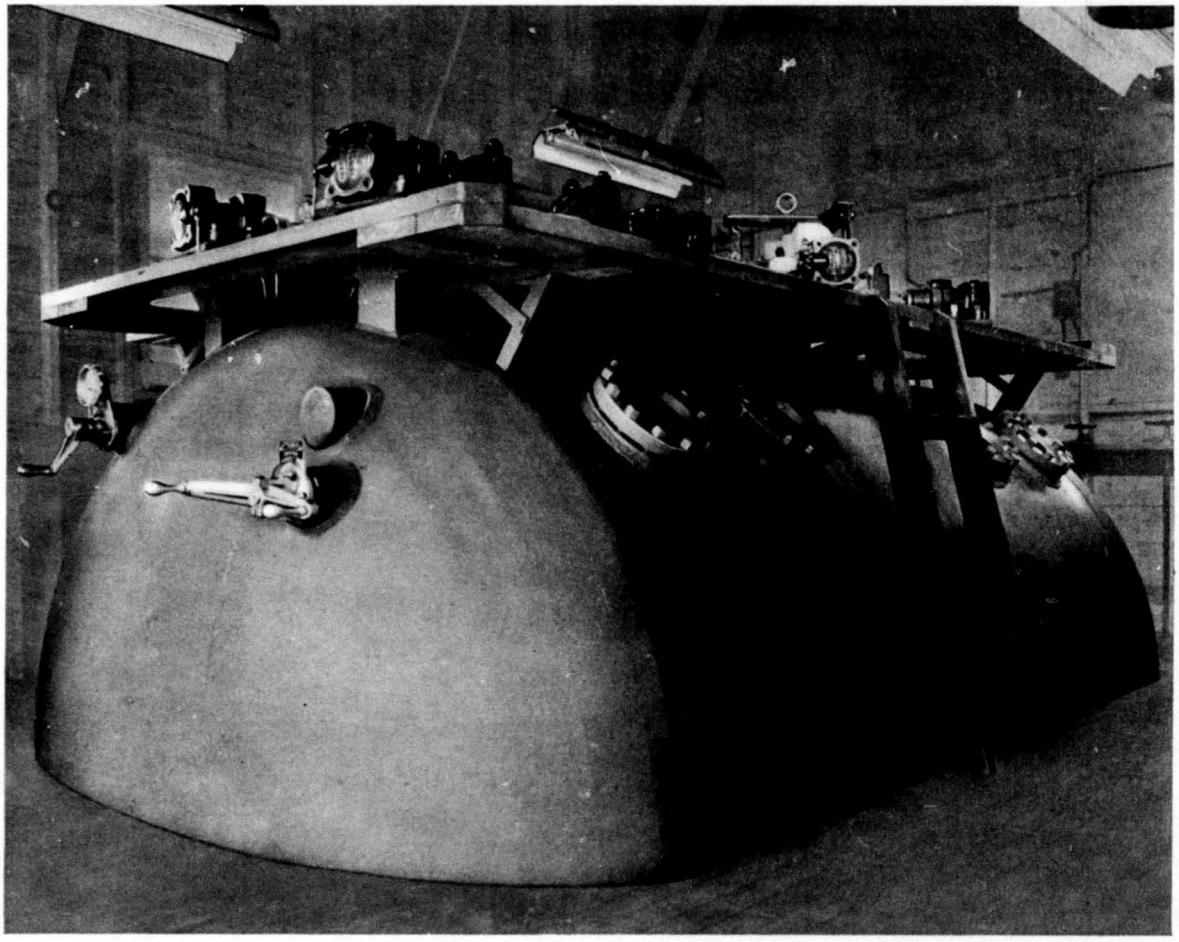


FIGURE 3. View of high-pressure tank, showing side viewing ports.

Semmes; David Taylor Model Basin; U. S. Naval Mine Warfare Test Station; California Institute of Technology; New London Laboratory; University of California, Division of War Research; Massachusetts Institute of Technology, Underwater Sound Laboratory; Harvard University, Underwater Sound Laboratory; Columbia University, Division of War Research, Field Engineering Group; Woods Hole Oceanographic Institution; Freed Radio

3.2.4 The New London Laboratory

Laboratory Facilities and Equipment

The original plan for Section C-4 of NDRC, as already stated, included the establishment of two principal laboratories, one on the east coast and one on the west coast. The most suitable location in the east appeared to be New London where it would be possible to keep in close touch with the ComSubLant and his staff, the U. S. Navy Submarine Base, and the Electric Boat Company, where submarines would be available for target ships without too much difficulty. A contract was drawn up between the United States Government and Columbia University to establish and staff a laboratory which became known as the New London laboratory.

By arrangement with the Navy, a building was provided on the Coast Guard Training Station Reservation, Fort Trumbull, New London, Connecticut. The building, with approximately 6,500 sq ft of floor space, was partly occupied, although unfinished, on July 9, 1941. A substantial addition to this building was made by the Navy from January to March 1942, and at the time of termination of Contract OEMsr-1128, the New London laboratory had been enlarged so that it occupied a total area of about 50,000 sq ft divided into approximately 22 per cent office space, 52 per cent laboratory and shop space, and 26 per cent storage and warehouse space. In addition, a test station which provided

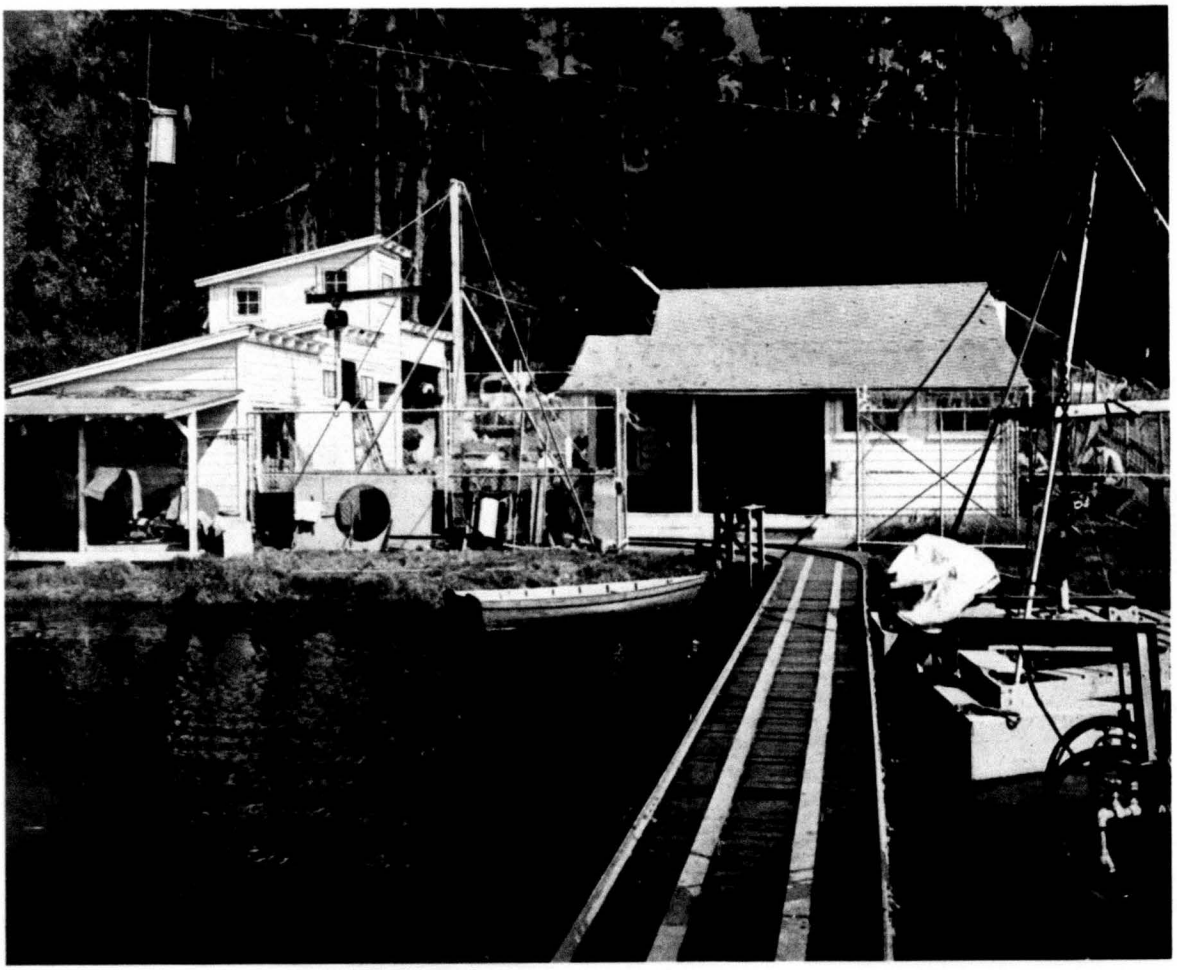


FIGURE 4. The Orlando test station as seen from the pier. Heavy equipment is loaded onto a mine car by means of the boom and chain hoist at the left. The rails on which the mine car runs are shown in the foreground.

a natural test tank approximately 80 ft deep, had been set up at Booth's Quarry, 5 miles from Fort Trumbull. This was used principally in testing fast-sinking depth charges and related ordnance items.

The Navy also provided a staff of officers and men, under Lieut. Commander J. B. Knight, Jr., and through them provided policing and security arrangements, and liaison assistance in securing local vessels and services.

By October 1941, the program was sufficiently crystallized to warrant discussion in a general conference with the Navy. Such a conference was held on October 6, 1941. Although certain other NDRC topics were discussed at that meeting, the bulk of the discussion had to do with the work of the New London laboratory. Detection of submarines by magnetic methods, measurement of submarine depths, improvement of standard supersonic equipment, antisubmarine ordnance methods, and radio sono buoys were discussed in detail. Work on improving the speed of descent of depth charges was described.

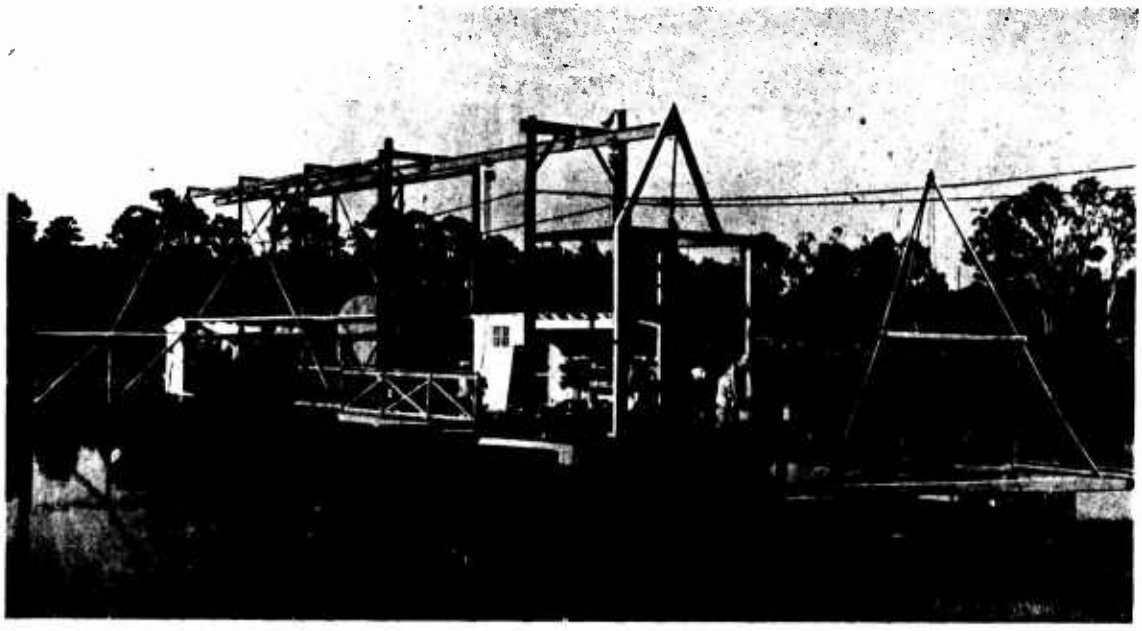


FIGURE 5. General view of the Orlando testing pier.

Originally, the work of the New London laboratory was confined to the field of submarine detection. This meant that the work was largely in the field of acoustical detection, and to a minor extent in the field of magnetic detection from aircraft. Certain preliminary work was done on optical detection methods, but this work was subsequently dropped.

Because of the complexity of the problems related to the field of antisubmarine warfare, particularly submarine detection, it was necessary for the small staff to spend the initial months of work during the summer of 1941 in making a general analysis of the problems, estimating the possibilities of profitable work along particular lines, and doing preliminary experimental and theoretical work to explore these possibilities.

The desirability of emphasizing, as rapidly as research would permit, the most important of the various projects was recognized, and as work continued through the fall months, efforts were made in this direction. By December 10, 1941, sufficient additional progress had been made to warrant a second general meeting at New London. Rapidly descending standard depth charges, streamlined smaller depth charges with contact and magnetic fuzes, magnetic detection from aircraft, attack-course plotters, depth-measuring apparatus, and modifications of standard echo-ranging equipment were featured at this meeting. A new and rea-

sonably accurate method of measuring depths of submarines was described in detail. The complete program also included certain supplementary problems on which the New London laboratory was working, including direct listening equipment for surface vessels, listening equipment for our own submarines, and calibration methods.

were cleared for action by the elimination of many programs and many lines of effort which, although promising from the long-range viewpoint, could not be regarded as likely to culminate in essential equipments on a foreseeable date. Instead, a group of high-priority problems was selected which was within the scope of existing personnel and facilities for solution

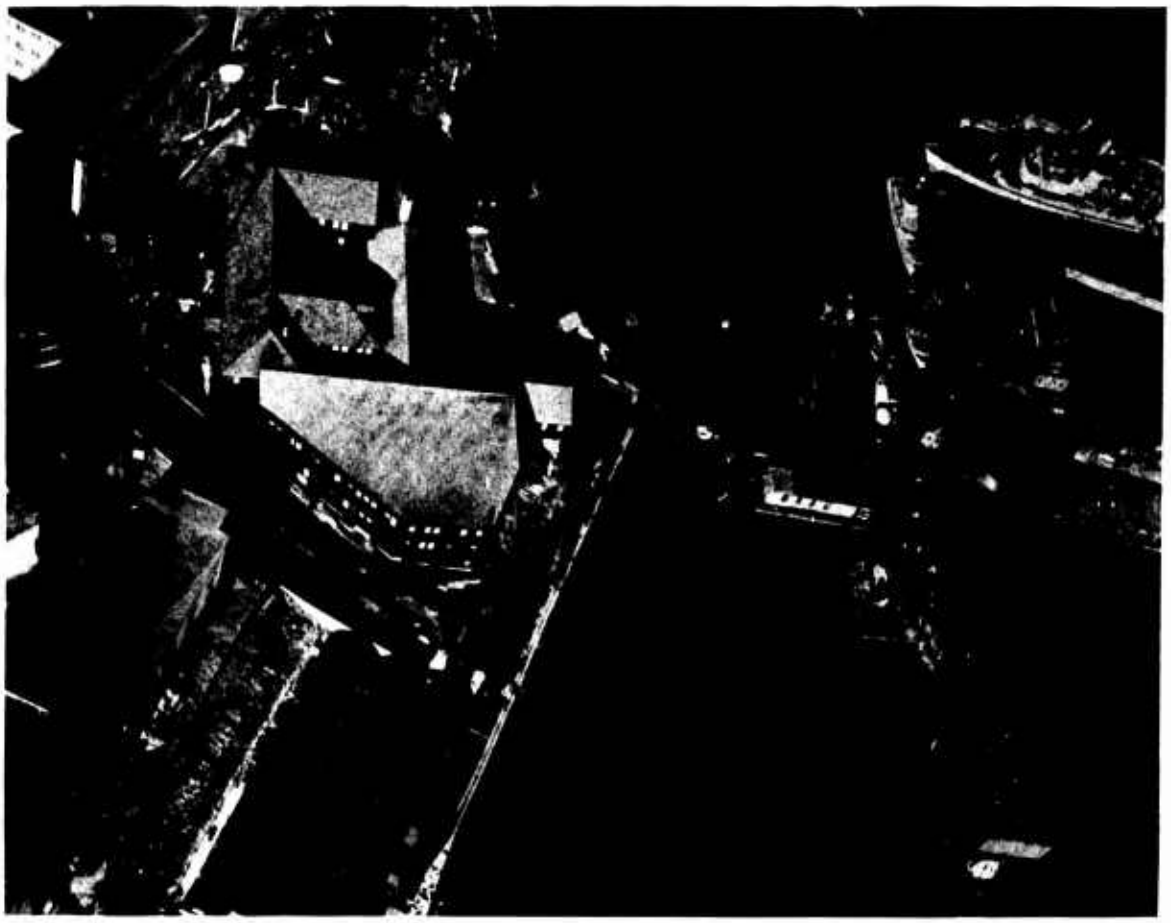


FIGURE 6. Air view of the CUDWR Underwater Sound Laboratory at Fort Trumbull, New London, Connecticut.

The coming of war in December 1941, laid stress on (1) those projects which promised practical apparatus in the shortest time, and (2) those projects which were most closely related to the tactical situations presented to the country after its entry into the war.

Although the element of time was always foremost, the objectives of the laboratory changed frequently as experience was accumulated. After the initial exploratory period, decks in time to be of operational service to the Navy. This policy never was relaxed, and from it were developed managerial and technical methods which should be of interest to any similar future organization.

Test Vessel Fleet. The test vessel fleet was maintained and operated entirely by the U. S. Navy, under the Commanding Officer, U. S. Navy Underwater Sound Laboratory. Navy personnel included a complement of 36 officers

and 263 men, of whom approximately 21 officers and 195 enlisted men were ships' crews.

Surface vessels, submarines, and aircraft furnished by activities other than the New London laboratory for specific sea trials or extended test programs were not, of course, part of the permanent laboratory facilities, but perhaps should be discussed under this section in the interest of uniform subject treatment. Aircraft were frequently required in connection with sono buoy tests and were obtained on short notice, usually from the Naval Air Station at Quonset, R. I. Surface vessels in this category were used principally as submarine escorts for tests or exercises conducted in areas outside of Block Island Sound and were normally scheduled by the submarine base.

In one instance, a submarine was assigned exclusively to the laboratory for a long-time test program. This was the USS S48 (SS159), on which the first triangulation-listening-ranging system was installed. Semi-exclusive use of another submarine, the USS *Mackerel* (SS204) was arranged over an extended period in connection with the development of sonar improvements culminating in the JT sonar system. The USS *Mackerel* was primarily assigned to the training of submarine personnel, but arranged its operations so as to be available for simultaneous JT sonar system work on a regular basis.

In cooperation with the ComSubLant, the laboratory instituted and administered a care-

TABLE 1. Test vessels assigned to the U. S. Navy Underwater Sound Laboratory.

Classification	Name	Length (ft)	Displacement tonnage
PY31	*Cythera*	205	700
PYc26	*Cymophane*	161	450
PYc12	*Sardonyx*	175	470
IX54	*Galaxy*	131	360
IX87	*Saluda*	88	
IX97	*Martha's Vineyard*	138	141
SC665	.....	111	110
YP252	(ex *Wild Duck*)	104	73
YP253	(ex *Montauk*)	127	137
YP256	(ex *Phantom*)	70	29
CGR1985	(ex *Lady Luck*)	48	15
CGR3080	(ex *Valor*)	112	
C-2068	(*Flying Cloud*)	50	15
222093	(*Billie B*)	35	7
11818	Motor boat	35	6½
17625	Motor launch	30	4
17627	Motor launch	30	4
C-36109	Plane personnel boat	24	2½
6593	Motor boat	21	
766	Motor boat	18	



FIGURE 7. Pier at New London laboratory showing part of the Navy facilities.

fully formulated plan for requesting the services of submarines for one-day or short-time sea trials.

The importance of completely adequate laboratory facilities for the efficient prosecution of engineering developments was recognized by the management as fundamental. The procurement of machine tools, electronic equipment, and materials in a period of war shortages required unremitting effort by the laboratory purchasing group and frequent supplementary assistance from the Washington offices of OSRD, in order that the supply of working tools might be kept at a level commensurate with the needs of the staff.

Group Laboratories. The general plan for the provision of laboratory facilities and supporting activities followed that favored by most industrial laboratory managements. Individual laboratories were provided for scientific groups assigned to specific phases of the development programs or kinds of work. A common machine shop, an electronic shop, and stock rooms were so designed and operated as to permit maximum flexibility in meeting the needs of individual engineers and in fulfilling, with the ever-needed dispatch, the demands of group projects. The laboratory equipment included all reference standards necessary to the studies of acoustic phenomena in both air and water.

Individual project or group laboratories were provided and, in addition, a development shop which contained essential machine tools and other adjuncts of a well-equipped shop was available for use directly by the engineers in preliminary model building.



FIGURE 8. Interior view of the calibrating barge showing open sea well.

Barge Facilities. "Floating" laboratory facilities for carrying out equipment tests and measurements in sea water were provided by the calibrating barge (described in the discussion of "Electronic Design and Measurements" in this chapter) and by the *Amada*, a converted houseboat. The barge was permanently moored at the laboratory piers. The *Amada* was used at

sea for carrying out the type of work conducted on the barge.

Shops and Drafting Room. The central electronics shop occupied 1,800 sq ft and was staffed by skilled technicians under the direction of a foreman.

The machine shop, similarly, was staffed by skilled machinists under a foreman's supervision and occupied 6,500 sq ft, including the welding and sheet metal shop. A stockroom for raw materials and a tool room were included.

A drafting room containing 21 tables under the supervision of a chief draftsman handled a substantial part of the design work as familiarity with both the equipment and the problems of its design increased, thus relieving the engineers of a large part of their detailed design work load. Electronic drafting was also handled under the supervision of the chief draftsman.

A photographic shop provided facilities for making and maintaining a complete photographic record of every phase of the laboratory's activities. Blueprint and photostat shops supplemented the work of the drafting department and other services.

Recording Laboratory. The Recording Laboratory should be regarded, perhaps, as having a development or engineering function in its own right, but nevertheless, it was an indispensable adjunct to the other development groups. At its maximum strength, this group included six men in addition to the supervisor.

Staff Organization

The contract stipulated in part that, "The Contractor shall . . . staff . . . (the) laboratories and other necessary facilities and services. . . ." Here again, as in the case of the acquisition of laboratory equipment and machinery, the management found itself in competition with the accelerating demands of industrial and nonindustrial research and development organizations during a period of unprecedented wartime expansion. In addition, it was the policy of the Office of Scientific Research and Development to offer salaries which, though representing no financial loss to prospective employees, would not in themselves constitute a monetary inducement to join the laboratory. It was believed, and the belief has been shown sound, that the effective fulfillment of the broad policy of discharging responsibilities with the utmost dispatch rested ultimately on the extent to which each individual was willing to forget self-interest and to accept as his reward the satisfaction of a task well done.

The mechanics of recruiting personnel were influenced by the same sense of urgency and need as that influencing the acquisition of property and facilities. In the early days of the laboratory, the scientific nucleus was recruited from among the engineering acquaintances and professional colleagues of the laboratory supervisors. It soon became apparent that other and wider sources of supply were needed. A personnel representative traveled widely in search of additional staff members. Colleges, schools, and industrial organizations were combed for needed talent and proved to be valuable sources.

The field interview method of recruiting was employed through the early part of 1942, but after July of that year most of the additions to the staff, while selectively interviewed in the field, were not employed until they had visited New London for further discussions and had been evaluated for assignment to specific projects. This procedure became especially desirable as the later staff additions were mostly made to fill definite "spot" openings in a generally balanced organization.

The nonscientific staff included the personnel employed in the various mechanical and electrical shops, the drafting room, clerical, stenographic, and maintenance forces, and the several service groups which will be discussed in greater detail at a later point. For the most part, nonscientific personnel were recruited in the New London area, although the search for people with specific qualifications, particularly in the skilled grades, occasionally made necessary a more extended search. Until the autumn of 1942, the laboratory personnel was 100 per cent male because of Naval Reservation restrictions. At that time inability to retain the younger men of the nonscientific staff in the face of Selective Service demands made it necessary to employ women for work for which they were qualified.

The fluctuating draft deferment policy under which the Government was obliged to operate

plagued this laboratory throughout its existence. Important technical employees, especially among the younger men, were constantly faced with uncertain draft status, and their efficiency was frequently impaired. It cannot be too strongly stated that a clear and uniform draft policy is essential for the effective operation of Government-sponsored research groups.

Distribution of Personnel. Although it is recognized that the particular personnel problems, the scope of the work, and the relative needs for a scientific and nonscientific staff were somewhat unique at New London, it might be helpful to the formulation of personnel policies of future laboratories to set down the distribution of the total laboratory staff among the various employment classifications.

Table 2 shows the distribution of the total personnel on August 30, 1943, when Contract OEMsr-20 was terminated, and on January 1, 1945, shortly before the management was assumed by the Naval Research Laboratory. In studying the table it must be borne in mind that the group shown includes only the civilian staff employed by Columbia University and does not include the naval complement responsible for the maintenance and operation of the physical plant and the fleet of test vessels.

TABLE 2. Growth of personnel.

Employment classification	August 1943 (OEMsr-20)	January 1, 1945 (OEMsr-1128)
Scientific staff	94	116
Nonscientific staff		
Mechanical shops	29	43
Electronic shop	21	34
Drafting department	16	24
Accounting and financial	6	7
Building maintenance and general service	36	38
Purchasing and warehousing	13	11
Marine facilities	4	3
Dining room	9	11
Photographic	8	7
Stenographic and general clerical	29	34
	265	328

Apparatus Development Groups. Basically, the apparatus development work was concentrated in individual groups under a number of development supervisors who had had extensive experience in industry. Each group encompassed the work on a number of more or less related problems and the development supervisor was assisted by project leaders who were individually responsible for a single project. During the spring and summer of 1943 the work was concentrated in the antisubmarine warfare field. Four principal development groups were in operation, including in their schedules the completion of work already begun in 1942, and the development of new devices for which requirements had been established subsequently. These principal fields of endeavor were: ordnance, listening detection devices, echo-ranging detection devices, and underwater acoustic devices.

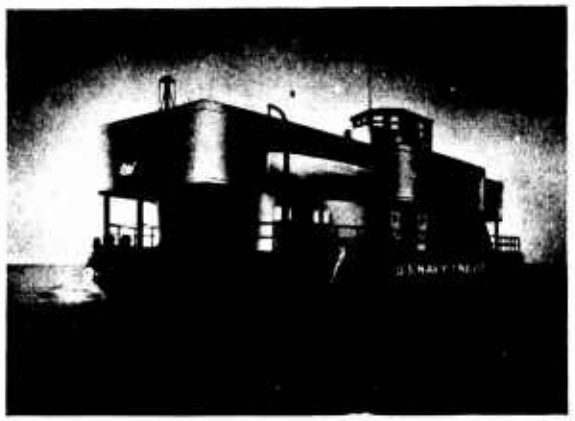


FIGURE 9. The YNG22 barge used for training naval sonar personnel.

An attempt was made to assign to each project a group of men whose individual skills were consistent with the technical requirements. By this time it was possible to recruit men on the basis of specific types of needed experience. Intensive recruiting was continued throughout the spring of 1943. The assignment of engineers on the various projects was changed from time to time as requirements dictated but, generally speaking, men assigned to apparatus development work continued in this field throughout the remainder of their employment with the New London laboratory.

Keeping in mind the fact that the New London laboratory was intended to concentrate on the provision of equipment to the operating

forces, by the summer of 1943 it appeared that further development on new devices in the antisubmarine warfare field would not, by and large, result in the provision of equipment to the Services until sometime late in 1944. Production had begun on most of the devices then under development and, except for "spot" jobs, the need for long-term investigations along new lines was not immediately apparent. About this time, as a result of close association with the submarine force at New London, it was believed desirable to explore the needs of our own submarines in future Pacific operations. Following a visit to Pearl Harbor in August 1943, the management, with the assistance of the Navy and under the guidance of Division 6, organized a program of development work for the submarine forces. A number of additional development groups were organized and those groups then in operation embarked on the new program as their work in the antisubmarine field diminished.

Technical Service. Early in 1943 it was recognized that the apparatus development groups could not be individually staffed with all of the specialists required. Consequently it proved expedient to set up and maintain a technical service and consulting department which could supply special measuring or design service on short notice and for as long a time as was necessary to the individual project groups. The head of this staff department reported to the director of the laboratory and ultimately became an assistant director of the laboratory. It is probable that comparable laboratory operations would find value in such a centralization of technical staff resources. The particular technical service functions at New London were administered by five group leaders and included the following: sound recording; hydrophone production development, including acoustical calibration; acoustical studies, including measurements and listening tests at sea; electronic design and measurements; data analysis and computations, including oceanographic studies. About 30 members of the scientific staff were employed in this work. Although it was not the policy to insist that all work of the above nature be done by these groups, in practice most of it was turned over to them because of their special knowledge and facilities.

Sound Recording. Sound recording activities of the New London laboratory were of exceptional value in the development of training programs. During the past few years, the use of "direct recording" which eliminates the need for record processing except in cases where many copies are required, has greatly extended the value of records as a technical aid. Full advantage was taken of the latest techniques. Initially, the principal use of sound recording was to demonstrate, in the laboratory, underwater sound conditions at any given time during a test at sea and to illustrate typical forms of water noise and ship signals. Later it became apparent that sound recording techniques had numerous applications not originally foreseen and a recording group was formally established. It then became the general practice to use the recordings to preserve the acoustic phenomena of field tests or to transfer them to the laboratory for more detailed study and analysis. For instance, in the case of changing sounds, such as torpedo noise which varies rapidly because of the speed of the torpedo, the only way to make an analysis is to record the sound and then repeat it many times through an analyzer. In other cases, machinery sounds of submarines have frequently been recorded in a few minutes or seconds and then analyzed at length in the laboratory, thus minimizing the demands on submarine operating time.

A direct result of these activities was the collection of an extensive group of recordings of underwater acoustic phenomena, selections from which could be used to give listeners, at one sitting, a comprehensive audition of any phase of underwater sound. Steps were taken to segregate the recorded material into divisions dealing with specific subjects in a record library and a record catalog was then issued. This catalog, kept current by means of periodic supplements, contained over 2,000 records at the close of the contract.

Increasing use was made of recordings for personnel training, both for listening and echo ranging. Special trainer equipments were developed using the phonograph records as a

principal element. Among these were the model QFL and QFM trainers, for teaching operation of the tactical sound range recorder and torpedo detection, respectively, and the radio sono buoy trainer. Several thousand complete sets of several training record series were distributed by the laboratory and the Navy to the forces afloat throughout the world and to naval training activities and other laboratories.

of film in many instances, principally because of the distance from satisfactory film processing facilities and the time and care required for high quality processing. However, magnetic wire and film-embossing recording facilities were used extensively where their characteristics were suitable.

In almost all cases it was found that changes and improvements were required to fit com-



FIGURE 10. Sonar training class studying the operation of the sound range recorder.

Disk recording was employed for most purposes because of its many advantages and the wide distribution of disk reproducing equipment. The frequency and volume characteristics of the equipment were adequate for full-quality recording of all acoustic phenomena under investigation, and in no case was the usefulness of a record impaired or the making of a record of completely satisfactory quality rendered impossible by deficiencies in the response of the equipment. No photographic film sound recording was attempted, in spite of the advantages

mercial apparatus to the needs of the laboratory. Consequently, the work of the Sound Recording Department involved the design and construction of much recording equipment and the modification for laboratory use of several types of recorders and recording mediums. As a result, a great deal of consulting work was done on recording problems and test information has been furnished to the Navy and to other interested groups on the performance of a variety of magnetic, engraved-disk and embossed-film recorder-reproducer equipments.

Electronic Design and Measurements. Because sonar equipment invariably involves a great deal of electronic apparatus, often of great complexity, electronic design occupied a large portion of the time of the New London laboratory. It was found convenient to set up a group which would be available to do electronic design or measurements work for the development supervisors. Thus, the electronic work was done by engineers specializing in these techniques and the time of engineers capable in field work was conserved and could be applied to the field testing of the equipment. No pressure was put on the staff to use these services if they preferred to do their own electronic design work, but it was found that the seven engineers comprising the group were heavily loaded at all times. The type of work done by them is shown in the following list of representative projects:

1. Special impedance bridges, detectors, measuring amplifiers, and field test sets.
2. Test specifications for amplifiers and other electronic equipment.
3. Equipment design, including the NL-105 NL-117A and NL-118A listening amplifiers, single sideband underwater-telephony transmitters, a submarine echo-ranging signal generator, the OAY sound measuring equipment, and the depth charge range estimator prototype model.
4. Design of special transformers and filter networks to meet specific needs.
5. Radio transmitter and receiver problems in connection with the expendable radio sono buoy and the directional radio sono buoy.

Hydrophone Development and Calibration. The Hydrophone Production Development Group stood ready to provide a commercially practicable design of hydrophone for any project undertaken by the laboratory. The problem would be reviewed and if a crystal device were decided upon, an outside laboratory or manufacturer would be engaged to produce the design. For most of the projects at New London, magnetostriction hydrophones seemed to possess the qualities most desired. These hydrophones were developed by the New London laboratory. Problems involved were the heat treatment of nickel, and measuring techniques to control the heat-treating process; plastic-casting techniques in vacuum; new cements and waterproofing compounds; and methods of winding and magnetically polarizing the hydrophones. Entirely new methods of fabrication were devised and the techniques were taught to manufacturers.

Since acoustic calibrations were required at every step in this work, this group also operated the calibrating barge moored at the laboratory pier. This barge was equipped to make rapid calibrations of all types of hydrophones and new calibration methods were developed as the requirements of the hydrophone program made them necessary. The barge was also available for calibration of all acoustic devices used by the laboratory, whether developed by the Hydrophone Production Design Group or not. Close liaison was maintained with USRL at Mountain Lakes, New Jersey, and the standard hydrophones used on the barge were periodically returned to them for calibration. The barge was located only a few hundred feet away from the laboratory, and a sufficient staff was maintained so that high priority jobs could usually be done on the day when the service was requested. This speeded up the development work significantly. The extensive complement of equipment on the barge was fully justified, since effective development depends to an important degree on accurate measurements furnished when needed.

This group, together with the Transducer Research Group, developed a set of rigorous tests for magnetostriction hydrophones, for which the necessary test equipment was procured. The NL-124 and NL-130 hydrophones are examples of instruments capable of passing these tests and exemplify the work of the group. Compared to the original JP-1 hydrophone, the NL-124 is 17 db (sevenfold) more efficient, is split and sectionalized for right-left indication and delobing, is permanently magnetized, is not subject to corrosion or denting, has a separable cable connector, withstands hydrostatic pressure of 500 psi, and is undamaged by the shock wave produced by the explosion of 25 lb of TNT at a distance of 15 ft.

Data Analysis and Computations—Oceanographic Service. This group was established at

about the halfway mark in the laboratory's existence and was an immediate success. It operated under the direction of an engineer who had been generally active in both the acoustical measurements and development groups of the laboratory. His experience enabled him not only to grasp quickly the analysis and computation problems of others, but also to suggest ways of field testing or recording data in such a manner as to simplify the analysis work. The group carried out for the project groups a great many of the time-consuming calculations, curve plots, and graphical analyses that are a necessary part of any scientific program. In a few instances, members of the Data Analysis Group participated in actual analysis of phonograph recordings of submarine auxiliary noises, and participated in enough field tests to keep them acquainted with the changing requirements for data analysis.

The Oceanographic Service functions were established within this group because they consisted so largely of analysis and computations based on data gathered at sea by the two members of the scientific staff assigned to this work, and by members of ships' crews trained and supervised by them. Many times the oceanographic studies were able to explain seeming anomalies in important test results and thus clarify and make usable certain data that would otherwise have been merely confusing. Their work demonstrated the fact that no laboratory doing underwater sound experimentation can afford to be without the services of oceanographers.

Acoustic Measurements and Listening Tests at Sea. This group operated Columbia University's test vessel *Amada* and carried out a large number of specific project investigations as well as a general program of fundamental listening studies, the latter on an "as time permits" basis. All members were experienced in the techniques of field measurements employing electronic and acoustic apparatus, and frequently were loaned to project development groups for varying periods to conduct special tests involving their type of knowledge. An example of this was an investigation of the effectiveness of rubber isolation mounting for the JP-1 hydrophone, which occupied the time of one man in the submarine listening equipment program for several months. Examples of the problems investigated by the group as a service to others are the following.

1. Investigation of the probable aircraft detection range of listening devices on a submarine.
2. Selection of the best hydrophone for the directional radio sono buoy.
3. Use of the *Amada* as an artificial sound target for many listening tests and particularly for interference tests during the triangulation-listening-ranging development.
4. Measurement of background noise and the sound output of vessels and submarines under various specified conditions.
5. Construction and installation of artificial sound-source equipment on a target boat for training purposes.

Pearl Harbor Division

By July of 1944 the prosubmarine program of the laboratory had reached a point where a number of developments were in the production stage. These items were sufficient in number and variety to cause concern over the probable load to be thrown on the submarine forces installation and training activities, especially since in only one or two instances were the manufacturers in a position to provide field supervision of installation of the gear. The management, under the guidance of the Chief of Division 6, NDRC, proposed the establishment of an engineering group at Pearl Harbor (1) to serve as an outpost of the laboratory in the introduction into use of new equipment designed at New London, (2) to assist the staff of ComSubsPac in the evaluation of suggestions from the operating forces, (3) to assist in the appraisal at Pearl Harbor of new devices under operating area conditions, and (4) to assist the ComSubTrainPac at that activity in the expansion of selection and training programs.

Although these initial plans contemplated a group of 25 men, including engineers, technicians, and office assistants, and the establishment of a small shop or testing laboratory, problems attendant on the housing and maintenance of such a large staff caused a reduction in the number such that at maximum strength,

12 men including 3 training specialists were stationed at Pearl Harbor.

The importance and value of the Pearl Harbor division of the New London laboratory cannot be minimized. During the 8 months of its existence, a total of some 800 letters flowed between the director of the New London laboratory and the supervisor of the Pearl Harbor Group. Most of these letters dealt with engineering and development matters and this illustrates the value of close liaison between the development laboratory and the forces afloat. Experience in the operation of this group leads to the conclusion that by the provision of means for rapid interchange of information between forces afloat and development groups, much time can be saved and the resulting devices can be caused to meet more adequately the requirements of the Services.

Termination Policies

The problems attendant on the termination of the contract with respect to the handling of personnel matters occupied the time of the management importantly throughout the latter half of 1944. Having expended a great deal of energy and thought on the proper treatment of staff members at the time of their employment and throughout their stay in New London, it followed logically that a conscientious effort should be made to terminate the employment of these men in a manner which would reflect credit on OSRD, NDRC, and Columbia University. It was thought that the attitude of these men as they left New London might influence, to some extent, the general attitude of the nation toward the conduct of research and development work in the postwar period and would make less difficult the recruiting of laboratory personnel should a need arise for their services at some time in the future.

The Navy's decision to continue operations at New London under the supervision of the Naval Research Laboratory and to assume responsibility for the operation of the laboratory on March 1, 1945, simplified these problems to a considerable extent. Almost one-third of the members of the scientific staff accepted employment with the Naval Research Laboratory and continued at New London. An equivalent number of men were transferred to the staff of the Radiation Laboratory at Cambridge, and the majority of the balance of the staff took employment with other research agencies engaged in war work. Every effort was made to place the men to the best advantage of the war effort and with a view to satisfying the employees' personal desires with the result that satisfactory employment was found for every member of the staff.

3.2.5 The San Diego Laboratory

General Organization

The arrangements for the establishment of the San Diego laboratory were completed during the late spring of 1941 and were authorized in correspondence among NDRC, OSRD, and the University of California. Dr. V. O. Knudsen, Dean of the Graduate School of the University of California at Los Angeles, was appointed as director. It may be noted that at first this laboratory was known as the "San Diego Laboratory, University of California Division of National Defense Research," and later after the United States entered the war, as the "San Diego Laboratory, University of California Division of War Research" [UCDWR]. More commonly, however, it has been referred to as the San Diego laboratory.

The terms of the OSRD contract with the University of California provided that the contractor would equip, staff, and operate a laboratory for studies and experimental investigations in connection with and for the development of equipment and methods involved in submarine warfare. Further provisions authorized the conduct of tests, the acquisition and equipping of vessels, and all other activities deemed requisite for the successful conduct of the program envisaged.

The initial nucleus of personnel under the direction of Dr. Knudsen was housed for the first few months in the same building as the U. S. Navy Radio and Sound Laboratory, then under the direction of Captain W. J. Ruble, USN. The group of scientists and their assistants grew slowly by recruiting from the staffs of universities, colleges, industrial lab-

oratories, and technical groups. These men had little or no indoctrination or training in the specific problems which they were to undertake or in the conduct of operations jointly with naval activities. In consequence, much of the early period was spent in acquiring some background of knowledge essential for the intelligent and efficient approach to the various problems with which they were confronted.

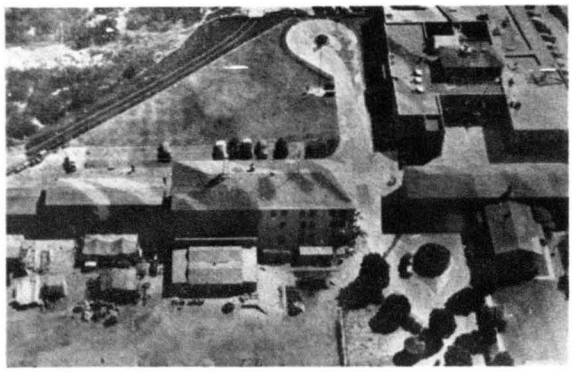


FIGURE 11. Aerial view of the U.S. Navy Radio and Sound Laboratory on Point Loma, San Diego, California.

As the staff grew and the scientific program took form, the need for proper procedures became apparent in order that the various duties and responsibilities of civilian and naval personnel should be understood and discharged. As laboratory personnel acquired competence in this novel field and merited confidence in their efforts, the difficulties initially encountered were considerably ameliorated. With the passage of months and successive changes in laboratory organization and cooperating naval commands in the area, a cordial relationship of mutual understanding and assistance became established. It is evident in retrospect that the effectiveness of the scientific group increased in direct proportion to the improvement in local liaison and the establishment of intimate working relations with the U. S. Navy Radio and Sound Laboratory, the U. S. Fleet Sonar School, the local Submarine Squadron, and other naval commands.

In accordance with the terms of the contract, the University of California undertook to conduct such studies and experimental investigations as might be requested from time to time by the contracting officer of the OSRD or his authorized representative. Members of this division and section constituted an advisory committee for the subsurface warfare program of which this laboratory was an integral part. Representation of the laboratory through its director, Dr. G. P. Harnwell, who succeeded Dr. Knudsen on April 1, 1942, and who was a member of Division 6, provided the point of view of the laboratory scientists in the broad planning and allocation of the work and insured an appreciation by the laboratory of its role in the program as a whole. Frequent conferences between the division and representatives of its contractors contributed immeasurably to liaison between the various groups engaged in studies and experimental work and fostered intimate collaboration between groups which were geographically widely separated.

Liaison with the Navy. The first was a central liaison between the Navy and OSRD through the Office of the Coordinator of Research and Development for the Navy. Problems which arose in operating units of the Navy were referred to appropriate naval bureaus, and these in turn submitted recommendations to the Office of the Coordinator in those instances where it appeared appropriate to enlist OSRD assistance. Proposals made by the Coordinator to the Director of OSRD were then considered and assigned to the appropriate subdivision of the civilian agency. If they lay in the field of subsurface warfare, cognizance was generally assumed by Division 6 and the projects authorized in the laboratory of one of the division's contractors. In many instances, initiative was assumed by a contractor or an NDRC division, and comments and cooperation were invited from the appropriate naval bureau through the channels indicated above.

Upon the establishment of a project in the San Diego laboratory, the second type of liaison, to bring about the necessary close local cooperation, was authorized by the Office of the Coordinator. For instance, the program of assistance in the selection and training of sound operators and officers was greatly facilitated by the establishment of direct channels of communication between the laboratory and the

sonar schools and Operational Training Commands on both coasts. Such arrangements were necessary for the conduct of day-to-day operations, and proved most fruitful in the stimulus they afforded both civilian and naval participating groups. The responsible OSRD officers, the naval coordinating office, and the interested bureaus and commands were kept informed of the progress of all undertakings through the periodic reports issued by the laboratory.

laboratory's activities directed toward one or another aspect of prosubmarine warfare, the visits to the laboratory of Admiral C. A. Lockwood, Jr., Commander Submarine Force Pacific Fleet, and his interest in many of the devices under development greatly stimulated this part of the program. By the middle of 1944, the laboratory had representatives in the Pacific area attached to the submarine command almost continuously, and a newer and



FIGURE 12. Aerial view of the laboratory buildings located near the West Coast Sound School.

Late in 1943 it became apparent that the success of our military operations justified a careful reconsideration of the projected program. Beginning in the latter part of 1943 and for the remainder of the period of active work, the diminishing threat of submarine action and the great activity of the submarine force in the Pacific, caused the prosubmarine aspects of the laboratory program to assume major importance. This aspect of the laboratory's work was promoted most effectively by the increased intimacy of working relationships with the Submarine Desk of the Bureau of Ships and the ComSubPac. With more than half of the closer relationship with the Bureau and the Navy laboratory tended materially to reduce the formal administrative routine associated with the travel and assignment of laboratory personnel and equipment in connection with these duties.

With the possible termination of World War II in view and considering the necessary period between initial research and combat employment, the desirability of associating this work with a permanent organization, rather than a temporary emergency agency such as OSRD, became increasingly obvious. Supervision of the San Diego laboratory program was

accordingly transferred to the Navy Department on March 1, 1945, and later, responsibility for the contractor's work was assigned to the Bureau of Ships.

Objectives. A consideration of the activities and procedures of this laboratory should be prefaced by a survey showing the growth of the organization from a small, loosely knit group of a score of scientists in the summer of 1941 to an integrated organization of some 600 persons comprising physicists, engineers, geologists, psychologists, writers, artists, machinists, draftsmen, and others by the summer of 1945.

The original primary objective of the laboratory was the prosecution of fundamental sonar studies. This conception controlled the initial selection of personnel and the organizational division. Subsequent developments and shifting emphasis raised work in the fields of antisubmarine and prosubmarine devices and training to a comparable level, and this was reflected in the organization.

In the initial organization, the director was Dr. Knudsen, a man of wide experience in the field of fundamental acoustic investigation. The largest group of scientific personnel, concentrated on underwater acoustics, was directed by Dr. L. J. Sivian, on leave from the Bell Telephone Laboratories. This group was responsible for the fundamental measurement program as well as for the equipment necessary to its accomplishment. Another small group was headed by Dr. K. S. Van Dyke, on leave from Wesleyan University, whose special field had been piezoelectricity, a fundamental technique in transducer design. These persons were concerned chiefly with the investigation and development of detection devices. The third group, with no nominal head, served largely as a consulting body and was concerned with many special methods and techniques that were suggested in the early conferences leading to the laboratory's establishment.

There was little change in organization for the next 6 or 8 months, although the number of employees increased to nearly 100 by the early spring of 1942. The division of responsibility remained approximately the same, except that a somewhat more detailed breakdown was made in the lower levels. In April 1942, Dr. Knudsen's services were urgently requested for work with the central directing organization of NDRC, and he was relieved by Dr. Harnwell, Director of the Randal Morgan Laboratory of Physics and Chairman of that department at the University of Pennsylvania. Concurrently with the assumption by Dr. Harnwell of the directorship, conditions led to a rapidly increasing growth in the laboratory's activities. By August 1942, approximately 200 persons were employed.

Dr. Sivian and Dr. Van Dyke were both called away for other important work and gradually the organization shifted. In April 1943, a training division was established under Dr. H. E. Hartig who supervised work at the Navy sonar schools at Key West and San Diego and device development work within the laboratory. The Fundamental Research Division, subsequently known as the Sonar Data Division, was headed by Dr. Carl Eckart who had cognizance of high- and low-frequency propagation programs and also of the Oceanographic Section which contributed directly to both of these. The Sonar Devices Division, under Dr. F. N. D. Kurie, had again expanded greatly and was concerned with all matters of combat device design.

The following year represented a rapidly expanding period for the laboratory and by the autumn of 1944, it achieved its maximum size of approximately 600 persons. The laboratory population continued at about this figure until termination plans were put into effect.

Also, at the request of the Navy, a substantial program of maintenance manual preparation was undertaken, and the necessity of liaison with the Bureau of Ships, the Executive Office of the Secretary of the Navy, Navy manufacturers, and publishing firms indicated that this activity should be established in the east. Dr. J. C. Morris of Tulane University was secured to take charge of this undertaking, and its geographic separation clearly indicated its establishment as a separate laboratory division whose work was closely related to that of the training division. Earlier experience of the laboratory led the director to assign a business director to this group from its inception, and

this materially improved the effectiveness of its operations on the other side of the continent.

Engineering Division

A major step in improving the effectiveness of the scientific divisions was the establishment of an engineering division under Dr. R. O. Burns. Services such as drafting, electronics, and machine work were grouped together and operated as a unit in serving the needs of the scientific divisions. As the design of training and combat equipment advanced and prototypes were made for operational tests, the Devices and Training Divisions drew very heavily upon the Engineering Division. Certain other local services, such as the Photographic and Recording Laboratories, likewise reported to Dr. Burns and served the three scientific divisions about equally. The need for larger numbers of prototypes for testing and the necessity of supplying small numbers of units of training equipment in particular led to the establishment of groups concerned with extension engineering and contract consultation. These groups essentially expanded the facilities of the laboratory by including those of manufacturing plants in the San Diego and Los Angeles areas. Some of this work was done on purchase order and some on subcontract, and the program played an important part in the ability of the laboratory to accede to the many requests received throughout this period for prototypes and service equipment by the Navy. The extensive activities of the laboratory in this field were coordinated with similar phases of the work of other OSRD contractors by R. J. Coe, transition aide to the chief of Section 6.1, NDRC.

As has been mentioned, the scientific work was carried out by three groups, (1) the Sonar Data Division, (2) the Sonar Devices Division, and (3) the Training Aids Division. A brief description of each division will be given.

Sonar Data Division

The Sonar Data Division was concerned with fundamental research, primarily directed to the investigation of all acoustic propagation phenomena. This was the chief specific assignment to the laboratory upon its initial organization, and as the laboratory developed, approximately one-third of the effort of the staff was directed to the work of this division.

In addition to a broad program of acoustic measurements, a corollary oceanographic program was carried out which was essential to the proper interpretation and understanding of the acoustic results. A second subordinate phase of investigation lay in the field of psychoacoustics because of the importance of hearing in all practical naval applications.

The efficient conduct of the Navy and NDRC programs as a whole required the establishment of direct liaison between divisions within the laboratory and groups elsewhere in the country or abroad concerned with similar problems. In the experimental work, close relations were maintained with the Scripps Institution of Oceanography and the Woods Hole Oceanographic Institution and also with the Sonar Analysis Group of NDRC which was continued later in association with the Bureau of Ships, Code 940. This latter group had the general responsibility of integrating the work of the contractors in basic sonar research, and later assembled and issued a number of the Summary Technical Reports covering the entire program.

In addition to research cooperation, external connections were established for making the results of the program available directly to those naval offices and commands most directly concerned. Charts of various types prepared in the laboratory were submitted to the Hydrographic Office for official issuance. In some cases, and prior to such issuance, charts prepared by hand were furnished directly to ComSubPac. Also, in the bathythermograph program, direct liaison was maintained with the Service forces of the Pacific fleet, and the Hydrographic Office and Bureau of Ships were kept informed of these activities as they developed.

Sonar Devices Division

As has been indicated, the Sonar Devices Division grew somewhat more slowly than the Data Division because of the initial philosophy under which it was presumed that the developing and designing of combat devices could be

laboratory, and throughout the entire life of the contract the effect of this could be clearly noted. The groups concerned with the design and development of crystal and other trans-

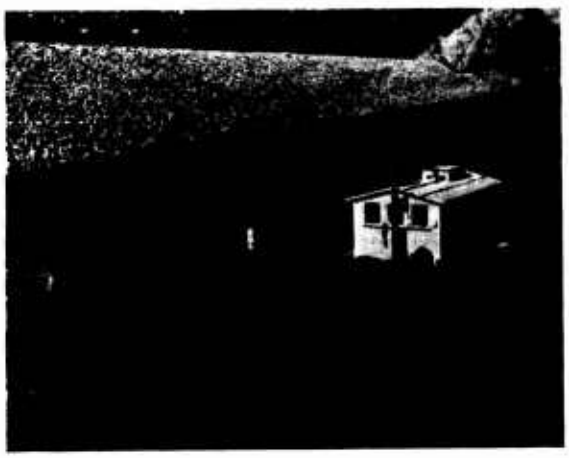


FIGURE 14. Barge at El Capitan Lake which was used primarily for proving sonar decoy devices.

ducers remained a part of the Devices Division, and the testing and calibrating stations were likewise sections under this division throughout the laboratory's existence. These groups contributed most directly to the sonar and countermeasures projects in hand by the Devices Division, but they were also of broad general use to the Training and Data Divisions as well. Cooperative work with the latter division has been briefly touched upon earlier and the relationship with the Training Division was equally close. One of the first major development undertakings of the laboratory was in the field of practice targets, and here the conduct of the work was actually in the hands of the Devices Division although it constituted essentially a training function. On many other occasions, mutual services were performed by these divisions. These became evident formally on the adoption of laboratory-developed devices by the Navy and the institution of training programs for operators of them at the sound schools or training commands.

The external liaison of this division was almost as extensive as that of the Data Division. The work was integrated with that of eastern laboratories through Section 6.1, NDRC, and the maintenance of adequate channels of communication with the Bureau of Ships required the almost constant presence of one or another member of this division in Washington. In procurement and manufacturing matters, the transition aide of NDRC was frequently utilized, and the services of more distant manufacturers were drawn upon. Direct naval liaison became particularly important in connection with the submarine work, and the OLA and Sound Beacon programs necessitated the continuous retention of laboratory representatives at west coast Navy Yards and in Pearl Harbor, and led to many individual trips farther into the Pacific.

TRAINING AIDS DIVISION

The developments leading to the establishment of a training aids division have been indicated previously, and as the work progressed the division assumed a definite character presenting a number of points of contrast with the Data and Devices Divisions.

The operation of the Training Division as a whole is outlined in more detail in a separate chapter, but the actual method of bringing the laboratory's contribution most effectively to bear on the Navy's problems in this field deserves brief mention here. The need for training assistance was sometimes appreciated first within the Navy itself, sometimes at a sonar school or training command, sometimes within an evaluation command such as AsDevLant, and sometimes by the civilian scientists themselves. The wide area from which these suggestions might emanate points clearly to the necessity for a widely dispersed but closely integrated and flexible organization. To some extent, integration was supplied by the Selection and Training Committee of Division 6, NDRC, and to some extent by the staff of the Commander-in-Chief. Upon the recognition of a need for a device, conferences between all persons properly concerned led to the establishment of a laboratory program for design and development. Subsequently, with the continuing cognizance of everyone, initial units were furnished to training or evaluation commands, and preliminary instructional programs were undertaken. As a result of careful and critical study, errors and inadequacies were recognized and steps taken to effect the design and assist

in the procurement of an adequate supply of the device for Navy use. Thereafter the training-techniques group continued to work closely with training commands, utilizing a device in the perfection of instructional techniques. The nature of the external liaison implied in the operation of this division is sufficiently clearly indicated in the summary of its method of operation, and it is clear that the maintenance of close and harmonious relationships between a wide variety of civilian specialists and naval officers played a particularly important role in this aspect of the laboratory's undertakings.

Engineering Services Division

The laboratory had two chief service divisions, the Engineering Services Division and the Business Division. Since we are concerned here primarily with the technical facilities, these will be described in more detail. It became apparent early that technical services could best be furnished by a division of the laboratory independent of those persons charged with the conduct of particular scientific problems. This separation into scientific and service activities was not entirely clean-cut in all cases, and, in particular, it was by no means true that scientific personnel were employed exclusively in the scientific divisions and nonscientific personnel in the service divisions. The Engineering Services Division in particular included many people of high technical skill. As instances, the Design and Drafting Department, the Electronics Laboratory, and the Recording Laboratory were staffed by specialists engaged in work essentially comparable to that of equipment designers and electronic engineers in the Training and Devices Division. The service groups, however, were distinguished by the assisting role which they played in collaboration with the scientific divisions. Particular jobs were assigned to them on job-order requisitions from project leaders, and continuity of occupation of the several subdivisions of the service groups contributed greatly to the efficiency with which their work was performed, besides adding importantly to the flexibility of the laboratory's operations.

The Engineering Services Division performed a wide variety of functions for the scientific groups of the laboratory, and, in magnitude, its payroll was approximately one-quarter that of the laboratory as a whole.

Design and Drafting. One subdivision of the Engineering Services Division, concerned with the operation of all local engineering service activities, was the Design and Drafting Department which was drawn upon by all divisions almost equally for design work involved in their programs. Central records of plans and drawings were kept by this group which also assumed responsibility for their classification and custody. This was of assistance in bringing about uniform procedures and also was invaluable in connection with the Extension Engineering Contract Departments when the assistance of external manufacturers had to be

Machine Shop. The machine shop was the largest of the local service groups and together with the sheet metal shop formed a mechanical unit for the construction of experimental equipment and service prototypes, in addition to undertaking on occasions with urgent priority jobs which could not be produced to specification by commercial shops in the area.

Electronics Laboratory. The Electronics Laboratory, as its name implies, designed, fabricated, and tested electronic components of equipment required by the scientific divisions, collaborating closely with the Drafting and Mechanical Construction Departments as was required in the construction of the units. Skilled electronic designers were of particular assistance to the Sonar Data Division because few of its personnel with the requisite electronic experience were available for the design of the equipment required for their measurement program. All divisions made equal use of the Electronics Laboratory and the Transformer Laboratory for the actual construction of experimental and service equipment.

Recording and Communications. The other subdivisions of the Engineering Services Division were more or less independent units less closely integrated with engineering services than with the programs of particular scientific projects or routine services to the administrative group of the laboratory. The Recording

Laboratory, for instance, divided its time nearly equally between work for the Sonar Data Division and the Training Aids Division. Occasionally, work was done for the Devices Division as well, but the routine recording of sea results of the transmission program and the construction of training recordings occupied most of the time of this group. It rendered an invaluable service through these two associations and demonstrated the essential role played by skilled recording personnel, in sonar research and training. The connection between the Recording Laboratory and the Communications Group was a close one, as much of the work handled by both involved the receipt of radioed information from laboratory and naval vessels at sea. The Communications Group was also linked by common interests and personnel with the Electronics Laboratory, and the closest cooperation was maintained between these groups and the local naval communications authorities.

Photographic Laboratory. The Photographic Laboratory was initially instituted as a subdivision of the Engineering Services Division, but its work was divided about equally between assisting the scientific divisions on the one hand and the reports group on the other. Some assistance was rendered the Personnel Department in the taking of employee photographs and other routine services, and a special program was set up for the development of oscillographic recordings taken by the Sonar Data Division. However, the greater portion of the time was devoted to photographing devices in various stages of completion and in furnishing suitable prints for all types of reports. At a later stage of the laboratory's operation, this group was transferred to the Publications Division, as this proved to be a more efficient arrangement when the laboratory effort was largely directed to the reporting of its previous program.



FIGURE 15. The USS *Jasper* (PYC13) used principally by the Sonar Data Division for deep sea measurements.

Marine Facilities. The Engineering Services Division also had charge of the equipping and maintenance of the laboratory's marine facilities. The *E. W. Scripps* and the *M. V. Torqua*, which were not naval vessels, required a certain amount of ordinary marine maintenance, and this was furnished during most of the laboratory's existence by a small group organized for this purpose. The general supervision of personnel aboard these ships was also in the province of the Engineering Services Division. These two vessels, and also the naval vessels assigned to the program, carried extensive installations of scientific apparatus for the conduct of the various projects. In general, this was designed and built by the Engineering Services Division and then installed and maintained by engineers assigned to the Marine Facilities Department of this division. These men served essentially as equipment curators aboard the vessels. Their services were indispensable in maintaining the equipment in operating condition and in adapting it to the day-

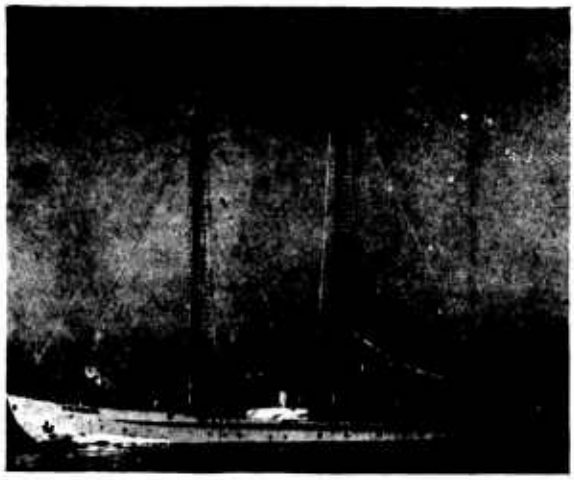


FIGURE 16. The *E. W. Scripps* also used for deep sea work.

to-day requirements of the various scientific programs which shared its use.

Procurement. One of the most important functions of the Engineering Services Division was that of procuring devices constructed to laboratory specifications from suppliers both in the Southern California area and elsewhere. When designs had reached a stage at which no further research or development was anticipated, units were procured by purchase order in suitable quantity for operational test. When it was anticipated that further research would be required, the Government's interests were protected by the procuring of devices under subcontract. The group of engineers forming the Extension Engineering and Subcontract Department of the Engineering Services Division performed the essential functions of assisting the Purchasing Department in locating suitable suppliers, interpreting laboratory specifications to them, and furnishing technical advice and supervision in the course of the manufacturing program. Through this section, the laboratory's ability to provide those services requested by the Navy was greatly expanded. It would have been impossible to provide the necessary space and facilities in the laboratory itself for the manufacturing programs that were from time to time undertaken, and had the attempt been made to do so, it would have reacted unfavorably on the experimental and pioneering development which was the chief obligation of the laboratory. On the other hand, adequate naval evaluation required the provision of many units of different types of devices, and this was accomplished both expeditiously and economically through enlisting the services of local manufacturers whose efforts were integrated with the laboratory's program through the activities of the Engineering Services Division.

3.2.6 The Harvard Laboratory

Establishment and Objective

The operations of the Harvard Underwater Sound Laboratory [HUSL] covered the period from June 5, 1941 to January 31, 1946. The laboratory was established under a contract between NDRC and Harvard College. It was continued under a renewal contract which in turn was extended by 14 supplements.

Harvard Group Proposed. The establishment of HUSL grew indirectly out of work begun in December 1940 by Massachusetts Institute of Technology [MIT] under a direct Navy contract. Learning that research having to do with underwater warfare was being undertaken by a division of NDRC, leaders of the MIT group suggested that there might be a valuable program which could be conducted under Harvard auspices. In a letter of June 5, 1941, Frederick V. Hunt, associate professor of physics and communications engineering at Harvard, and Philip M. Morse, professor of physics at MIT, wrote T. E. Shea, director of the New London laboratory, outlining certain types of investigation which they believed might be prosecuted advantageously. Work at the laboratory which was later to be known as the Harvard Underwater Sound Laboratory began almost immediately and was soon formalized under a contract which bore the effective date of the original proposals, June 5, 1941. Dr. Hunt was named director.

Phases of the Program. During the first phase of the laboratory's program, which lasted from its establishment until July 1, 1942, the work of the laboratory divided itself rather naturally into three parts. First, there was urgent need to increase the effectiveness of submarine detection equipment already installed in Navy ships. Second, it was desirable to devise and experiment with new forms of equipment which offered the possibility of greatly improved performance. Lastly, in the fall of 1941, a third major project was established when the labora[illegible] was requested to undertake work which i[illegible] hoped might lead to the construction of a[illegible] ubmarine ordnance which would home itsel[illegible] its target by acoustic means.

The first period, as [illegible]ght be expected, was largely one of expl[illegible]tory study, of rapid growth in the numb[illegible] of employees, and of expansion of facilitie[illegible] carrying on research.

The fact, however, [illegible] the work of the laboratory was to a gr[illegible]ctent exploratory did not mean that signi[illegible]t developments were

not achieved. During this early phase of the program, the bearing deviation indicator (described in a later part of this volume) was developed and successfully tested. This device, auxiliary to current submarine detection gear, improved the accuracy and speed with which a target could be located. Other studies and experimental work during the first year of HUSL's operation, provided the basis for two other important developments which matured later. One of these was the antisubmarine acoustic mine; the other was a type of scanning sonar gear which was continuously alert in all directions.

A move to new and larger quarters in Harvard's Hemenway Gymnasium marked the beginning of the second phase of the HUSL program which was to extend from July 1942 through December 1943.

Work continued on the development of improved forms of sonar equipment, but at the same time the intensity of the enemy's submarine activities along the Atlantic coast made imperative the development of improvements immediately applicable to detection equipment already installed on convoy escort vessels. A number of improvements of this type were completed, and HUSL provided manufacturers with technical assistance in their production and provided the Navy with assistance in installing them and in training naval personnel to use them.

Work on the acoustic mine was continued and before the end of 1942 the device had been successfully air-launched and sent in pursuit of artificial targets. By February 1943, production units had become available for full-scale tests and late in the spring of 1943, the weapon had been put into operational use.

The third period of the HUSL program extended from January 1944 to the termination of the contract in January 1946. This period saw an addition to Hemenway Gymnasium of almost double the available working space, and saw the laboratory reach the peak of its activity in the summer and fall of 1944.

Scanning sonar was developed to the point where the Navy felt justified in deciding to incorporate it as a feature of "ultimate" sonar equipment. Parallel work on the acoustic control of standard Navy torpedoes brought results which justified starting manufacture on one full-size acoustic torpedo for launching from submarines. Further work led to the successful application of acoustic control to an air-launched steam torpedo and a high-speed electric torpedo, and to the advanced development of acoustic control by echo ranging, a system more difficult for an enemy to counter.

As the termination of the HUSL contract approached, the development projects which were still active were progressively transferred to the Navy. The sonar development program was transferred to the Naval Research Laboratory, and the torpedo development program to the Ordnance Research Laboratory at Pennsylvania State College.

PERSONNEL

As in all other wartime laboratories, one of the most acute problems with which HUSL had to contend was that of securing adequate numbers of competently trained personnel.

Recruiting. The recruiting of personnel suffered under many handicaps. For example, in attempting to persuade a likely candidate to join the HUSL staff, security reasons might well make it impossible to describe the work of the laboratory in sufficiently convincing detail to make it clear that it was more important than the work the candidate was then doing.

The management of HUSL used every possible means and device to secure lists of potential research workers. In the end, it usually came down to a matter of leg work, with a recruiting officer from the laboratory going into the field to track down, interview, and pass judgment on personnel who seemed to show promise.

Salaries. The fact that employment with HUSL was for the duration only and that it meant moving mature scientists from one working environment to another made the determination of salaries a complex problem. In fixing a starting salary numerous factors had to be considered, including the employee's educational background, his training and experience, previous salary history, the responsibilities which he would have in the HUSL organization, and the personal complications which

would result from his transfer to a new environment. The governing principle was that the individual should be transplanted without imposing on him a financial penalty on the one hand, or offering him a financial reward on the other.

It was the policy of the laboratory management to conduct periodic salary reviews, usually at intervals of 6 months, at which time possible adjustments of previous salaries could be made in the light of an employee's proved ability to handle more important assignments.

The salary policy covering the employment of the service staff of the laboratory (as distinct from the scientific staff) was governed in large part by conditions in the local labor market. In recruiting the service staff and fixing service salaries the Office of Personnel Relations of Harvard University provided invaluable assistance by giving applicants a preliminary screening and by correlating the salary scale of HUSL with the salary rates prevailing in other laboratories operating at Harvard under OSRD contract.

Scientific-Service Staff Ratio. One of the administrative problems involved in the management of a research laboratory is that of determining the proper ratio between the number of scientific investigators and the service staff required to support their efforts. During the early months of HUSL's operation, it was not unusual to find scientists with doctor's degrees doing their own drafting, constructing and assembling their own apparatus, wiring their own electronic chassis, and writing their own reports in longhand. It did not take long to recognize that this was a waste of talent. A recruiting program, by July 1942, had brought the ratio of supporting service staff to scientific staff to 1 3.

Women Employees. The failure of Selective Service to provide unequivocal deferments for scientific personnel, plus the general scarcity of available male workers, early led the laboratory to employ women as drivers, messengers, technicians, and apprentice machinists. Women electronic technicians were in general given on-the-job training. A system of employing novice girl technicians at electronic salvage, that is, the unwiring of experimental chassis for the recovery of components, proved highly satisfactory in that it showed their supervisors whether or not they possessed manual dexterity and were generally reliable and suited to electronic wiring work.

A complete cumulative roster of all those employed by HUSL included a total of 818 persons. The peak of employment occurred in August 1944 when the total laboratory personnel reached 462. Of the total staff of 818 employees, 238, or 29 per cent, had college degrees. Of the 158 research associates, 96 per cent had college degrees, 58 per cent had masters' degrees, and 30 per cent had doctors' degrees.

Physical Plant

One of the premises underlying the original proposal for research on underwater sound at Harvard University was the availability of a limited amount of space in the Cruft Laboratory and the Research Laboratory of Physics. Early work was conducted in the large "battery room," 35x51 ft, in the basement of the latter building. Procurement was handled through the regular university channels.

As new recruits were added to the laboratory staff the research work expanded into other rooms adjoining the battery room, but the program grew at such a rate that by the spring of 1942 experiments were being conducted in space providing less than 60 sq ft per capita. A survey of other available buildings showed that Hemenway Gymnasium, erected in 1938 to replace an older building of the same name, would be adequate to house the expanded activities of the Underwater Sound Laboratory. Plans for altering the gymnasium went forward speedily.

Hemenway Gymnasium. Hemenway Gymnasium comprised a tier of six squash courts below ground level, another tier of six squash courts above ground level, and a top floor containing a regulation basketball floor and a badminton court. Each tier had three squash courts on each side of a mezzanine corridor. By erecting temporary floors to carry these mezzanine levels across the courts, the floor area available in the squash court section of the building was doubled and ultimately contained about 24,000 sq ft. Somewhat later, advantage was taken

of the high ceiling of the baskball floor to surround the floor with a balcony 13 ft wide, and at level of this balcony a temporary floor was built over the badminton court. Thus in addition to the two floors below ground level, the gymnasium was remodeled so as to provide four floors above ground.

Gannett House. As wartime requirements reduced the number of law students in residence, HUSL was able to obtain the use of an adjacent frame building, Gannett House, previously occupied by certain law school activities. Reception, personnel, business, and procurement of HUSL were transferred to Gannett House on July 19, 1943, and convenience of access was assured by the erection of a covered overpass connecting the second floor of Gannett House with the fifth floor of Hemenway Gymnasium.

Other minor additions to the laboratory building were made from time to time and warehouse space for unclassified material was acquired in other university buildings. All these steps, however, were insufficient to keep up with the expansion of the laboratory's scientific personnel required by the continuing pressure to accelerate the completion of vitally needed developments.

Hemenway Annex. As a result, authorization was sought and granted in November of 1943 for the construction of a large temporary annex to Hemenway Gymnasium. Temporary, factory-type wooden construction was used and the addition was ready for occupancy early in March 1944. The additional space provided by the annex nearly doubled the floor area available for the laboratory's research and development work.

Field Stations. Soon after the establishment of the laboratory, two small field stations were set up. One of these was at the tip of Pier 1 in East Boston and the other at Pier 8 in the Charlestown Navy Yard.

Shortly afterward, difficulties encountered in the use of these stations made it necessary to construct a measurement barge, 61x21x5 ft. This barge, delivered in April 1942, provided enclosed working space including a large well for lowering test equipment into the water. Initially, it was operated in the slip of the Hodge Boiler Works in East Boston, but the high ambient noise level produced by ship construction activities at the neighboring Charlestown Navy Yard made this location unsuited for acoustical measurements.

It was arranged, therefore, that the barge should be anchored in the lower Charles River Basin, where it stayed throughout the remainder of the war as the Charles River Calibration Station. In September 1942, a smaller barge was provided which was later tied permanently to its larger predecessor in order to provide auxiliary well space for tests on standard projectors.

The Charles River Basin furnished unusually favorable conditions for acoustic measurements



FIGURE 17. Gannett House and Hemenway Gymnasium before and after erection of the annex to Hemenway.

in the supersonic frequency range. The lower part of the Basin, in which the measurement barges were anchored, is approximately three-quarters of a mile wide, and over most of this width, the depth of the water is approximately 20 ft. The soft mud of the bottom provided a high degree of acoustic absorption and there

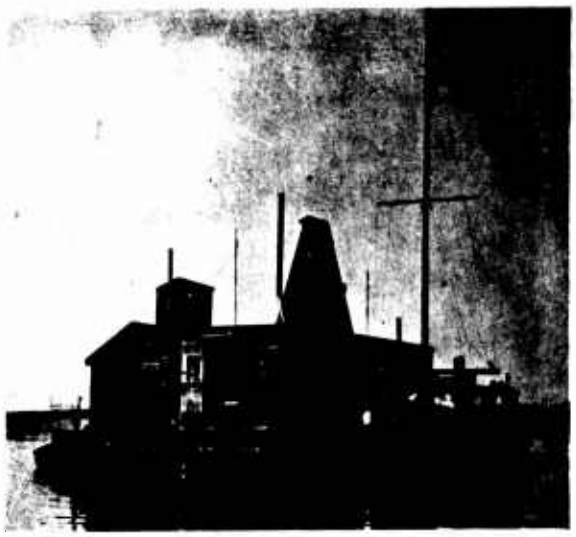


FIGURE 18. The barge measurement station in the lower Charles River basin.

was practically no man-made underwater interference. A waterproof cable from shore provided reliable power.

Some of the early experiments on the anti-submarine mine were conducted off Nahant, Massachusetts. Running tests and preliminary steering trials were conducted there and, by arrangement with the Naval Air Station at Squantum, it was possible to carry out trials leading to the development of successful methods of dropping mines from aircraft. In May 1943, the Board of Selectmen of the town of Nahant gave HUSL semi-exclusive use of the town dock for experimental work. Permission was obtained to make necessary alterations, including the erection of a temporary building on the pier end of a derrick for handling the heavy torpedo bodies.

Another measurement station was constructed at Spy Pond in Arlington, Massachusetts, 3½ miles distant from the laboratory. The Spy Pond Station relieved the Charles River Basin Station of some of the load of measurement work. The facilities at Spy Pond included a ramp extending 36 ft from the shore to the 32x20 ft measurement building. Two heavy steel girders framed a well which provided an unobstructed working area 30x4 ft. The handling facilities were sufficiently rugged to cope with full-size torpedo bodies.

Since cold weather arrives in the early fall off the New England coast, it became apparent in September 1942 that a warm, deep-water site for the year-round conducting of experiments with homing torpedoes was imperatively needed. The result of an extensive survey of possible sites was the determination to locate the new installation near the Coast Guard Station at Fort Lauderdale, Florida.

The Navy Bureau of Ordnance leased the peninsula constituting the eastern end of Fort



FIGURE 19. Fort Lauderdale Station (U.S. Navy).

Lauderdale's 15th Street, which had been occupied by a fishing resort and a small fuel dock operated by the Gulf Oil Company. The establishment created at this location was operated entirely by the Navy and was known as the Naval Ordnance Unit.

Operations at Fort Lauderdale commenced on September 8, 1942, and provided research and field testing facilities, not only for HUSL, but for groups from the Bell Telephone Laboratories and General Electric Company, operating under NDRC contracts, and for a Brush Development Company group operating under a Bureau of Ordnance contract.

Floating Facilities. In addition to shore stations and barges, seagoing facilities were

needed and these were provided through use of USS *Galaxy*, on which an experimental model of QCL equipment was installed in January 1942. Later the need for additional facilities for the sea testing of sonar equipment led to the purchase in June 1942 of the *Aide de Camp*, a 110-ft twin-screw diesel yacht which was provided with two wells and other hull openings for experimental work. Later, other smaller vessels were added. The entire HUSL fleet is shown in the following table.

TABLE 3. Vessels of the HUSL fleet.

Vessels	Type	Overall length (ft)	Load water-line (ft)	Beam (ft)	Draft (ft)	Cruising speed (knots)	Power plant
Navy craft							
USS *Galaxy* Built 1930 by Pusey and Jones, Wilmington, Del.	Yacht	130	121⅔	21⅓	7	11½	Two 245-hp Winton diesel engines, 4-c 6 cylinder
Flying Cloud Converted motor launch. Duty rating "work boat"	Launch	50	47	13	4	6 Max. 9	D. D. Buda 60-hp diesel engine
HUSL craft							
Questor Purchased May 1942	Motor sailer	31	34	11⅓	4⅙		Chrysler ace gasoline engine 70-hp 6 cylinder
Aide de Camp Purchased June 1942	Diesel yacht (twin screw)	110	102	18⅙	6		Two 200-hp Winton diesel engines, 4-c 6 cylinder
Tommy Purchased May 1943	Sedan cruiser (twin screw)	30	29	8½	1⅝	21	Two 95-hp Chrysler engines, 6 cylinder
Juldi Walla II Purchased December 1943	Motor sailer	40	38	12⁵⁄₁₂	⅓		One 135-hp direct-drive Chrysler engine, 8 cylinder
Tyler Too Purchased May 1942	Barge	61		21			
Tippecanoe Purchased July 1942	Barge	31		14			

ORGANIZATIONAL DEVELOPMENT

As has been noted, the program of HUSL was divided chronologically into three periods, the first extending from June 1941 to July 1942, when the laboratory moved to its quarters in Hemenway Gymnasium; the second extending from July 1942 through December 1943, when the annex to Hemenway Gymnasium became available; and the final period from January 1943 to the termination of the laboratory contract at the end of January 1946.

Informal Beginning. During the initial period, the number of HUSL employees grew from 3 to 125. They were predominantly research personnel. The members of the group worked together in a small area and it was comparatively easy to keep everyone informed about the progress of the work being done and to maintain continuing contact with NDRC and the Navy. There was little need for much attention to be paid to a more formal organization.

As the research staff grew, the individual project groups developed their own group leaders and these constituted an informal committee providing a channel by which administrative decisions could be made known to the staff as a whole. This system of administration functioned adequately, a contributing factor being the lack of need for the establishment of any management services, since procurement, janitor and telephone service, and the many other service functions were performed by the University's Departments of Physics and Communications Engineering.

The removal to Hemenway Gymnasium

brought a full realization of the extent to which the laboratory had been the beneficiary of these service facilities. Supplying them on the laboratory's own account created many heavy administrative problems.



FIGURE 20A. USS *Galaxy* (IX-54), experimental facility of the Bureau of Ships, provided a vehicle for experimental work in all phases of HUSL's sonar program.

Administration by Committee. The second period, following the move to Hemenway Gymnasium, might be designated as "Administration by Committee." Administrative functions were allocated in such a way that two or more



FIGURE 20B. The *Aide de Camp*, an HUSL experimental yacht used for the early experimental work in the scanning sonar development program.

individuals shared primary and secondary responsibilities with respect to the administration of each service function. By this arrangement, it was nearly always possible for a troubled staff member to find without delay a member of the administrative group who had sufficient authority to deal with his particular problem.

Early in 1943 the various project group leaders were organized into an administrative council, the members of which divided among themselves the multitude of administrative duties which must be performed if a laboratory group is to operate successfully.

But as might have been anticipated, this method of organization and administration began to reveal its inadequacies as the laboratory population continued to grow. With the advice of Division 6 and Harvard University officials, a reorganization was effected in January 1944 to provide for a more systematic allocation of responsibility for various phases of the laboratory program.

Organization by Divisions. Under the new plan of organization, the HUSL development program was broken down into two major technical divisions, Sonar and Ordnance, each under an associate director. A technical service division, under a technical service manager, was responsible for supervising the operation of the various machine and electronics shops, the design and drafting departments, and the other technical units which provided services to the two research divisions.

The responsibilities of the Personnel Office, which previously had been concerned only with the service staff, assumed in addition the chore of recruiting research and technical personnel. The Business Office, in addition to its function of accounting and procurement, assumed complete responsibility for the maintenance and improvement of the laboratory plant.

An editorial division was created which had responsibility for the Document Library and for the editing, printing, and publication of all laboratory reports, instruction manuals, and other documents prepared for external distribution. The laboratory's patent attorney, who was responsible for the preparation of the invention reports required by the OSRD contract, served also as security aide to the director.

In retrospect, those responsible for the management of HUSL believe that organization by major technical divisions might profitably have been introduced much earlier in the laboratory's growth. They are equally convinced that the organization's plan as finally evolved could, with only minor modifications, serve for the effective conduct of an even larger activity. The "happy family" plan of organization char-

acterizing the middle period of HUSL history is the sort that provides a congenial atmosphere, but it is applicable only to a group small enough so that all participants in the administration can remain continuously informed concerning all phases of the effort.



FIGURE 21. The engineering room, the machine shop, and the main drafting room.

If HUSL's tardiness in realizing the need for a more formal organization requires apology, it is to be found in the fact that the members of the administrative staff were caught up in an activity far more complex than any to which they had been previously exposed, and that the progressive education of this group in management principles constituted a major, though anonymous, training project.

RESEARCH AND DEVELOPMENT PROGRAM

Since the major aspects of HUSL's research and development program are dealt with in detail in other parts of this volume, only a brief review will be included here.

The laboratory's preliminary research program included sound-field surveys in which HUSL extended into the ultrasonic frequency range the survey measurements already being conducted under the MIT project. HUSL also did research on underwater acoustic impedance measurements and work to determine the depth of submerged submarines, the directivity of sound sources, and the possibility of devising an echo-ranging system in which directional control of the transmitting or receiving beam could be obtained by variation of frequency rather than by the mechanical training of a projector. The laboratory made an extensive survey of sonar literature.

The development at HUSL of improvements for searchlight-type sonar equipment included the bearing deviation indicator, various automatic gain control systems, devices for utilization of the doppler effect, and other devices which are described in Part IV of this volume. Also discussed in Part IV is the development work by HUSL on scanning sonar equipment, sonar testing equipment, and equipment devised as training aids.

In Chapter 9, the work of HUSL on transducer development is discussed in some detail. The laboratory's ordnance development program is covered in Chapter 13.

The development of one device may properly be touched on here since it has administrative and financial as well as technical implications. This set of equipment was known as the *beeper*. In the practice firing of torpedoes a certain percentage did not perform according to speci-

fications and though the Navy attempted to recover them, a considerable number was lost. HUSL devised a noise-making mechanism which could be carried within the torpedo and a receiver to be installed on a boat patrolling for lost torpedoes. At current contract prices for naval torpedoes, the total value of the more than 700 "sinkers" recovered with the assistance of HUSL beeper equipment is almost equal to the total sum allocated for all operations under the HUSL contract.

Costs

The grand total of disbursement by HUSL was $7,233,900, of which $286,600 was expended during the early formative period from June 5, 1941, to June 30, 1942. The remaining $6,946,300 disbursed from July 1, 1942, to January 31, 1946, breaks down as follows.

Total salaries 45.8 per cent (of which 18.6 per cent was for the salaries of research associates, 9.2 per cent for technicians' salaries, and 18 per cent for the salaries of all others); expendable supplies, 26.1 per cent; capital equipment, 9.2 per cent; construction and building restoration, 8.2 per cent; miscellaneous expenses, 6.8 per cent; and overhead charges, 3.9 per cent.

Interpreting these numerical data in another way, it may be said that it required approximately $22,000 a year to hire a research associate, to supply him with supporting technicians and service staff, apparatus equipment and expendable supplies, and to defray all other costs (except rent and depreciation on the laboratory building) in connection with his work.

3.2.7 Airborne Instruments Laboratory

As has been mentioned in an earlier chapter, Dr. L. B. Slichter had been interested in the detection of submarines by magnetic methods considerably before the formation of Section C-4 of NDRC. At the request of Doctors Colpitts, Coolidge, and Mason, Dr. Slichter prepared a memorandum on this subject and on December 21, 1940, sent a copy of this memorandum to Dr. Bush. The limitations of magnetic methods were clearly realized but Dr. Slichter recommended that the method be thoroughly explored.

Dr. Slichter's trip to England in April and May of 1941 with Dr. Tate gave him a broader picture of the antisubmarine problem and particularly of the work that the British were doing in the field of magnetic detection. By the time he returned, Section C-4 had been established, and under a contract with Columbia University, he organized a group to undertake some preliminary investigations at MIT. Later the group working on this project was transferred to the Naval Air Station at Quonset Point, Rhode Island. There, office and shop space was made available in land hangar No. 1. For flight test use, a PBY with pilot and crew was made available. Since the early work of this group was confined largely to the testing of equipment developed elsewhere, these facilities were completely adequate. Dr. D. G. C. Hare joined the group at this time and was later made director of the Airborne Instruments Laboratory. In the winter of 1941, development work on what proved to be the most successful solution to the problem was begun within the group at Quonset Point. This necessitated a considerable increase in personnel. In addition, shortly before our entry into World War II, equipment developed by the Gulf Research and Development Company in Pittsburgh had made successful tests with friendly submarines. With the outbreak of the war and the appearance of enemy submarines off our coast, a very marked interest in this was evidenced by the Navy. These two factors made it advisable to move the center of the activities to a place providing more space and which was less isolated than the Naval Air Station at Quonset Point. Accordingly, a survey of facilities adjacent to large airports was made and in March of 1942 the center of activities was moved to a portion of the TWA hangar at LaGuardia Field, New York. All the facilities at Quonset Point were maintained but activities there were largely confined to the testing of equipment developed at LaGuardia.

Laboratory Facilities and Equipment

In July 1942, the headquarters of the laboratory were in a portion of the TWA hangar at

LaGuardia Field with an experimental base at Quonset Point Naval Air Station, where about 20 per cent of the scientific staff was stationed. Operational bases were maintained at the Lakehurst Naval Air Station, New Jersey, and Langley Field, Virginia.



FIGURE 22. Main AIL buildings, 150 and 160 Old Country Road, Mineola, N. Y.

In September 1942, the lack of sufficient space necessitated a move to Mineola, Long Island, to occupy a building at 150 Old Country Road, and a residence at 92 Old Country Road. The official name then used was the Airborne Instruments Laboratory. Through an arrangement with the Long Island Biological Association, a field laboratory was maintained at Cold Spring Harbor where experiments and test work requiring magnetic quiet were carried out. The laboratory acquired an experimental airplane, a Grumman G-21A (twin-engined amphibian), in September 1942, which was housed in a Navy hangar at Roosevelt Field. Two protected rooms provided adequate space for flight equipment and plane supplies in this hangar. The total floor space in the Mineola vicinity, including storage warehouses, was 30,097 sq ft.

Early in 1943, increased activities on the west coast made it necessary to provide laboratory, office, and storage space for the men engaged in experimental and Service installations in California. Through the cooperation of the Harlow Aircraft Company at Alhambra, a temporary frame building for laboratory and stock use together with suitable office space in a fireproof building were made available.

In addition to the main and branch laboratories at Mineola and Alhambra, certain facilities were provided at 19 Army and Navy bases.

Laboratory Airplane. The bimotored Grumman G-21A amphibian plane (Navy designation JRF-5) which was urgently needed for



FIGURE 23. Administration Buildings, Alhambra, California.

magnetic airborne detection [MAD] research and installation activities was purchased in September 1942 following approval by the Joint Aircraft Committee. As delivered, it was



FIGURE 24. Field Station, Tucson, Arizona.

equipped with normal flight and navigation instruments as well as standard Navy transmitting, receiving, and direction-finding radio equipment. Later, a lightweight commercial-type transmitter and receiver were installed for normal airway communications. The plane was powered by two 450-hp Pratt and Whitney Wasp Jr. engines and was operated at a maximum weight of 8,500 lb. It had a useful load of 2,500 lb and a cruising speed of 140 mph. The

plane was painted the standard Navy two-tone blue and carried the CAA designation NX-1604.

A 3,800-hour pilot and an experienced aircraft and engine mechanic were employed by the laboratory to assure satisfactory flight operations and maintenance. The plane was



FIGURE 25. JRF—experimental plane.

equipped with chest-type parachutes which are carried on certain types of test flights, and with CO_2 inflatable life preservers which were carried when the plane was used in overwater operations.

The plane was normally based at Mineola, New York, where it was housed in hangar F of the Roosevelt Field Naval Air Facility. The various regulatory bodies (CAA, FCC, PAW, Fighter Commands, etc.) waived wartime flight restrictions to permit effective use of the plane as required in the work of the laboratory.

Since its purchase, the plane served as a prototype for dual MAD installations and was used extensively in the test of MAD equipment and accessories. It was flown in experiments over submarines off San Diego, and over magnetic loops at the Mojave Bombing Range and at Langley Field, Virginia. Its most frequent target for test work was the partially submerged hull of the torpedoed tanker "Gulf Trade" located about 3 miles off Barnegat Light, New Jersey. The plane was used frequently to ferry engineers and MAD equipment from the laboratory to Langley Field, Virginia, and Quonset Point Naval Air Station, Rhode Island, when tight installation schedules were tied in with the departure dates of operating Service squadrons.

By July 14th, the plane had accumulated a total of 439 air hours and at that time it was laid up for complete overhaul. It was returned to service on August 25th after the addition of a new AN/ASQ-2 installation and an independent 24-volt d-c, 50-ampere capacity auxiliary power supply.

The availability of an experimental plane has been of great value to the laboratory since it has expedited the working out of MAD installation and compensation techniques aboard air-



FIGURE 26. Loop, Langley Field, Virginia.

craft and has provided means for quickly obtaining information as to the performance of equipment in flight. Satisfactory design of airborne electronic equipment is highly dependent upon such flight tests. In this connection it may be of interest to note that members of the laboratory staff flew a total of 6,335 hours in the 12-month period ending August 31, 1943.

PERSONNEL

The original group on this project consisted of Dr. L. B. Slichter, who initiated the work; Dr. J. N. Adkins; Dr. N. A. Haskell; Judson Mead; and C. S. Pearsall. Dr. D. G. C. Hare joined this group in August of 1941. In addition to this group at Quonset Point, several groups were working on various phases of this problem elsewhere. Among these may be mentioned V. V. Vacquier and L. D. Palmer at the Gulf Research and Development Corporation;

W. J. Shackleton, E. P. Felch, and T. Slonczewski at the Bell Telephone Laboratories; A. W. Hull and others at the General Electric Company; and R. T. Knapp and M. Serrurier at the California Institute of Technology. In November of 1941 eight additional people were added to the staff at Quonset Point and in January of 1942 the staff there totaled about 25. A large number of men was added in March and April and the total at the end of the first year was about 80. The total staff on this work grew to 160 by the end of 1942 and to over 350 by the end of 1943.

Research and Development

As mentioned, the problem was that of detecting submerged submarines from aircraft. The most promising method seemed to be that of measuring the distortion in the magnetic field of the earth caused by the presence of the ferromagnetic mass of the submarine. The magnetic field of the earth has a total intensity of about 60,000 gammas (1 gamma equals 10^{-5} gauss), and the distortion of this field due to the presence of a submarine at a distance of a few hundred feet is of the order of 1 to 10 gammas. Since the problem deals with a vector field, any relative motion between the sensitive axis of the measuring device and the direction of the field must be either neutralized or such motion must be eliminated by stabilization. At the start of this work, devices capable of measuring a few microgauss were available and, therefore, the major portion of the effort of this program was to eliminate the effect of those motions of the aircraft relative to the magnetic field which might give rise to spurious signals in the equipment.

The British System. The division's work on the problem of magnetic detection of submarines from aircraft began in the spring of 1941 when Dr. J. T. Tate, then Chief of Section C-4, and Dr. L. B. Slichter conferred in England with those of the British interested in this work. The British had developed a two-coil gradiometer system with which it had been possible, under favorable conditions, to detect a submarine at the range of 200 ft. The British expressed the opinion that this range was too small to be of operational value but that, if the range could be doubled, an instrument of great value would be available. The British equipment consisted of two large coils about a foot in diameter, mounted coaxially in a rigid framework and separated by about 8 ft. Each coil, which was as far as possible identical to its mate, was wound with a large number of turns of wire such that the product of its area in square centimeters and the number of turns was about 10^8 to 10^9. These coils were connected in opposition, thus forming a gradiometer. Magnetically, a submarine is very nearly equivalent to a magnetic dipole. The magnitude of such a field varies with the inverse third power of the distance from the dipole. An airplane carrying a balanced coil system will measure the space change of the gradient which varies with the inverse fifth power of the distance. Thus, to achieve the result desired by the British necessitated an increase of the usable sensitivity by a factor of 32. Since measurements of this sort are nearly always limited by the background noise present, this requirement effectively calls for a reduction in the noise level by the same factor.

Early investigations indicated that a large portion of the background noise was due to deflections of the coil mounts and, therefore, the first phase of this work was to devise a coil mounting sufficiently rigid to keep the electrical axes of the coils parallel to within extremely close limits. Work was begun independently at BTL and the California Institute of Technology on the design of suitable coil mountings and, in addition, amplifiers were constructed by BTL and others which were capable of amplifying the very small low-frequency voltage to be expected. Work on this project was continued until November 1941, at which time it was terminated in view of the satisfactory tests of the Vacquier equipment.

Vacquier Magnetic Detector Mark I. This equipment was developed as the result of work begun in November of 1940 by the Gulf Research and Development Company. In the form as tested at Quonset, it consisted of a saturated-core mu-metal magnetometer mounted on a gravity-erected gyroscope which stabilized it about the vertical. The system was held in azimuth by a servo motor which was controlled by

the output of a second mu-metal magnetometer.

This equipment was tested in November of 1941 at Quonset Point and the flight test made at that time showed that signals could be obtained from S-type submarines at altitudes of more than 400 ft. The equipment, when mounted in the hull of a PBY airplane, had a noise level in a straight and level flight of approximately 3 gammas. Its inherent noise level on the ground in a quiet location was about 0.2 gamma. This was the first device which showed promise of being operationally usable as the detector of submerged submarines from aircraft. Further tests made in conjunction with our own submarines indicated that, contrary to earlier considerations, it was necessary that the equipment function at all times during flight, including the period in which the aircraft was making rapid maneuvers. For several reasons, the noise level on the Vacquier equipment was unreasonably high when the airplane was maneuvering. The primary cause of this high background was that the gyroscope, being gravity-erected, would precess off the vertical as a result of the centrifugal force during a turn and would thus give rise to a large anomalous signal when coming out of a turn. Contributing causes to the background were the local fields due to the aircraft's ferromagnetic as well as conducting parts. These disturbing fields arise when there is relative motion with respect to the magnetic field of the earth. During the weeks following the first successful test of this equipment, efforts were made to reduce these sources of noise. It was soon realized that little could be done about the inherent limitation of the gyroscope. Considerable improvement was made in the residual noise due to the aircraft's structure by deperming hard steel members and compensating for the effects of others.

Other Methods of Stabilization. With the recognition of the limits of the gravity-erected gyroscope, work was immediately started independently on three alternative methods of stabilization. A group under A. W. Hull at the General Electric Company began development of the gyroscope which would be erected along the earth's magnetic field and for which the direction of the axis of erection would be independent of acceleration. It was suggested, apparently simultaneously and independently by several workers, that a system could be devised which would measure the magnitude of a vector field without reference to its direction. In general, these schemes involve mounting three measuring devices in an orthogonal system, thus measuring three mutually perpendicular components of the vector field. Since the magnitude is proportional to the square of the sum of these components, by squaring and adding the outputs of the three detectors, it is possible to measure the magnitude of the field only. The possibility of squaring and adding three currents or voltages to the necessary precision was the subject of active investigation by the group at Quonset Point and at the Bell Telephone Laboratories.

During November 1941, it was proposed that it would be possible to orient the detecting element along the magnetic field by means of two independent magnetometers mounted perpendicular to each other and to the detecting element in a set of gimbal axes. The output of these orienting magnetometers controlled servo motors which kept them at all times perpendicular to the magnetic field of the earth. The detecting element was thus held along the field.

Early in December, it was decided that the majority of the effort on this project should be centered on this latter method. Accordingly, independent developments were started at Quonset Point, at BTL, and at Gulf Research and Development Company. The equipment designated as Mark IV MAD was first flight-tested on February 15, 1942, and successful tests were made early in March by the group at Quonset Point.

Work on the magnetically erected gyroscope was continued by the group under Hull at General Electric and later by Vacquier working at the Sperry Laboratories in Garden City under an arrangement made by this laboratory. In April of 1942, BTL, realizing that the early servo systems used for orienting the magnetometers were perhaps unsatisfactory, began the development of a system which used the magnetic method of orientation but, in addition, squared the outputs of the three magnetometers and added them as a correction fac-

tor to eliminate servo failure. This work was satisfactorily continued although later developments of the servo system indicated that nothing could be gained by the square law compensation. Work on the magnetically erected gyroscope was concluded after successful flight tests in the summer of 1942. At that time, the magnetically stabilized system had been developed to a point such that the errors due to servo failure were entirely negligible in comparison to the other background noise.

Noise Elimination. The development of a streamlined housing which would contain the equipment and which could be towed some distance from the airplane was begun as a part of the two-coil program in the summer of 1941, and was continued throughout the year. During April and May a reasonably satisfactory housing was developed by Knapp of the California Institute of Technology and was flight-tested at Quonset Point. At about the same time, a tail cone mounting in which the equipment was mounted in a nonmetallic housing which was an extension of the fuselage, was developed to enable the equipment to be used in an Army B-18. Both of these methods allowed considerable reduction in background noise and general development work in this field was continued throughout the contract.

In November of 1941, a definite program was begun with the objective of developing techniques for the compensation of anomalous magnetic fields produced by the aircraft. During the spring of 1942 this work had progressed to a point where maneuver noise was reduced in many cases by factors of 10 to 1. Techniques were developed for the compensation of effects due to permanent and induced magnetization of the airplane's structural members and preliminary work was begun on the reduction of noise due to eddy currents generated in the conducting members near the detecting element. This general work was perhaps one of the most important and fruitful projects of the contract period.

Use on Surface Craft. A test installation of a Mark IV unit was made on a PC boat at the request of the Navy and trial runs indicated that satisfactory operation shielding ranges of from 300 to 400 ft might be obtained with adequate compensation. In view of other developments by the Naval Ordnance Laboratory for this purpose, this project was not continued.

Summary of Activities

Chronologically, the outstanding developments in MAD equipment were as follows.

Mark IV-B2 MAD—July 1942. This was an improved production-model magnetic airborne detector designed by Airborne Instruments Laboratory.

Studies of Magnetic Fields above Submarines —September 1942. A large number of measurements of the static magnetic fields above submarines have been made. On the basis of this information, dynamic signals have been computed and checked by model measurements. This information is of great value in the development of tactics and in the evaluation of bombing probabilities.

Attack Trainer—October 1942. The *magnetic attack trainer* [MAT] is a device developed to allow practice on various suggested MAD tactics. Its function is twofold: (1) to evaluate suggested MAD tactics, and (2) to train Service personnel (pilots) in the use of MAD, following approved tactics.

Mark VI MAD—December 1942. (Army-Navy Designation — AN/ASQ-1—AN/ASQ-1A). This is a lightweight version of the Mark IV-B2 and incorporates increased sensitivity and stability. It entirely superseded Mark IV-B2 from the production standpoint. Identified originally by the laboratory designation Mark VI, this equipment is now coded under the standard Army-Navy method of nomenclature as AN/ASQ-1 (when used with earlier polar head) and AN/ASQ-1A (when used with the new universal head).

Automatic Release Mechanism—January 1943 (Army-Navy Designation—CP-2/ASQ-1). This apparatus is designed to identify, for the purpose of automatic flare and bomb release, the peak of the MAD signal obtained from a submarine.

The Universal Head—January 1943 (Army-Navy Designation—DT/3/ASQ-1A). This is an improvement on the earlier magnetically oriented detector mounting and offers the very great advantage of permitting operation with-

out mechanical change in any magnetic latitude.

MABS—February 1943 (Army-Navy Designation—AN ASQ-2—AN ASQ-2A). The *magnetic airborne bombsight* [MABS] is equipment designed to determine the lateral position of the submarine with respect to the airplane at the time the magnetic signal is received so that bombs will be automatically released only if the plane is within effective barrage range. A visual indicator shows whether the submarine is to the left or right of the plane. MABS is now coded AN ASQ-2 or AN ASQ-2A (polar or universal heads).

Compensation—March 1943. This refers to the development of techniques for compensating the disturbing magnetic effects of the airplane on the detector. These techniques have been developed to a very high degree and, at the present time, permit satisfactory compensation of the permanent, induced, and eddy current magnetic effects of all airplanes which have been suggested as MAD carriers.

Each of the developments mentioned above is described in greater detail in another volume of this report.

3.2.8 Other Laboratories

The preceding sections of this chapter have been concerned with the laboratories or groups especially and specifically established to carry out the work of Division 6. It is not implied that all the research and development work in the field of subsurface warfare or even all of the work of Division 6 was carried on by these organizations. The Navy had large programs at the Naval Research Laboratory, at the Naval Ordnance Laboratory, and under contracts with civilian agencies. In fact, almost all of the progress in the art of locating submarines by supersonic methods that was made during the period between the end of World War I and the beginning of World War II was due to the Naval Research Laboratory operating on a very limited peacetime budget. As soon as World War II appeared imminent, the program of the Naval Research Laboratory, as well as those of other groups under the Bureau of Ships, was greatly increased.

Likewise considerable work relating to subsurface warfare was carried on by other divisions of NDRC. Division 3, for instance, carried on many important ordnance developments making use of rockets. The Radiation Laboratory developed radar to detect surfaced submarines at night and in fog. Several months (October 1, 1940) before Section C-4 was started, a contract had been negotiated with the Woods Hole Oceanographic Institution under the directorship of C. O'D. Iselin to study the transmission of sound in the ocean. This work was so intimately related to the fundamental research undertaken by Section C-4 and later Division 6 that the Woods Hole contract was placed under the general supervision of this division. The Woods Hole Institution made a very large contribution in manpower, laboratory space, and ship facilities to the program of the division.

The existing industrial research laboratories also made a large contribution to the work of the division. Because of its very great experience in the air-acoustic field, the staff of BTL was of invaluable help in setting up a program. Several large contracts were let with the Western Electric Company, Inc., under which research and development were done by BTL. These included work on the development and construction of primary and secondary standard underwater acoustical receivers and projectors, the design of a supersonic prism for underwater scanning, the investigation and development of equipment for locating submarines by magnetic methods, the investigation and development of listening systems and harbor-protection devices, the development of special types of torpedoes, and for the development of special batteries for electrically driven torpedoes.

Likewise several contracts were let with the General Electric Company. These covered the detection of submarines by magnetic methods, by light pulsing and by special acoustical methods, and the development of special types of torpedoes. Other contracts concerned with the development of special torpedoes were with the American Can Company, Westinghouse Electric Corp., Newark College of Engineering, Electrical Engineering and Mfg. Corp., and the

Leeds and Northrup Co. In connection with the detection of submarines by magnetic methods, contracts were drawn up with the Gulf Research and Development Co. and the Goodyear Aircraft Corporation. Extensive equipment was set up at the California Institute of Technology for the study of underwater trajectories of bombs and torpedoes and for the study of cavitation and other phenomena utilizing a high-speed water tunnel. Additional work of this same character was carried on at the Iowa Institute of Hydraulic Research of the University of Iowa. Other contracts covering particular projects were let with the Massachusetts Institute of Technology, Armour Research Foundation, Radio Corporation of America, and the Sangamo Electric Company.

The important part that these various industrial and academic contractors played in carrying out the work of Division 6 will be apparent in the technical descriptions of their contributions in other volumes of this report.

Conspicuously omitted in this chapter on the organization of the Subsurface Warfare Group are discussions of the divisional units dealing with Operational Research, Selection and Training, and Field Engineering. This is because these three branches of the work of Division 6 are described in later chapters in greater detail than would be possible here.

PART II

OPERATIONS RESEARCH

Chapter 4

THE ROLE OF OPERATIONS RESEARCH IN ANTISUBMARINE WARFARE

By *Philip M. Morse*

As DIVISION 6 got under way, the vista of possibilities for technical assistance to the Navy widened rapidly.

Scientific help has been useful in the design of engines of war since the time of Archimedes. But until comparatively recently the resulting devices were simple enough so that the details of tactics and strategy could be left to the nonscientific military staff. In modern war, however, the equipment in use is so complicated that a scientific investigation of various tactics utilizing all available mathematical and statistical techniques can result in large improvements in operational effectiveness. This is particularly true of antisubmarine operations, the effectiveness of which depends upon the properly integrated use of an array of extremely complex gear. It is not surprising, therefore, that the first operational research group organized in the United States was in this field.

As has been pointed out, the first responsibility of Division 6 was in the direction of improving the design of underwater sound equipment for the detection of submerged submarines. As the field of activities of the division expanded, it soon became apparent that effective assistance could be provided only if the scope of the division's studies was widened to include all the gear taking part in the attack by a surface vessel on a submarine. In order to evaluate the relative importance of the multitude of problems which presented themselves, it was necessary to study the tactics of the attack. As the scope of the investigation thus widened, some of the theoretical aspects seemed to be of interest to those in the Navy directly concerned with operations against the submarine, that is, the actual users of the equipment.

Thus by a natural development completely analogous to the earlier development in England, scientific aid in antisubmarine warfare began by assisting in the design and production of equipment and finally was extended to the assisting in the planning of operations using the equipment. This extension of scientific aid into the realm of operations called Operations Research or Operational Analysis, is an innovation of World War II.

4.1 ANTISUBMARINE WARFARE IN WORLD WAR II

4.1.1 Period III—April 1941 to December 1941

April 1941, when Division 6 of NDRC was just getting under way, marked the beginning of the U-boat war's third period, which was to last until December 1941.

It has been shown how Allied countermeasures forced the Germans to abandon the tactics with which they had commenced operations, by attacking in daylight at periscope depth, in favor of night attacks on the surface. Period III was to see U-boat commanders once again forced to modify their attack procedures, due in no small part to the equipment which science had placed in the hands of the antisubmarine forces. The effectiveness of Allied escort vessels equipped with the high-frequency direction finders and radar was making the close surface night attack by one or two U-boats increasingly hazardous. The German answer was adoption of the wolf-pack system of attack. In this system, a U-boat encountering a convoy withheld its attack until it could summon other submarines in the vicinity for an attack in unison.

An additional reason for the adoption of the wolf-pack system was that because of deaths due to Allied action and the expansion of the U-boat fleet, seasoned submarine officers and men were being spread thinner and thinner. The wolf-pack attack in concert enabled less experienced U-boat crews to be guided by their more experienced colleagues.

April 1941 saw the enemy extending the

areas of submarine attacks south and west. Of the 41 merchant ships of 240,000 gross tons sunk by U-boats in April, nearly 30 per cent were sunk in the Azores and the Freetown areas. In May 1941 sinkings by U-boats mounted to 58 ships of 325,000 gross tons, more than half of the loss being in the Freetown area. By June of 1941 U-boats were raiding as far away as Newfoundland and south of Greenland. Losses to U-boats for the month were 57 ships of 296,000 gross tons. On the other side of the ledger, however, 5 U-boats were sunk.

In the face of these sinkings it became clear to the Allies that the only means of safeguarding shipping was to provide an escort clear across the Atlantic even though this meant spreading the limited number of available escort vessels even thinner. In July 1941, President Roosevelt announced that the safety of the United States required the basing of American antisubmarine forces in Iceland.

During July, August, and September 1941, 100 merchant vessels fell victims to the submarine. They had a total tonnage of 385,000 gross tons.

September 1941 was marked by the declaration by the United States that it would protect all ships carrying lend-lease materials regardless of the ship's nationality. On September 16 convoy HX-150 sailed from Halifax with warships of the United States Navy appearing for the first time among the escort vessels.

In October 1941, the United States Navy suffered its first casualties as the result of U-boat action. USS *Reuben James* was torpedoed and sunk. USS *Kearney* was torpedoed but succeeded in making port in Iceland. Shipping losses for the month of October totaled 32 vessels of 137,000 gross tons.

Only 12 ships of 62,000 gross tons were sunk by U-boats during November 1941. This comparatively low rate of sinkings could be attributed in part to the fact that the British offensive in Libya was causing the Germans to divert some of their submarines in the Atlantic to the Mediterranean. But an important contributing factor was the work of the British Coastal Command whose aircraft made the U-boat commanders prefer to stay outside their patrol range of some 400 miles offshore. Experience in the evasive routing of convoys was also having its effect.

Between December 7, when the United States was thrust into the war by the Japanese attack on Pearl Harbor, and the end of the month, Japanese submarines sank nine Allied vessels of 42,000 gross tons. During December, 10 ships of 50,000 gross tons were sunk in the Atlantic and 7 ships of 27,000 gross tons were sunk in the Mediterranean. The Allies, however, were making the enemy pay for his successes. Five U-boats were sunk in the Mediterranean and in one attack by six U-boats on an Atlantic convoy, four of the attacking submarines were sunk, though at the loss of merchant ships, one escort vessel and HMS *Audacity*, the first British escort carrier.

The third phase of the antisubmarine war was marked by a number of technical innovations.

CAM ships, merchant vessels equipped with fighter aircraft launched from catapults, were introduced. An analysis of attacks on submarines by aircraft showed that in at least one-half of them the aircraft dropped the depth charges while the U-boat was still visible or had submerged less than 30 seconds before. This led to a change in the depth setting for all depth charges to 50 ft and later to 25 ft.

During this phase of the war, the British adopted the hedgehog, a multiple spigot mortar mounted on the forepart of an escort ship which could forward-fire a pattern of bombs armed to explode on contact. Aircraft patrols over the Bay of Biscay were intensified and had the effect of forcing U-boats to run submerged in their transit to and from the French ports, thus increasing their transit time and correspondingly decreasing the time they could remain at sea.

The British during Period III made several notable advances in the use of radar. The short-wave 10-cm radar device was developed and fitted on British corvettes.

During the period a total of 44 enemy submarines were sunk, 22 German and 8 Italian submarines in the Atlantic, 6 German and 7 Italian submarines in the Mediterranean and one Japanese submarine in the Pacific.

These losses, however, were more than being offset by the new U-boats coming off the ways as the result of the intensified construction program. At the start of the period, the Germans had approximately 54 U-boats available and were able to keep about 18 at sea in the Atlantic at all times. At the close of the third phase of the war, the number of available U-boats had risen to approximately 200 and the average number in the Atlantic at any one time was about 36.

This great expansion of the U-boat fleet, however, had its effect in a telling loss of efficiency. The larger number of U-boats at sea were able to sink only about 34 ships of 166,000 gross tons per month in the Atlantic during Period III, or about 25 per cent less than during the previous period. This meant that the average U-boat was sinking only one ship of about 5,000 gross tons per month at sea and was therefore only about one-fourth as effective as in the previous period.

During the antisubmarine war, third phase, the British were able to increase the number of escort vessels from 375 to approximately 500 and the entry of the United States into the war added 175 destroyers to the number of available escorts.

There was some improvement in the Allies' shipping position. Losses averaged 363,000 gross tons per month as against 175,000 gross tons of new construction making a net loss of 188,000 gross tons per month, which was 45 per cent less than during the previous period. Despite this hopeful sign, total net losses for the period brought shipping available to the Allies down to 33,000,000 gross tons at the period's close.

4.1.2 Period IV—January 1942 to September 1942

Period IV of the antisubmarine war found the U-boats extending their range to the very shores of the latest principal participant, the United States.

The crisis in the U-boat war came during the first 6 months of 1942. By this time the Germans had about 200 ocean-going submarines, and new ones were being commissioned at the rate of about 20 a month; thus it was possible for the Germans to maintain a large-scale U-boat offensive over widely spread areas. The average number of U-boats at sea in the Atlantic increased steadily from 22 in January 1942 to 93 in September 1942. The relatively unprotected coastal shipping along the American seaboard was their target. Transatlantic convoys had been getting rather expensive to attack, as has been mentioned in the first chapter of this volume. In December 1941, for instance, 4 U-boats had been sunk in an attack on one convoy where only 2 merchant ships were sunk. It was natural that the submarines would turn their efforts toward a less well-protected prey.

The United States, with their antisubmarine forces reduced by the destroyers turned over to the British, by their commitments in transatlantic escort, and by the demands of the war in the Pacific, were caught unprepared for the scale of attack launched by the U-boats on the Atlantic coast in 1942. The forces available to combat these enemy activities were relatively untrained and inexperienced. With a limited number of antisubmarine craft, both surface and air, at their disposal, the U. S. Navy was unable to start convoying of coastal shipping immediately, but tried during the early months of 1942 to cover this long coastal route by patrol. This produced a number of attacks on U-boats, but it failed to prevent extremely heavy losses of shipping which were sailing unescorted along the coast.

Submarine activity in the west Atlantic began on January 12, 1942, when the first sinking in the U. S. strategic area occurred. A force of about 20 U-boats began to operate off the Atlantic seaboard of the United States, picking off tankers and larger cargo ships by preference and avoiding convoys. As long as worth-while targets abounded in the form of unarmed and unescorted ships, the U-boats kept clear of the escorts.

These submarines inflicted their heaviest losses in January in the eastern sea frontier, along the eastern coast of the United States, sinking 14 ships of about 100,000 gross tons. A large proportion of these losses occurred at

focal points of shipping such as Cape Hatteras and Hampton Roads. About 50,000 gross tons of shipping were sunk by U-boats in the northwest Atlantic, Canadian coastal, and Bermuda areas. There was comparatively little activity in the remainder of the Atlantic. The total losses for the month, 61 ships of 324,000 gross tons, were higher than those in any month of the previous period.

The situation became much worse in February 1942 when the world-wide shipping losses to U-boats reached a new high for the war with 82 ships of 470,000 gross tons being sunk by submarines. This loss was considerably greater than the rate at which we were replacing shipping. About 90 per cent of the losses occurred in the U. S. strategic area. As the number of U-boats operating in the west Atlantic increased and U-boat activities spread further south to Florida and the Caribbean Sea, tanker losses continued to be severe. Tanker traffic to and from the West Indian and Venezuelan oil fields was an obvious objective of the U-boats.

During March the U-boats continued their same tactics with increased success, sinking 94 ships of 530,000 gross tons. The most active area continued to be in the eastern sea frontier with over 150,000 gross tons of shipping being sunk there by U-boats. The one encouraging feature of the month's operations were the first successful attacks on U-boats in the U. S. strategic area. Two U-boats were probably sunk in March as a result of attacks by U. S. Navy aircraft in the northern part of the area. On the fifteenth of April, USS *Roper* sank U-85 off Cape Hatteras, picking up 29 bodies, for the first confirmed sinking of a U-boat off the U. S. coast. The number of attacks on U-boats in the U. S. strategic area had increased from about 15 in January to about 60 in April.

The increase in the counterattack probably played some part in causing a small decrease in shipping losses in April, but a more important factor was the temporary suspension of sailing in certain areas. U-boat activity spread to the Brazilian area during April.

In the middle of May 1942, the U. S. Navy was able to provide convoys for shipping along the east coast. The effect of the institution of these convoys was immediately apparent. The U-boats avoided escorted shipping, and the tonnage sunk by U-boats in the eastern sea frontier in May dropped to a mere 23,000 gross tons. The U-boats, however, simply sought out the remaining soft spots where unescorted traffic had to pass through focal areas, and operated actively off the mouth of the Mississippi and in the Yucatan channel between Cuba and Nicaragua. Though the average number of U-boats at sea in the Gulf sea frontier in May 1942 was only about four, these U-boats sank 41 ships of 220,000 gross tons there during the month, an all-time high for sinkings by U-boats in any area. The average number of ships at sea in the Gulf sea frontier was about 75, so the average life of a ship at sea was less than two months at that rate of sinkings.

It was, of course, realized that the only solution to the heavy losses off the Atlantic coast during the early months of 1942 was the institution of convoying of the coastal shipping. However, the U. S. Navy, because of its commitments in transatlantic escort and in the Pacific, did not have enough escorts to start the convoying. To provide additional forces, British antisubmarine trawlers were allocated for service on the American coast, and a few British corvettes were turned over to the U. S. Navy. Further, the whole system of transatlantic escort was recast, and all antisubmarine forces, U. S., Canadian, and British, were pooled in a single cross-Atlantic convoy scheme. This resulted in some economy and released a limited number of U. S. destroyers.

With the forces thus available and with the increased production of antisubmarine ships in the United States, it was possible to start convoying in the western Atlantic in May 1942. This convoy system was gradually extended into the Gulf, the Caribbean, and finally down the coast of South America as more and more vessels became available.

The effect of convoying in reducing shipping losses is clearly illustrated by the experience in the U. S. strategic area during the first nine months of 1942. There were about 600 ships on the average at sea in this area throughout this period. During the first six months before extensive convoying of coastal shipping was

started, only about 40 per cent of the shipping was in convoy. There were on the average about 30 U-boats at sea in this area during the first six months, and each U-boat was sinking about 2.7 ships a month. About 20 per cent of the independent shipping, and about 4 per cent of the convoyed shipping was sunk each month by U-boats.

During the next three months after extensive convoying of coastal shipping had started, about 80 per cent of the shipping was in convoy. The average number of U-boats at sea in this area had increased to about 50, but each U-boat was able to sink only about 1.4 ships a month, about half as much as during the first six months. Thus, despite the fact that the loss rates for both independent and convoyed shipping had increased during the last six months of this period, the efficiency of the average U-boat in sinking ships was halved. This was due mainly to the fact that about 40 per cent of the shipping was exposed, during the latter three months, to the much lower loss rate experienced by convoyed shipping instead of to the high loss rate experienced by independent shipping. Thus, convoying proved a very valuable defense in the crisis, but it was still not enough.

At the beginning of 1942 the U. S. Navy sent out all available planes and blimps to battle the U-boat along the coast. They were helped by the First Bomber Command, an Army Air Force contribution which was activated in December 1941. In addition to the Army and Navy flying, there was also patrolling by the Civilian Air Patrol [CAP] mostly within a hundred miles from shore. The flying hours by U. S. Army and Navy aircraft in the eastern sea frontier increased from about 5,000 hours in January to a peak of about 25,000 in July 1942. Similar increases came in the other frontiers, although at a somewhat later date.

The U. S. aircraft made about 30 attacks a month on U-boats during this first six months of 1942, starting from about 12 a month during the first four months to about 45 a month during the next few months. About 20 per cent of these attacks resulted in some damage to the U-boat, while only about 2 per cent resulted in the sinking, or probable sinking, of a submarine. Thus there was a large margin for improvement in the use of aircraft against U-boats.

4.2 ANTISUBMARINE ORGANIZATION IN U. S. NAVY

The organization responsible for the antisubmarine effort of the United States was also somewhat complex at the start.

The convoy and routing section of the COMINCH (Commander-in-Chief, U. S. Fleet) staff had the duty of organizing and routing all convoys from American ports to some midway point where the convoy control was taken over by the British. Destroyers for this task were taken from the Atlantic Fleet, and ComDesLant (Commander Destroyers Atlantic Fleet) was responsible for readying these destroyers, training their crews, and for devising antisubmarine tactics for the escorts.

The protection of the coastal shipping was in the hands of the various sea frontiers, eastern sea frontier taking the region from Maine to Florida, Gulf sea frontier taking the Gulf region, Panama sea frontier the Panama approaches, and Caribbean sea frontier the northern portion of South America and the Antilles. These sea frontiers operated local patrol craft, and also naval aircraft supplied by ComAirLant (Commander Aircraft Atlantic Fleet) and Army land-based bombers from the First Bomber Command. These craft were used for general patrol work along the shipping lanes, and later were used to a considerable extent in escorting coastwise convoys when these convoys became established.

Intelligence concerning submarine movements could be obtained from sinking and sighting reports. These reports were turned in, through the sea frontiers, to the Operational Intelligence Division, COMINCH, where they were evaluated and analyzed, and a coordinated report sent back to the interested frontiers. Each frontier kept its own plot where shipping and estimated submarines were shown and from which patrol, convoying, and attack plans could be made.

The lines of authority of these various com-

mands were of necessity somewhat vague at first. The scope of submarine warfare in the Atlantic exceeded that of any of the frontiers, and at times and in certain areas extended beyond the operating area of the Atlantic Fleet. For instance, when submarine warfare spread to the coast of Brazil, the Fourth Fleet, a separate entity, was called on to carry out antisubmarine activity.

It was felt that the control of convoys and, probably, the decisions on tactics, training, and equipment should be centered in COMINCH, since this would assure uniformity. But such a centralization could not be achieved immediately, and at first tactics and usages varied considerably from place to place. Some difficulty was also encountered in transferring aircraft and patrol craft from one frontier to another as enemy submarines shifted the location of their principal activities.

4.3 NEED FOR STATISTICAL ANALYSIS

It was soon apparent that the craft, personnel, and equipment available, and soon to be available, would have to be used to their utmost capabilities in order to beat back the submarine. The attacking team, whether on a destroyer or in an airplane, would have to know how to use its detection gear and its ordnance to the limit of its collective ability in order to make a kill. New equipment was being devised by the naval laboratories and by NDRC, and tactics suitable for this new equipment would have to be devised. All attacks would have to be studied carefully in order to derive the utmost from experience.

In order to analyze past operations and in order to utilize their lessons in devising new tactics, the Atlantic Fleet in February 1942 set up the Antisubmarine Warfare Unit, Atlantic Fleet, in Boston under Captain (now Rear Admiral) Wilder D. Baker. This unit was made up of officers acquainted with submarine operations, officers from destroyers, a Navy air officer, and an Army air officer. A tactical manual was begun, and analysis of antisubmarine operations was made the subject of a monthly bulletin.

It soon became apparent to Captain Baker and others of his unit that advice from scientifically trained civilians would be useful to the Antisubmarine Warfare Unit. Much of the new antisubmarine equipment was relatively unfamiliar to most naval officers and advice was needed from time to time in interpreting operational results. Also it was believed that some of the modern mathematical techniques could profitably be used in studying the statistics of past operations, in order to learn tactical lessons from them. Consequently a letter was sent from Captain Baker to the Navy Coordinator of Research, requesting the help of NDRC personnel in the study of antisubmarine tactics. The request was transmitted to NDRC and as a result, Research Group M (or ASWORG, as it was alternately known) came into being.

Chapter 5

NDRC BACKGROUND

THE EARLY DEVELOPMENT of the NDRC antisubmarine effort has been discussed in the previous chapter. As was mentioned in that chapter, there was some doubt on the part of certain naval officers as to whether or not NDRC could contribute help rapidly enough to be of use in the emergency. Thus, requests for aid were at first restricted to the field of underwater detection.

It was true that most of the personnel of the NDRC laboratories had to learn the art of antisubmarine warfare from the beginning. But it is surprising how rapidly several dozen of the best technical men of the country can learn a field, especially when they are spurred with a sense of urgency; for by the middle of 1941 it was obvious that the antisubmarine problem was of vital importance. As the groups began to find their way about in this new subject, a number of possible improvements in underwater detection equipment was suggested, a few of which turned out to be useful. As the work progressed, however, it began to be apparent that underwater detection gear might not be the crux of the problem.

The Naval Research Laboratory, it turned out, had done an excellent job in designing the U. S. underwater echo-ranging gear. Naturally a number of improvements were devised and are now included in the standard gear, but these improvements increased by only a slight percentage the chance of success in the final attack. The difficulty seemed to be that the rest of the antisubmarine gear had not been correspondingly improved. The ordnance (depth charges) had hardly changed at all; and equipment designed to help aircraft make submarine attacks was practically nonexistent. It seemed that confining the activities of Section C-4 to underwater detection failed to take many important factors into account.

5.1 STUDIES ON A/S ORDNANCE

A series of important and illuminating studies by Doctors L. B. Slichter and S. S. Wilks emphasized this fact. They seemed to indicate that with the best underwater detection system possible (allowing for the refractive effect of temperature gradients in the water) only about 1 attack out of 20 would be likely to succeed if the usual depth charges were dropped. This conclusion was tentative, since it was based on assumptions regarding the actual operational behavior of both submarine and destroyer. At the time of the study, these factors did not seem to be known in this country with sufficient accuracy to enable one to say whether the studies of Wilks and Slichter represented the true conditions or not.

5.2 NEED FOR OPERATIONS STATISTICS

In fact, it was becoming apparent that the Bureau of Ships, at least, did not know in any quantitative manner the operation characteristics of their antisubmarine craft and gear when used by the average crew in actual wartime conditions. This lack of quantitative knowledge was not the fault of the Bureau of Ships, for they did not seem to have access to quantitative analyses of operational results. In 1941, of course, there were no U. S. results to analyze; but even after several months of 1942 had passed, such analyses were still not forthcoming, despite the fact that a number of our ships and aircraft had already attacked German submarines.

Those in authority began to realize that no such detailed quantitative analyses of operational experience were being made anywhere in the Navy. This was not surprising; for almost every person in the Navy with any operational experience in antisubmarine warfare had been hurriedly drafted to go out to sink submarines or to carry out other important executive tasks, and not to analyze operations. There was a shortage of experienced skippers, operators, and personnel in general. Personnel with adequate scientific background to analyze

reports when they came in were not available. The Atlantic Fleet ASW Unit, which was a central planning unit at that time, did not have the time, nor did its members have the necessary specialized mathematical and scientific skill, to make technical analyses.

Consequently when Dr. Tate, as head of Section C-4, NDRC, replied with a ready affirmative to the request of Captain Baker for the assignment of technical and statistical experts to analyze operational antisubmarine data, the prompt response created a feeling of considerable relief.

Nor was the feeling of satisfaction one-sided. In addition to the value which the Navy felt that such studies would have in devising tactics, there was a belief in NDRC that such analyses would assist in the development of antisubmarine gear better suited to meet operational needs.

Before Captain Baker's request had come, Section C-4, as previously noted, had been expanded in scope to cover the whole of subsurface warfare. The advantages of such an arrangement had already been felt in a number of promising developments being worked on at the laboratories. This same broadening of the scope of the section made it quite logical that it should assume the responsibilities of organizing a group of scientific consultants to the ASW Unit of the Navy.

5.3 BRITISH EXPERIENCE WITH OPERATIONS RESEARCH

The need for technical and scientific experts to advise at the operational level had been felt earlier in England. TRE (Telecommunications Research Establishment) had been developing and building coastal aircraft-warning radar sets. As these were established along the British coast in 1940, considerable difficulty was encountered in coordinating the sets with the operations of the defending fighter aircraft and also with the antiaircraft batteries. A small group, headed by Professor P. M. S. Blackett, was organized by TRE to study the effectiveness of these sets in actual operation. They soon found that it was necessary to work closely with the operational commands of Fighter Command RAF and also with the Army Anti-Aircraft Command. It also became clear that this group could profitably study operational problems other than those involving early-warning radar. Then came the realization that if the group was to be effective in its broader scope, it needed to be attached to the interested Services rather than to a development laboratory such as TRE.

As a result, the Operational Research Section was set up for Fighter Command; and the Army Operational Research Group was also established which eventually was headed by Professor (now Brigadier General) B. Schonland. After completing the organization of Fighter Command ORS, Professor Blackett together with Professor E. J. Williams set up a corresponding Operational Research Section with Coastal Command (ORS/CC). This section, in 1941, started publishing the results of its studies of antisubmarine and antishipping operations. Shortly after the establishment of Coastal Command ORS, a section was set up in Bomber Command with Professor Dickens as the head. Later, other sections were set up in other divisions of RAF and in other operating theaters.

5.3.1 Operational Research in the Admiralty

In the spring of 1942 Professor Blackett was asked to organize operational research in the British Admiralty. Initially he was simply designated as "Chief Advisor on Operations Research" [CAOR] to the First Sea Lord of the Admiralty (who corresponds roughly to COMINCH). Other scientists were assigned to various divisions of Admiralty such as the Anti-U-boat Division and the Mine Warfare Division. These scientists reported directly to their division heads, usually senior naval officers. They also consulted directly, however, with Professor Blackett as CAOR. Later, Operational Research was made an official division of Admiralty with Professor Blackett as "Director, Naval Operations Research" [DNOR]. Similar organizations were set up in other

parts of the British Services, such as the Combined Operations and Air Coordination.

These operational research groups have had varying degrees of success. In general, they have been quite useful and have performed scientific services which neither the officer personnel nor the development laboratory personnel were in a position to carry out.

It seems to be generally agreed by now in England (as well as in the United States) that there is definite need for scientifically trained civilians to act as advisors to the Operational Control officers. It is felt that they should have close contact with the higher echelon officers and should have complete access to operational plans and records. The following excerpts from an article by Professor Blackett, discussing the utility of Operational Research, indicate the point of view of the acknowledged authority in this field in England.

The object of having scientists in close touch with operations is to enable operational staffs to obtain scientific advice on those matters which are not handled by the service technical establishments.

Operational staffs provide the scientists with the operational outlook and data. The scientists apply scientific methods of analysis to this data, and are thus able to give useful advice.

The main field of their activity is clearly the analysis of actual operations, using as data the material to be found in an operation room, e.g., all signals, track charts, combat reports, meteorological information, etc.

It will be noted that this data is not, and on secrecy grounds, cannot, in general, be made available to the technical establishments. Thus such scientific analysis, if done at all, must be done in or near operation rooms.

The work of an Operational Research Section should be carried out at Command, Groups, Stations or Squadrons as circumstances dictate.

Experience over many parts of our war efforts has shown that such analysis can be of the utmost value, and the lack of such analysis can be disastrous. Probably the main reason why this is so, is that very many war operations involve considerations with which scientists are specially trained to compete, and in which serving officers are in general not trained. This is especially the case with all those aspects of operations into which probability considerations and the theory of errors enter. Serving Officers of the highest calibre are necessarily employed in important executive posts, and are, therefore, not available for *detailed* analytic work.

The records of some war operation (e.g., air attacks on U-boats for the previous six months) is taken as the data. This is analyzed as quantitatively as possible, and the results achieved are "explained" in the scientific sense, i.e., brought into numerical relation with the operational facts and the known performance of the weapons used. When this has been done, consideration is given to possible modification of the tactics to improve the operational results.

The first step—that of collecting the actual data—is by itself of enormous importance, for it is not uncommon for operational staffs to be unacquainted with what is actually being achieved. An Operational Research Section is not in general concerned with "hot news," though they should be prepared to so concern themselves if specifically requested to do so.

A typical problem is as follows:—a weapon A is calculated by a service technical department to be 50% more efficient than a weapon B. Actual operations over a given period show, say, 2 successes for A and 4 for B. Does this prove that B is a better weapon than A?

Such points arise continually and require the highest scientific judgment to resolve. In particular a grasp of fluctuation phenomena (i.e., Poisson's Distribution) is required.

The scientist, in considering an operational problem, very often comes to the conclusion that the common sense view is the correct one. But he can often back the view by numerical proof, and thus give added confidence in the tactics employed.

Or when two alternative qualitative views, "A is best" "B is best" are in dispute, he can often resolve this numerically into some such statement as that "A is x% better than B in January and y% worse in June."

In fact, the scientist can encourage numerical thinking on operational matters, and so can help avoid running the war by gusts of emotion.

Since new weapons and devices are inevitably put into service relatively untested, the first few months of the use of a new device must be considered as an extension of its development trials. An O.R.S. can function usefully here in a liaison capacity between the operational staff, the technical department which produced the device, and the development unit which tested it.

Further, it is often possible by collaboration between Controllers and the staff of an O.R.S., to arrange operations on certain occasions so as to obtain data to clarify some doubtful point. For instance, the relative merits of different forms of A/S sweeps by aircraft is a matter of (a) mathematical calculation, (b) test by actual operations, perhaps over a long period of time.

One of the functions of an O.R.S. is clearly to write periodical reports on various aspects of operations. Except when secrecy questions prevent, these should be given a wide circulation, e.g., in the Air Force to Squadrons to be read by the aircrews. In this way, the tactical education of the men on the job can be raised.

One of the most important duties of a Command is to state its requirements for new devices and weapons.

Such requirements are pressed, in general, through a department of Ministry (which acts partly as a filter room, partly as a specialized technical department and partly as a post office) to a service technical establishment.

The only places in this chain where the real operational facts are known is at the Command Groups and Stations. Unless the operational requirement is considered scientifically at the Command jointly by the operational staffs and scientists, it is very possible that the operational requirement decided on will not correspond (a) to the real need, (b) to the technical possibilities.

In other words, an O.R.S. can act usefully by interpreting

(a) the practical facts of life to the technical establishments, and

(b) the technical possibilities to the operational staff.

A considerable wasted war effort has occurred through lack of this joint discussion.

Nothing in this section or in section (b) should be taken as implying that an O.R.S. should be the only channel by which a Technical Establishment obtains operational experience—on the contrary the direct contact between a Technical Establishment and operational units is generally essential.

An O.R.S. should be an integral part of a Command and should work in the closest collaboration with the various departments at the Command.

The head of the O.R.S. should be directly responsible to the C. in C. and may with advantage, be appointed as his scientific advisor.

A considerable fraction of the Staff of an O.R.S. should be of the very highest standing in science, and many of them should be drawn from those who have had experience at the Service Technical Establishments. Others should be chosen for analytic ability, e.g., gifted mathematicians, geneticists, chess players.

An O.R.S. which contents itself with the routine production of statistical reports and narratives will be of very limited value. The atmosphere required is that of a first class pure scientific research institution, and the calibre of the personnel should match this. All members of an O.R.S. should spend part of their time at operational stations in close touch with the flying personnel, and where possible should occasionally go on operational or training flights.

"New weapons for old" is apt to become a very popular cry. The success of some new devices has led to a new form of escapism which runs somewhat thus—"Our present equipment doesn't work very well; training is bad, supply is poor, spare parts non-existent. Let's have an entirely new gadget!" Then comes the vision of the new gadget, springing like Aphrodite from the bureaus, in full production, complete with spares, and attended by a chorus of trained crews.

One of the tasks of an O.R.S. is to make possible at least an approach to a numerical estimate of the merits of a change over from one device to another, by continual investigation of the actual performance of existing weapons, and by objective analysis of the likely performance of new ones.

In general, one might conclude that relatively too much scientific effort has been expended hitherto in the production of new devices and too little in the proper use of what we have got. Thus, there is a strong general case for moving many of the best scientists from the technical establishments to the operational Commands, at any rate for a time. If, and when, they return to technical work, they will be often much more useful by reason of their new knowledge of real operational needs.

Chapter 6

DEVELOPMENT OF U. S. OPERATIONS RESEARCH

By *Philip M. Morse*

THE NAVY AND NDRC looked upon the establishment of an operational research group from somewhat different points of view and with different expectations. The Navy's interest was at first primarily in the statistical analysis of past operations and in assistance in the theoretical details of tactical doctrine; and only secondarily in helping to work out military requirements for gear. The NDRC, on the other hand, was interested more in learning about the operational behavior of various equipment to provide help in the design of new gear.

From a more general point of view, however, the needs were complementary. The NDRC in this case was one of the ultimate producers of antisubmarine equipment, and the operating forces were the ultimate consumers. Between these two was a long chain of intermediate organizations: the Office of Scientific Research and Development, the Navy Coordinator of Research, the various interested Bureaus of the Navy, the Office of the Chief of Naval Operations, and finally the Fleets. All this long chain of organization was necessary to carry on the usual business of development, procurement, and supply; the usual flow of requests, orders, plans, etc., had naturally to flow along its length. But, the chain was too long for technical intelligence to flow quickly along it. It came to be realized that if some new organization could be devised which could shorten the channel of communication with respect to technical intelligence, but which would not short-circuit the flow of authority in the performance of normal duties, this intelligence unit could speed up the process of getting new equipment into operation and at the same time speed up the development of new equipment in the laboratories.

From still another point of view, the introduction of a group of scientists at the operational level was an attempt to apply the stimulus of fresh minds at a new place in the organization. Just as it was found useful to send officers with operational experience into the development laboratories to give the technicians an understanding of practical needs, so also it was deemed to be useful to try applying scientific techniques to tactical planning.

The introduction of a technical intelligence link between the ultimate producer and the ultimate consumer was a somewhat delicate operation in itself. It was agreed by both sides that members of the group should be left in civilian status in order to free them from the time-consuming duties of the officer. If the officer could be likened to the executive of an industrial concern, the operational researcher was the laboratory worker, not concerned with ultimate decisions but with pondering and comparing. Beyond this it was felt that the rules of organization of the group would have to be worked out as it developed.

6.1 ORGANIZATIONAL BEGINNINGS

As one of the first steps in carrying out the commitment made to Captain Baker, Dr. Tate on March 20, 1942, asked Dr. Philip M. Morse, professor of physics at Massachusetts Institute of Technology, to head the new group. The possible contributions which the group might make to a more effective antisubmarine effort promised to be so important that Doctors Tate and Morse determined to get the best available men for the initial nucleus. Accordingly, not only were NDRC laboratories approached for personnel contributions, but also laboratories and institutions not yet engaged in war work. The Bell Telephone Laboratories loaned the services of Dr. William Shockley, who became the group's director of research and assistant supervisor. Dr. Shockley had just finished working on the design of the prototype of the SJ submarine radar. The Harvard Underwater Sound Laboratory, working under Section C-4, contributed two of its staff members, Dr. M. E. Bell and Mr. J. R. Pellam.

Professor S. S. Wilks, who had carried out the first statistical studies of depth-charge attacks for Section C-4, contributed part of his time

in getting the group started. He also recruited a number of very useful group members from among his students and acquaintances in the field of mathematical statistics.

6.1.1 Columbia Contract

Section C-4, NDRC, requested Columbia University to take on this operational research as part of the work under an existing contract, OEMsr-20. With Dr. Morse as director of the project, and Dr. Shockley as director of research, the organization was set up as "Group M," one of the five separate activities under this contract, coequal with the operations at the New London Underwater Sound Laboratory, the operations that became known as the Airborne Instruments Laboratory, the work of the Special Studies Group, and the operation of the Underwater Sound Reference Laboratories. It was felt that Group M was a logical addition under this contract, for it was believed that the studies of Group M would enable New London, and other Section C-4 laboratories to do a better job of developing A/S gear. As will be seen later, this hope was realized in a number of important items.

During the initial period, the Service liaison officer for the group was Captain Baker.

The group grew slowly but steadily. By May 1, 1942, there were 7 scientists. By July 1 there were 12; by September 1 there were 19 in the group and by January 1, 1943, there were 30. At the ending of Contract OEMsr-20 on August 31, 1943, there were 44 members in the group, of whom 24 were Ph.D.'s or were full Fellows of the Actuarial Societies (equivalent to Ph.D. in training). Of these 44, 6 were mathematicians, 14 actuaries, 18 physicists, 3 chemists, 2 biologists, and 1 an architect. The group was remarkably cohesive. By the end of August 1943, after 17 months of operation, only 2 members had left the group. One left to take a commission in the Navy, and the other left to return to his previous position in another war research project.

At the end of August 1944 there were 50 members in the group, of whom 28 were Ph.D.'s or were full Fellows of the Actuarial Societies. This 50 consisted of 7 mathematicians, 16 actuaries, 18 physicists, 5 chemists, 3 biologists, and 1 architect. It was decided to give the group two names: one, the Anti-Submarine Operations Research Group (ASWORG) for use with the Navy and for classified reports; the other, Research Group M for administrative and financial contacts, which were not classified.

6.1.2 Outline of Organization

By April 1, 1942, a number of persons had agreed to join and the group was given office space in the quarters of the ASW Unit, Atlantic Fleet, at the headquarters of the First Naval District, 150 Causeway Street, Boston, Massachusetts. The date of April 1 can therefore be considered the official birth date of Group M. Within a week the first members of the group were busy learning their jobs. Records of convoy escort actions were made available, and all the officers of the ASW Unit freely contributed of their time.

As the group grew, its members were assigned to various parts of the antisubmarine forces. Members were assigned to eastern sea frontier, Gulf sea frontier, and Caribbean sea frontier headquarters to work with the A/S operations officers. A number of members were sent to the headquarters of the First Bomber Command, AAF and to the Army's A/S tactical development group at Langley Field. Members were assigned to London to provide liaison with the operational research carried on by British forces; and, later, assignments were made to Argentia, Newfoundland, to the Fourth Fleet in Brazil, and to the Moroccan sea frontier in Africa. Others became attached to the Navy A/S tactical development unit at Quonset, to Seventh Fleet in Australia, and to Fleet Air Wing 2, in Hawaii.

In 1943 it began to be apparent that the pioneer work of Division 6, in aiding the forces in the field, could profitably be applied in other fields of activity. Operations Research, Field Engineering, etc., were not originally envisioned in the setup of NDRC. There was some fear that such activities were not a legitimate part of the work of a division, though eventu-

ally every active division found itself engaged in them.

OSRD set up a new office, the Office of Field Service [OFS] under Dr. K. T. Compton, to handle such activities. The personnel in the groups set up by this office were contract employees of OSRD, and were loaned directly to the Services, under arrangements approved by Congress. ASWORG was the first group to come under OFS, most of the members being transferred from Columbia to OSRD contract in January 1944. From this time on, the history of Group M or ASWORG is not strictly part of the history of Division 6; but the relationship continued to be very close for some time.

This, however, is getting ahead of the chronological story of the Operational Research Group.

6.2 FIRST RESEARCH

Lt. Commander (now Captain) A. B. Vosseller, who represented Naval Air on the ASW Unit and who had been particularly active in urging the formation of the group, suggested that some of its members should visit Norfolk, Virginia, to see some of the air antisubmarine equipment and planes. Morse, Shockley, and Wilks spent an instructive three days at Norfolk, conferring with a number of the pilots at the Naval Air Base, looking at equipment and being flown in operational aircraft. It was soon realized that the work of the group would be considerably more useful and practical if the members could be kept as closely as possible in touch with actual operations, either by frequent visits of a similar nature, or perhaps by stationing some of the members at outlying bases. Operational research could possibly best be done nearest to the operations.

During the first few months at Boston a number of studies were commenced, some of which were later to occupy the group's attention a great deal. The whole complex of problems which might be considered together under the single word "Search" soon became important. General search principles were laid down which have been subsequently changed only in detail. From these principles aerial escort of convoy plans were laid out, as well as search plans for surface escort. A more complete discussion of this problem will be given later in this review.

Detailed statistical analysis of operations was not commenced at first, partly because the Navy facilities for the collection of operational reports were not complete as yet. But some initial analysis of surface vessel attacks was made; and various members of the group were asked to contribute suggestions as to the material and form of the action reports, which were supposed to be filled out in case of an attack or sighting.

6.3 MOVE TO COMINCH

In the meantime, Captain Baker, head of the Atlantic Fleet ASW Unit, had been called to Washington for a series of conferences. It was to be expected that the headquarters of the Commander-in-Chief, U. S. Fleet, would be the proper place for central tactical planning for antisubmarine warfare, since only from there could doctrine be sent out which would be used by sea frontiers as well as by the Fleets. About the end of May 1942, therefore, Captain Baker was transferred to the Readiness Division of the COMINCH staff, where he was directed to set up an antisubmarine unit. He did this by bringing down some of the members of the Atlantic Fleet ASW Unit, by taking over the officer who had previously held the COMINCH ASW desk, Commander C. R. Todd, and by bringing in a few new officers.

At the same time Captain Baker was instrumental in setting up an antisubmarine unit in the eastern sea frontier headquarters, in New York City. Commander (later Captain) Hungerford was brought in to head this unit and the Army Air Officer, Lt. Col. Cecil Reynolds, who had previously been with the Boston unit, was brought to New York to provide liaison with the First Bomber Command AAF. Commander (now Captain) T. L. Lewis was left in charge of the Atlantic Fleet unit in Boston, and a few additional officers were brought in to complete his complement. Plans at one time were made for the setting up of a similar unit

at Gulf sea frontier in Miami; this, however, did not eventuate.

Plans also were made for the expansion of the activities of Group M in order to keep pace with this naval expansion. In June 1942, offices were obtained for the group in Temporary Building 2, opposite the Navy Department, in Washington. The main headquarters of the group was gradually transferred from Boston to Washington, leaving only four members with the Atlantic Fleet unit. After a few months, offices for the group were found in the Navy Department on Constitution Avenue. After one or two moves the group found its permanent location in the series of rooms 4303 to 4313, in the main Navy Building, which it has occupied ever since.

On the first of July members of the group were installed at eastern sea frontier, reporting to the ASW unit there. Here, closer relationship was established with the Army Air Forces First Bomber Command, which provided many of the long-range bombers used in antisubmarine patrols along the eastern coast. A number of the Army air fields were visited, in particular Langley Field, where a certain amount of tactical and equipmental experimentation was being carried out under Colonel W. C. Dolan.

6.4 ASSIGNMENT TO BASES

Also in June 1942, Dr. Shockley, together with Dr. A. F. Kip, visited the headquarters of Gulf sea frontier in Miami. As a result of that visit and the previous negotiations of Captain Baker, Dr. Kip was left on assignment with the Operations Officer of Gulf sea frontier. In July, Dr. Shockley made a similar trip to Caribbean sea frontier with Dr. R. F. Rinehart, who was then assigned to the Operations Officer at the headquarters in San Juan, Puerto Rico. Later he was transferred to the headquarters of the Trinidad sector of this frontier.

In November, Dr. Bell and Mr. Pellam went to the base at Argentia, Newfoundland, the headquarters of Commander Task Force 24, who had command of the American escort vessels escorting the transatlantic convoys over the American half of the trip. After this visit a request came to Washington for a man from the group to be assigned to the Task Force. In the middle of December, Dr. F. L. Brooks was sent to Argentia, where he stayed until a realignment was made in convoy escort responsibilities. As a result of a joint USN-Admiralty agreement to transfer North Atlantic convoy control to the British after April 1943, Dr. Brooks' services were no longer necessary at Task Force 24, and he returned to Washington at that time.

In January 1943 a request for a Group M member came from Commander, Fourth Fleet, Vice Admiral J. H. Ingram, whose headquarters were at Recife, Brazil, and who had the responsibility for antisubmarine warfare on the American side of the South Atlantic. Dr. J. J. Steinhardt was sent first to Trinidad with Dr. Rinehart for some base experience, eventually arriving at Recife to report to Admiral Ingram on the first of March 1943.

Other bases were also set up. The numerous letters of commendation received from the cognizant officers concerning the work of members of the group indicate that an important part of Group M's work was done at these outlying bases. This is not surprising for, although the general principles of tactics and military requirements for equipment can perhaps best be worked out at a central headquarters such as Washington, the detailed application of the general principles must usually be worked out at an operational base. This detailed local help was useful in teaching the application of the general principles to the local forces and was also immensely valuable in teaching ASWORG men the practical aspects of the problem. Also, Group M base men proved to be of use in collecting operational data of a detailed nature, and in transmitting these to Washington for analysis.

By the end of the first year of operation, a number of general conclusions as to organization were apparent. In the first place, in order that the group remain mentally healthy and scientifically aggressive, it was necessary that a fair percentage of its members be assigned to outlying bases where actual operations were going on. It was important that these men be

attached to the higher echelons of the various outlying task forces, so that the problems arising could be assigned to them quickly and their solutions could be returned quickly for possible action.

The operational forces controlled from these outlying bases were the ultimate users of the antisubmarine equipment, so that the usefulness or the difficulties involved in a new piece of apparatus could be best determined by one of the base men. New needs, either for tactics or for equipment, were often discovered first at these bases. Changes in enemy tactics which were discovered by the group were usually discovered by one or another of the base men.

6.5 WASHINGTON OFFICE

The central headquarters in Washington had individual importance. At the Navy Department, the official orders were issued and the general doctrine was written. Here, the experience of the various base members could be crystallized into suggested doctrine or orders for equipment or development work. Here, the reports of all the base men and the action reports from all of the antisubmarine forces could be collected and studied statistically. Here, contact could be maintained with the naval and NDRC laboratories. General theoretical analyses could be worked up in Washington, and the results sent out to the base men, who were usually too busy to work out long and detailed calculations. Correlated results from all the bases could be sent back out to the bases so that each could see how the others were doing. All the work could be supervised by the proper naval authorities, clearances could be given, permission for publication and distribution could be obtained, and the general terms of reference of the group with the related services could be maintained.

It also became clear that there should be a certain amount of rotation between base men and central office men. Each man at each base should return to Washington at least every six months, so that he might catch up on new developments at home, and might give the home-office men the benefit of his experience. While he was absent from his post, his place would be taken by a home-office man who needed such field experience.

In view of this interrelation between base and central office in Washington, it is not surprising that the make-up of the central office was at first preponderantly statistical. As the base men began to return from their first tours of duty, a greater percentage of men trained in the physical sciences could be maintained in Washington. By then the group had matured.

6.6 RELATIONS WITH THE ARMY AIR FORCES

At about the time that the eastern sea frontier unit was organized and several Group M members were assigned to New York, the group began to be acquainted with the activities of the staff of Brigadier General Westside T. Larson, commander of the First Bomber Command, Army Air Forces. This Command, among other duties, supplied long-range bombers for antisubmarine patrol, under the operational control of the Eastern Sea Frontier. Its offices were at 90 Church Street, the same building which housed the Eastern Sea Frontier headquarters. Dr. Shockley and a number of other group members visited several of the First Bomber Command airfields to learn firsthand the Army problems in antisubmarine warfare.

Shortly thereafter the group was brought into contact with Dr. E. L. Bowles, scientific consultant to the Secretary of War, who at this time was much interested in the use of radar in antisubmarine operations. Search radar installed on aircraft was promising to be of considerable use in finding surfaced submarines, by day as well as by night. The first studies made by Group M on the operational flying of First Bomber Command radar planes indicated that average radar ranges of first sightings of submarines were definitely larger than average visual ranges of first sightings.

Dr. Bowles put the group in contact with Brigadier General H. M. McClelland, at that time Director of Technical Services of the Army Air Forces, who had cognizance of radar problems for the Air Forces. The experience

of his staff, in particular of Dr. Dale Corson, was of considerable benefit to Group M in commencing the study of the operational use of radar. Dr. Corson had worked at Radiation Laboratory, then had become one of Dr. Bowles' assistants, and had been assigned to General McClelland. In December 1942, General McClelland was named a liaison officer for Group M, and in May 1943, General Larson was also made liaison officer.

6.7 SEA SEARCH UNIT

In the summer of 1942 it was decided by the Army that it would be useful to set up a sea search attack and development unit to study the tactical and equipmental problems of antisubmarine operations by aircraft. This unit was organized under Colonel Dolan and installed at Langley Field, Virginia. During its period of operations, it worked on and was instrumental in getting into service the SCR 517 and 717 search radar, the magnetic airborne detector equipment [MAD], searchlights, and bombsights for antisubmarine aircraft operation.

For various reasons, the Sea Search Attack and Development Unit [SADU] was not placed under the control of the First Bomber Command but was under the control of General McClelland's office, the Directorate of Technical Services, Army Air Forces. Colonel E. E. Aldrin of General McClelland's office was the supervisory officer in Washington and was made liaison officer for the group in April 1943.

The first week in September 1942, H. H. Hennington, a Group M member, was sent to Langley to work under Colonel Dolan for SADU. By winter it was apparent that more men would be needed to work on the problems which Colonel Dolan was assigning the group, so Dr. Bell was transferred from the Boston office of the ASW Unit Atlantic Fleet to head the Langley group. D. D. Cody was also assigned there in February 1943.

This group of ASWORG members worked on a variety of problems during their stay at Langley. It helped to some extent in arranging contacts between NDRC laboratories and the Development Unit. It helped to prepare programs for tactical tests and then to write up the reports of the tests. A series of exercises was devised to check the proficiency of crew and gear in low-level bombing, such as is used in A/S attacks. Programs and reports were written on tests of sono buoys, searchlights, forward-firing rocket-flares, bombsights, odographs, and other equipment which might be of use in A/S operations. A full-dress tactical test of MAD tactics at Key West was supervised by Cody. Before SADU was closed, Group M members had been instrumental in the publishing of an Army manual, "Operational Use of Radar in Sea Search."

6.8 ANTISUBMARINE COMMAND

In the fall of 1942 also came a request from General Larson to assign one or more men to the headquarters of the First Bomber Command, which about that time became the Anti-Submarine Command, AAFAC. In October, Dr. A. A. Brown and M. E. Ennis, Group M members, were assigned to AAFAC headquarters, with Dr. Brown as head of the unit. In December, A. W. Brown also was assigned to this unit. This group worked on problems of training and material for the AAFAC staff. A complete study and report was made of all types of bombsights, resulting in a subsequent series of development projects at Wright Field and elsewhere to perfect a suitable antisubmarine sight. Coordinate grids were developed to measure photographs of A/S attacks, and a procedure was evolved to obtain adequate photographic coverage of all attacks. Group members accompanied various officers of the AAFAC staff on their inspection trips, in order to provide specialized advice on the spot.

In the meantime Brown was assisting in the writing and editing of the AAFAC Monthly Intelligence Report. He worked up the A/S operational statistics for the monthly report and wrote many of the articles on equipment and tactics.

During the winter of 1942-43 the Anti-Submarine Command established a special antisubmarine operational training unit, the 18th

Squadron, based at Langley Field. Lt. Colonel R. W. Finn, the squadron commander, requested the aid of ASWORG in setting up a program of tactical training. Dr. G. R. Pomerat was assigned there in May 1943 and stayed through the summer. He helped in establishing lecture schedules, training flight schedules, and standards for bombing exercises. He had begun work on the scenario for an antisubmarine training film when the training unit was discontinued in the fall.

6.9 RELATIONS WITH THE BRITISH

By the fall of 1942, the group's directors, Doctors Morse and Shockley, felt themselves to be well enough acquainted with the American antisubmarine problems so that a visit to England would be profitable. It was thought likely that one or more of the group members should stay in England continuously to form liaison with the British antisubmarine forces, and in particular with the Coastal Command and Admiralty Operations Research Groups. Captain Baker's permission for Dr. Shockley and Dr. Morse to go to England was granted in November.

After the plans for the trip had been made, another development occurred which made the trip particularly timely.

In order to assist the British Coastal Command in the antisubmarine air patrol of the Bay of Biscay, it was decided in the fall of 1942 that the United States Army Air Forces should contribute a squadron or two of antisubmarine planes. It was contemplated that these planes should participate in the particularly heavy air patrol of the Bay planned for the time of the landing in North Africa. The planes were to be sent first to England to help in the Bay patrol and then later to Africa to operate against submarines in African coastal waters.

The first squadron was hastily assembled and was sent off to England November 1, 1942, under the command of Lt. Colonel Jack Roberts. It was based in England at St. Eval, Cornwall, and was operationally controlled by the British. Since this squadron had been supplied by the Anti-Submarine Command, General Larson asked Morse and Shockley to look it up when they got to England, and to give the squadron what technical help they could.

6.9.1 Liaison with British Operations Research

Doctors Morse and Shockley arrived in England about the middle of November 1942. Captain Baker had arranged for them to report to the Naval Attache's office in London. They were assigned to Captain T. A. Solberg, head of the Technical Section of the Attache's office. In this office also were other civilian scientific experts, representatives of the Bureau of Ships, Naval Ordnance Laboratory, etc., maintaining scientific liaison with the corresponding British Bureaus and laboratories. Captain Solberg was instrumental in arranging a number of valuable contacts for Morse and Shockley.

Since, to facilitate travel authorizations, the men went over as special OSRD representatives, they also reported to Bennett Archambault, head of the OSRD London office, who also arranged for liaison with British war research laboratories, for office space, and for transportation facilities. Archambault gave very valuable aid in arranging contacts for the two members.

A great number of such contacts had to be made. In the first place there was Admiralty, which had operational responsibility for antisubmarine warfare, routed the convoys, controlled the destroyer escorts on their side of the Atlantic, and which also had operational control over the Coastal Command's antisubmarine planes. Meetings were arranged with Captain Philip Clark, Director of Anti-Submarine Warfare [DASW], with Professor Blackett [CAOR], and with other operational research people working in antisubmarine warfare, among them being Dr. J. H. C. Whitehead and Dr. E. C. Bullard. The work of these people was discussed with them, and arrangements were made for the future interchange of ideas and reports.

The next contacts were with Coastal Command. Arrangements were made to go to their headquarters to meet the head of Op-

erations Research Section, Coastal Command [ORS/CC], at that time Professor Williams. A meeting was held with the head of Coastal Command, Air Chief Marshal Philip Joubert. The particular problems of the AAFAC squadron at St. Eval were discussed at this meeting, and it was agreed that Dr. Shockley was to spend the majority of his time with Colonel Roberts' squadron until it got under way.

Soon afterward Dr. Shockley went to St. Eval and established contact with Lt. Colonel Roberts and the Squadron of B-24's which was there. It turned out that this squadron was the first operational squadron of antisubmarine planes in England to have S-band radar sets. This produced many complications since all the British plans, arrangements for blind landings, etc., were built around the longer wave ASV Mark II sets. This, combined with the fact that the American squadron had been assembled in a hurry and had not had a thorough radar training, meant that the inherent advantages of the S-band gear were not immediately realized. After numerous discussions, the squadron was allowed extra time to spend in further training, and it was just about in shape when it was transferred to a base in Casablanca, North Africa. It subsequently proved most useful there; and mention will be made of its operations in the sections dealing with the work of ASWORG men assigned to Moroccan sea frontier.

At the meeting with Air Chief Marshal Joubert and at other subsequent ones, arrangements for liaison with ORS/CC were worked out. These arrangements were materially aided by the presence of J. P. T. Pearman, a pioneer member of ORS/CC, who was familiar also with our research program. Earlier in 1942, Pearman had visited America at the time a Coastal Command squadron was sent here to help out in antisubmarine work in the Caribbean. Pearman had made contact with ASWORG and had spent considerable time in bringing the group up to date on the work of ORS/CC. He had returned to England early in the fall and was on hand at Coastal Command to welcome the visiting ASWORG members and to introduce them to people at the headquarters.

Professor Blackett arranged for Dr. Morse to meet Colonel (now Brigadier General) Schonland, head of the Army Operations Research Group. A visit was made also to the Eighth Bomber Command, U. S. Army Air Forces, and to the Army Operations Research Group assigned to that Command. This group, under J. M. Harlan, had just recently arrived and was busy exploring the problems with which it would be called upon to deal.

6.9.2 London Office

As one of the results of their visit to England, Doctors Morse and Shockley became convinced that at least two ASWORG men should be kept in England to provide liaison with the British antisubmarine operations research work. These members could be assigned to Commander Naval Forces in Europe [ComNavEu] and would work under the direction of Captain Solberg. One of these two men could spend most of his time in liaison with ORS/CC, and the other could spend most of his time at Admiralty with the operations research workers there. This idea was welcomed by the British workers and was also satisfactory to Captain Solberg. Upon the return of Dr. Morse to this country the plan was formalized with Navy approval.

6.10 INCORPORATION INTO THE TENTH FLEET

By the end of 1942 it had become clear that improvement in the quantity and quality of antisubmarine equipment and personnel could not by itself win the battle of the Atlantic. A centralized planning and operational authority was needed.

There were numerous examples of divided authority, resulting inevitably in reduced effectiveness. The squadrons of the First Bomber Command (later the Anti-Submarine Command), AAF were controlled operationally by the eastern sea frontier. Later, a few of the squadrons were assigned to England, where they were controlled by the Coastal Command, RAF. Several squadrons were subsequently sent to Africa where they were under still an-

other operational command. Army squadrons were supplied to the Caribbean sea frontier by the First Antilles Air Task Force (later the Antilles Air Command) of the Army Air Forces.

It was suggested by some in the AAF that all of the Army air antisubmarine effort be unified under the Anti-Submarine Command, which would have its squadrons eventually all around the North Atlantic. This would have provided a certain unity as far as training and equipment went, but the operational control of these Army planes would still have been divided. In addition there was the situation of the more or less autonomous sea frontiers, each with its own tactical doctrine, planning staff and intelligence organization.

During the spring of 1943, the Commander-in-Chief's staff was engaged in a detailed study as to the best organizational means of improving this complex command relationship. The time was opportune for some central authority to be placed over all of these activities to determine unified doctrine, to arrange for unified distribution of intelligence, and to unify operational planning. Resulting from these studies, the Tenth Fleet was established in May 1943 under the direct command of Admiral (later Fleet Admiral) E. J. King, Commander-in-Chief, U. S. Fleet, with Rear Admiral F. S. Low as Chief of Staff.

6.10.1 Improvement of ASWORG Effectiveness

The complications due to the divided command naturally had affected the work of Group M. Those assigned to the Anti-Submarine Command of the Army found themselves working with plans for training and matériel which were often at variance with the Navy plans for naval aircraft. Tactical doctrine differed and there was a certain amount of rivalry in pushing new equipment developments, which made for duplication of technical effort. The interpretation and use of operational doctrine and intelligence differed from frontier to frontier. Group M members assigned to outlying bases often had found themselves to be the sole messengers of unified doctrinal planning, which sometimes led to embarrassments in Command relations.

This lack of unified authority had particularly hampered the work of the Washington office of Group M. Many of the statistical and analytical studies of the group directly suggested new operational procedures. There had been no central authority to whom to report these suggestions nor one who could take action on them if action was deemed advisable. Lack of central operational authority meant that the Washington office could not carry on operational research in the strict sense of the word.

As the direct result of the establishment of the Tenth Fleet, Group M was enabled to work more effectively. Under the careful and understanding guidance of Admiral Low and his staff, its research improved greatly.

One of the first tasks of the Tenth Fleet was to settle the question of the Army's part in the antisubmarine effort, and, in particular, to study the recommendation that all Army A/S flying be unified under the Anti-Submarine Command. This unification appeared desirable, but from a more general point of view it would have introduced an inevitable duality between the Army and the Navy antisubmarine flying. The Army had originally been asked to contribute to antisubmarine flying because at the beginning of World War II the Navy planes were needed elsewhere and the Army had planes available along the east coast. By the first of 1943 this situation had changed to some extent. Although Navy planes were not easily obtainable, there were enough to spare from Pacific operations to make it possible for the Navy to begin taking care of all antisubmarine flying in the Atlantic. This, of course, would result in a much greater unity in the effort and if a decision to relieve the AAF of A/S duties were to be made eventually, it could best be made at the time of formation of the Tenth Fleet.

Consequently, it was decided by high authority that the Navy would gradually take over all the antisubmarine effort in the Atlantic, that the squadrons of the Army Air Forces Anti-Submarine Command in England and in Africa would eventually be replaced by

naval squadrons, and that the Anti-Submarine Command would be returned to its original position of First Bomber Command. This was gradually accomplished during the first half of 1943; the squadrons under Lt. Col. Roberts, which had first been sent to England and then to Africa, being among the last ones to be replaced.

During this same time, the activities of Group M that had been connected with the Army's antisubmarine effort were correspondingly curtailed, and its activities at the various naval bases were being increased. The ASWORG unit at Langley Field was closed in August, and the men assigned to AAFAC headquarters in New York were returned and given other assignments. Mr. Pellam, who had been sent over to England to work with Lt. Col. Roberts' squadrons and who had accompanied the squadrons to North Africa, transferred his allegiance to the naval authorities at Moroccan sea frontier. The change was authorized by the Tenth Fleet, as were the other changes.

6.10.2 Relations with Tenth Fleet

In the meantime, Group M was made an official part of the Tenth Fleet. After discussions between Admiral Low and Dr. Tate, Chief of Section C-4 (by then Division 6) NDRC, a directive was written by Dr. Tate on July 7th and endorsed by Admiral E. J. King on July 9th defining the activities of Group M and its relation to the Tenth Fleet. The official name of the group was given as the Anti-Submarine Warfare Operations Research Group [ASWORG] although the title "Group M" was continued with the Columbia University administrative department in order to maintain security.

The Tenth Fleet was, in a way, a fifth division of the COMINCH staff, the other four divisions being Plans (F1), Combat Intelligence (F2), Operations (F3) and Readiness (F4). Admiral Low was appointed Assistant Chief of Staff (antisubmarine) of COMINCH, and Chief of Staff of Tenth Fleet (FX). The staff of Tenth Fleet paralleled in part the standard naval staff, having an operations section (FX-30) and a readiness section, which in this case was called A/S Measures (FX-40). Convoy and Routing, under Rear Admiral M. K. Metcalf, was made FX-37. ASWORG was placed under A/S Measures, and the head of ASWORG, Dr. Morse, became FX-45.

The original head of the COMINCH Anti-Submarine Unit, Captain Baker, had returned to sea in November 1942, his replacement being Captain J. M. Haines. When the Tenth Fleet was formed, Captain Haines became head of Measures, FX-40, and ASWORG reported to Admiral Low via Captain Haines. In September 1943, Captain Haines also returned to sea, his replacement being Captain H. C. Fitz.

6.11 ASDEVLANT

About the same time that the Tenth Fleet was being formed, another need, long felt by the Navy Antisubmarine Forces, was satisfied; a need for an organization which would carry on tactical experimental work in antisubmarine operations and which would also provide operational training for antisubmarine air crews. This need had been met for the Army by the establishment of SADU and an operational training unit [OTU] at Langley Field. These units were not under the same command, SADU having been under the Director of Technical Services, General McClelland, and the OTU under AAFAC.

In the case of the Navy, the first move in this direction was the establishment in February 1943 of the Aircraft Anti-Submarine Development Detachment, Atlantic Fleet [AirASDevLant]. This unit was under Commander Air Forces, Atlantic Fleet [ComAirLant], and combined the activities of the tactical development unit and the specialist training unit. The Commanding Officer of the Detachment was Captain Vosseller, who had been with the Atlantic Fleet A/S Unit in Boston, and who had been connected with the early developments of ASWORG. The unit was located at Quonset Point, R. I.

Shortly after its formation, AirASDevLant requested the assignment of several ASWORG members. Doctors C. F. Squire and W. J. Horvath were sent in May 1943, and Dr. Bell was

sent in July, as soon as he could finish his work for SADU, at Langley Field. The ASWORG Unit at Quonset worked on a great variety of problems for ASDevLant. They helped devise tactical and operational tests of new equipment, and helped to write manuals and tables to aid in the use of some of this equipment. Assistance was given in tests of various types of low-altitude bombsights, calculations were made for proper sighting and intervalometer settings for glide bombing, operational procedures were computed and tested for rockets, and a variety of tests were devised and analyzed concerning visual and radar sightings. The group members were active in helping to devise methods of utilizing sono buoys, a development of the Division 6 New London laboratories. Tactics for searchlight planes were also a subject for investigation.

In July, the responsibilities of AirASDevLant were broadened to include tactical experimental work with surface craft, and the name of the unit was changed to Anti-Submarine Development Detachment [ASDevLant]. The original unit became the Aircraft Division of the new detachment and a new, coequal Surface Division was added. Arrangements were made in the activating directive for very close coordination between the detachment and Tenth Fleet, and Tenth Fleet undertook to provide ASDevLant with ASWORG members to assist both divisions.

Dr. R. M. Elliott was assigned to the Surface Division and assisted Comdr. H. R. Hummer, the head of the Surface Division, in tests of various sonic and other detection gear. He assisted in the devising and interpreting of tests of various countermeasure equipment. J. K. Tyson also assisted the Surface Division at ASDevLant by analyzing trials of surface vessel attack procedure. By the end of 1943 there were six ASWORG members assigned to ASDevLant.

6.12 OTHER FIELDS

An extremely important development in antisubmarine warfare in 1943 was the appearance of the carrier escort group. In order to study at first hand the problems peculiar to this operation, Dr. W. E. Albertson, a group member, was sent on an operational trip. On his return, work was commenced on CVE (Convoy Escort Carrier) tactics which will be discussed later.

Group M meanwhile had grown to consist of approximately 50 members.

By the fall of 1943 it began to be apparent that operational research could be of use to the Navy in studying other than antisubmarine problems. It came to be understood that, as the antisubmarine war receded, the efforts of Group M would be gradually transferred to other problems. The first development was in the direction of aiding our own submarines. This came about partly due to the relationship with Division 6 NDRC, which was the division concerned with Subsurface Warfare, and interested in the development of equipment for our own submarines as well as for antisubmarine craft.

In order to find out the ways in which Division 6 could be of aid to our submarine forces in the Pacific, Dr. Tate visited Pearl Harbor and discussed the situation with Commander Submarines, Pacific Fleet [ComSubPac]. Shortly thereafter a request came to the Tenth Fleet for the assignment of several ASWORG members to Pearl Harbor to assist the ComSubPac staff. In November 1943 Doctors G. E. Kimball and R. F. Rinehart were sent to Pearl Harbor, Dr. Kimball to return in a month, and Dr. Rinehart to stay on at Pearl Harbor.

Later, four other Group M members were sent to work under Dr. Rinehart for ComSubPac, and an IBM machine setup was installed at Pearl Harbor for their use. A great number of important and interesting problems were solved by this group. A corresponding submarine group was set up in Washington to work on statistical and analytical problems. This group, headed by Dr. Charles Kittel, was loaned by Tenth Fleet to the head of the submarine desk in COMINCH Readiness, first Comdr. E. E. Yeomans and later Comdr. C. C. Smith. Capt. A. R. McCann, at the submarine desk, Naval Operations, Fleet Maintenance (later taken over by Capt. F. T. Watkins) was named as joint supervisory officer. The two groups at Pearl Harbor and at Washington, working on

problems for our own submarines, were informally labeled as SORG to distinguish them from the main group, ASWORG.

In 1944, other opportunities opened for Group M members to be assigned in the Pacific. Vice Admiral T. C. Kincaid, Commander Seventh Fleet, in the Southwest Pacific area, requested an antisubmarine analyst for his staff. Dr. Steinhardt, who had been with Fourth Fleet in Brazil, was assigned to this position and sent to Brisbane, Australia in March 1944. He returned in August and A. M. Thorndike was sent out to take his place. In June, R. E. Traber was sent to Hawaii to work with the Anti-Submarine Training Unit in Fleet Air Wing 2 (FairWing 2). After a short stay he was replaced, as had been agreed upon originally, by Gordon Shellard, who had returned from Trinidad.

In October 1944, the whole group was transferred back to Readiness Division, COMINCH, and was reconstituted as ORG, a part of the Research and Development Section, F-45. Dr. Morse became director, F-450, of Operations Research Group. ASWORG became a subgroup assigned back to Tenth Fleet, and other subgroups, SORG, AirORG, AAORG, PhibORG, were formally organized and assigned to the appropriate parts of COMINCH staff, CNO, or to Fleet Commands. By this time the group had become a recognized part of the naval staff organization.

Chapter 7

RESEARCH ACTIVITIES

By *Philip M. Morse*

OPERATIONAL RESEARCH MAY be arbitrarily divided into three main categories: statistical, analytical, and matériel. The statistical part of the work consists of the collection and statistical analysis of operational data, especially those from action reports of various operations. The more detailed the assessments of the success of the actions, the more useful will be the analysis, for the aim of statistical studies in operational research is to determine the most effective type of operation and not to provide a history of the past. The analytical part consists of combining knowledge concerning past operations with specialized knowledge concerning the behavior of equipment, in order to work out theoretically the best tactics to use in a new situation. The matériel part consists of the detailed study of the characteristics of new apparatus in order to indicate its most effective employment in operations and the detailed study of the behavior of equipment in action in order to recommend modifications in design or development of new equipment. In practice, no hard and fast line can be drawn between these categories, and most problems studied by Group M have had their statistical, analytical, and matériel aspects.

7.1 PUBLICATIONS

The results of Group M's studies were published in a variety of forms. Whenever the results were generally applicable, and if the COMINCH staff deemed them worthy of distribution to some part of the operating forces, these studies were published as ASWORG Memoranda, with a distribution list approved, by COMINCH. After the formation of the Tenth Fleet, résumés of most of the reports of this type were published in the U. S. Fleet Anti-Submarine Bulletin, the monthly official publication. Results of studies giving basic theory or mathematical techniques, which were not of general interest to the operating forces but which provided a useful basis for further operations research, were published as Inter-Office Bulletins [IOB]. These publications, after receiving Tenth Fleet approval, were sent to Group M members at the various operational bases, but were not for general distribution to Service personnel. Results of research, in response to specific requests or requests having limited interest, were usually published (after August 1943) as Research Reports [RR]. Many of these latter reports were handed only to the proper official in Tenth Fleet (via FX-40), and had no other distribution at all. These were kept on file to be of possible help in future work. A few have had somewhat wider, although still very limited, distribution.

By August 31, 1943, Research Group M had published:

- 40 Memoranda
- 13 Articles in the U. S. Fleet Anti-Submarine Bulletin
- 12 Inter-Office Bulletins
- 1 Research Report

By August 31, 1944 the list had swelled to:

- 45 Memoranda
- 52 Articles in the Anti-Submarine Bulletin
- 22 Inter-Office Bulletins
- 64 Research Reports

After the group was reconstituted as ORG in the Readiness Division, the report system had to be expanded. Four general categories were set up.

1. *Memoranda*—These consisted of results of short studies, usually in response to specific requests, and usually were distributed only to the officer making the request. Memoranda having no circulation outside the group were called "Memoranda for File."

2. *Studies*—These were reports on research involving more than one or two man-days of work, whose form and content had been approved by the responsible subgroup supervisor. Studies also had only a limited circulation outside the group, but they constituted a fairly complete record of the work carried on by each subgroup. The studies of each sub-

group were given distinctive labels: RR's for ASWORG, CC's for ORG, SS's for SORG, etc.

3. When a study received fairly widespread approval from the group, and when there were requests for fairly widespread distribution to the Navy, the study, after editing and approval by the proper authorities, was reissued as an ORG Report, or Publication.

4. Portions of studies sometimes appeared as ORG contributions in the form of articles in some official naval publication, such as the Anti-Submarine Bulletin, the COMINCH Bulletins on AA or Amphibious Actions, or the Fleet Training publications embodying official doctrine.

Any ORG manuscript was required to have the approval of at least one subgroup supervisor before being shown to anyone outside the group, and it had to have official approval by the appropriate naval officer before it received any distribution.

The present chapter will take up in detail a few of the more important research problems studied by ASWORG. The problems discussed have been chosen so as to be more or less typical of the various aspects of the work and so as to illustrate methods of solution and degree of success. The discussion covers only a small part of the work accomplished, but it is felt that a better picture can be given by going into detail on some parts, rather than attempting to outline the whole.

7.2 THE SEARCH PROBLEM

The problem of determining the proper methods of search for submarines and other craft has demanded the expenditure of a fair percentage of the energy of Group M since its beginning. The problem in all its ramifications enters into more than half of the antisubmarine tactics and into a great deal of naval tactics in other fields. The ocean is wide, and it is impossible to watch all parts of it all the time. Consequently, it is necessary to devise methods to determine the enemy's location from time to time, and means of estimating the efficiency of the methods. Special cases also arise that require plans for locating and apprehending all enemy craft trying to enter certain special regions of the ocean. Under these circumstances the problem is to determine the most effective course for the patrol craft, and to compute their chance of locating the enemy.

The determination of the best placement of escorts about a convoy is essentially a search problem, as is also the devising of barrier patrols to keep U-boats from going through specified passages such as the Straits of Gibraltar. The determination of the best course to be followed by a destroyer in trying to make sound contact on a submarine which has been forced down by aircraft is an application of general search principles; the proper combination of radar and nonradar flying against submarines which have radar search receivers is another complicated application.

One of the first tasks of Group M, in April 1942, was to set up the general mathematical principles of search and to define the various quantities which would have to be studied analytically and statistically. Memorandum No. 1 contains most of these definitions.

7.2.1 Range and Search Rate

In the first place there is the range of detection, by eye, by radar, or by sonar gear. The simplest assumption was made first; namely, that nothing was detected outside this range and everything was detected which came within the range. A ship, then, would have a definite sound detection range, which might vary from day to day, but which was definite in length for a given case. A nonradar plane would have a definite visual range for sighting ships which would vary with altitude and, of course, with meteorological visibility. Similarly a radar set on a plane or surface vessel would have a definite range on surfaced submarines.

More important than the range is the search rate, the rate at which a craft with its detection gear can search over the ocean for the enemy submarine or surface vessel. A measure of this rate is the number of square miles which a given craft can search in an hour. For the first crude results it was assumed that this was equal to the speed of the craft multiplied by

twice the range of detection for the gear in question.

The search rate varies widely from craft to craft, and its value indicates some of the advantages and limitations of the particular craft and detection gear. For instance, an aircraft with visual or radar search has a search rate against surfaced submarines of about 1,000 square miles an hour or more, whereas a surface craft with radar has a search rate of only 100 square miles an hour. On the other hand, the search rate for aircraft against submerged submarines is practically zero, but the search rate for surface vessels with echo-ranging gear is approximately 10 square miles per hour. Consequently, it is comparatively easy for an airplane to find a surfaced submarine, but it requires nearly one hundred times the effort for the surface craft to locate this same submarine after it has submerged. Of course, this is an oversimplified picture of a very complicated problem.

It was soon recognized that the simple assumption of a sharply limited search range, within which all objects were detected and outside of which no detection was possible, was a very crude approximation. Actually some surfaced submarines are seen at great distances by aircraft, for instance, and others under the same conditions are not seen until close in. Therefore, a more careful study of the search problem required the calculation of the probability that the submarine is seen at a given range. From this probability one can then compute the average range under certain conditions, and one can also compute the effective search rate; a little consideration shows that the effective search rate is not necessarily equal to the speed of the craft multiplied by twice the average search range.

7.2.2 Comparison with Operations

Some operational data was available for study—enough to indicate the nature of the problem. Reports of aircraft attacks on submarines usually included values of the range of first contact, and the nature of the contact (visual, radar, etc.). These data were being punched on IBM cards, and could be analyzed by machine methods. The results showed a wide variation of ranges of first sighting, as mentioned above.

It was hoped that empirical curves for the probability of sighting could be computed from these data, but several difficulties arose. Since the chances of sighting would differ for different elevations of the plane and for different meteorological visibilities, the data would have to be separated into groups according to elevation and visibility before analyzing. However, many reports did not give both elevation and visibility, and the reports which did were not numerous enough to provide a solid basis for the computations. Another difficulty was more basic: these reports were of sightings which resulted in attacks, and there were no corresponding reports sent in on sightings not resulting in attacks. There was reason to believe that these latter sightings were often the long-range sightings (where plane and U-boat both saw each other at a great distance and the U-boat submerged before the plane could attack). At any rate, it was probable that the attack data did not represent an unbiased sample of *all* sightings, so that sighting probabilities computed from this source would be open to suspicion. A well-reported sample of all sightings was needed.

The effective search rate could sometimes be obtained from other operational data. In some parts of the ocean it was possible to estimate with reasonable accuracy the number of submarines present at a given time. By estimating also the submergence tactics of the submarines, one could thus estimate the average number of submarines which could be sighted by planes in the area. If one knew the search rate of the planes and the number of hours of flying in that area, one could compute the sightings to be expected. Conversely, knowing the sightings and the hours flown, one could compute the effective search rate.

From the Eastern Sea Frontier and from the Biscay area, data were obtained giving the total number of hours flown and the total number of sightings (of all sorts) obtained. From this, an effective search rate was obtained for each of the areas. This effective search rate

turned out to be from one-third to one-twentieth of that computed by using the average range of vision and the speed of the plane. The factor of discrepancy was too large to be explained entirely by an error in estimating the number of submarines or their submergence tactics. Part of the factor could be explained by inefficiency in our own search tactics (overflying, etc., to be discussed later), but part had to be due to the fact that many submarines which "should" have been seen were not seen. The quantitative answer could not be given, however, until more complete data on sightings were available. Until the complete answer was obtained, one could never be sure how "tight" various barrier patrol plans actually were.

ASWORG never did get a large enough and statistically-unbiased enough sample of aircraft visual sightings of submarines from American operational forces to make this analysis. At the time when U-boat sightings were coming thick and fast, the procedure for reporting sightings was not in effective operation; and, even later, there was a natural indisposition to report contacts which did not lead to attacks.

Luckily, adequate data could be obtained from England. In the Bay of Biscay the sightings were quite regular in occurrence, since there was a constant stream of U-boats coming in and out of the French ports. The antisubmarine air bases in England were fairly close together, so that all could be visited and their original records of sightings studied. Coastal Command consented to allow Dr. Kip, an ASWORG member assigned to London, to make this study. A sample of 529 sightings with all the pertinent data concerning altitude of plane, meteorological visibility, range and bearing of first sighting, etc., were collected and sent to the Washington office. There the material was put on IBM punch cards and analyzed statistically by Dr. Kimball, who has been responsible for much of the theoretical development in this field.

7.2.3 Sighting Probability Curve

The first results of the statistical analysis showed that the average range of first sighting was proportional to the meteorological visibility and also proportional to the square root of the elevation of the aircraft at the time of sighting. These two relationships were to be expected, but it was gratifying to find the operational data checking the expectation. A range parameter could then be defined which was equal to the range of the first sighting divided by the meteorological visibility and by the square root of the elevation. One could then obtain from the data a plot of the probability of first sighting against this range parameter which was the needed sighting probability curve, the basis for all further work in air search plans. The scanty American data was also checked with this probability curve, and shown not to disagree.

On the basis of this sighting curve, obtained from operational data, different aircraft search plans could be compared in efficiency, and the best plan found. The plans resulting from this work have been incorporated in Fleet Tactical Publication 223 (FTP223), the official U. S. antisubmarine doctrine.

The basic sighting probability curve obtained in this manner was an empirical one. One further step was needed before the empirical data could be satisfactorily linked with fundamental theory, namely, the connecting of the empirical curve with the physiological properties of the human eye, for visual search. This step was taken by Dr. E. S. Lamar, who had worked with Dr. Kimball in the empirical analysis of the sighting data. Shortly after this analysis had been finished, Dr. Lamar was sent to the London office and discussed the interpretation of the British data with the members of ORS/CC. With their help he was able to obtain physiological data, from the measurements of Craik and MacPherson of the British Medical Research Council, which enabled the last step to be taken. (It is curious that in this work on visibility and search nearly all the data came from England and nearly all the theoretical analysis and application to tactics was made in Washington.) Further work on this basic problem has more recently been carried on by Dr. Lamar in cooperation with Prof. Selig Hecht of Columbia University.

These measurements on visibility showed

that there was a certain maximum range of vision for any given object, which depends on the apparent size of the object and on the brightness contrast between the object and its background. The brightness contrast depends directly on the meteorological visibility, since distance reduces the contrast, particularly on a hazy day. The apparent size (solid angle subtended) of the object depends on the altitude of flying if the object is flat on the surface of the water as is a U-boat wake. The final result is a rather complicated relationship between maximum range and visibility and altitude. For objects of intermediate size and for reasonable visibilities, this relationship reduces to a simple product (visibility times square root of altitude) which the empirical data had shown. Moreover, the theoretical constants check the operational data.

The more complete theory, however, has enabled the basic range probability curve to be extended to much smaller sized objects, such as life rafts and periscopes. Its application to other problems in surface vessel and aircraft tactics may also be quite useful, as for instance in the study of the efficacy of lookouts on our submarines in spotting enemy aircraft, and in the determination of the usefulness of various types of camouflage. Consequently one can say now that the fundamental problem of the visual search for, and sighting of, an object on the ocean from an airplane (or vice versa) has been solved in its main aspects, if not in all details.

The corresponding fundamental problem for radar sightings from aircraft is not in quite so satisfactory a state, primarily because of the insufficiency of data. The general operational behavior of the radar set is fairly well known, however, and the general shape of the probability curve for radar sightings is known sufficiently well to enable radar search plans to be laid out. Some fundamental questions, however, have not yet been answered.

7.2.4 Barrier Patrols

The fundamental studies of visual, radar, sonar, and MAD detection have been primarily useful as a foundation for the study of the more immediate problem of devising search procedure. In this more practical field also, the simplest problems were tackled first and the more complicated ones were only attempted after experience and basic knowledge had been gained.

The simplest practical search problem is that of the barrier patrol, a patrol designed to detect "every" enemy vessel which tries to enter a certain part of the ocean. The patrol course is retraced periodically, and for the barrier to be tight the strip of ocean searched out must be wide enough and the patrol craft must return often enough so that the enemy vessel cannot cross the search strip before the patrol craft returns. Certain geometrical considerations, due to the fact that the enemy vessel is usually traveling across the path of the patrol craft, require modifications in the shape of the patrol courses in order to obtain the greatest efficiency for the barrier. All this was set down in a number of articles written by ASWORG, and published in the U. S. Fleet Anti-Submarine Bulletin.

Several interesting applications of simple barrier patrols were devised by ASWORG base members to meet specific local operational needs. Pellam, while at Moroccan sea frontier, assisted in the devising of an MAD barrier patrol for the Straits of Gibraltar, against submarines coming into the Mediterranean. This barrier was carefully placed with respect to the deep channel through the Straits and with respect to the other antisubmarine patrol craft and planes. The patrol was first tried in January 1944, and resulted in the certain sinking of one submarine and the almost certain sinking of two more submarines within the first 4 months. The continuation of the combined barrier effectively stopped submarine transit into the Mediterranean from that time on.

Dr. Steinhardt assisted officers of the Fourth Fleet to lay out a barrier patrol on a much larger scale, to intercept German surface vessel blockade runners returning with important supplies from Japan. Planes were flown back and forth along carefully laid-out courses from Brazil to Ascension Island at a frequency suf-

ficient to provide a barrier patrol. Three of the four runners were caught by this patrol; it was found later that the fourth had passed through before the barrier had been set up.

7.2.5 Convoy Escort Plans

The aircraft escort of convoys constitutes a type of barrier patrol, for the basic requirement is that the planes are to sight all surfaced submarines well before they might reach the convoy. Plans for convoys and planes of various speeds were devised by ASWORG as early as May 1942, as the need for proper convoy coverage doctrine was urgent then. Since the group was inexperienced at that time, there was considerable doubt as to whether the plans which had been devised theoretically were likely to be effective in practice, and even whether they could be flown. Shortly after Dr. Rinehart had been assigned to the Caribbean sea frontier he obtained permission to test the escort plans which he had had a large part in devising. This practical test suggested certain minor modifications, and after very considerable discussion with many antisubmarine fliers, a final set of escort plans was drawn up. These still provide the basis for aerial escort doctrine, and are published in U. S. Fleet FTP223. The area covered by the escort plan naturally depends on the effective ranges of visibility of the plane for visual or radar sighting of a surfaced submarine. These are obtained from the fundamental sighting curve mentioned in Section 7.2.3.

A training film, in the form of an animated cartoon, illustrating the merits of the plans, was produced for distribution to the operating forces. J. L. Little, a group member, assisted in its preparation.

A large number of special plans for the protection of various task forces in the Pacific were worked out in response to requests from various Fleet Commands.

7.2.6 Hunt Plans

The next type of search plan studied was the hunt. A submarine is contacted either by a sighting (visual, radar, etc.) or as a result of an attack on a surface vessel; and the problem is to find the U-boat (which usually submerges when it realizes it is being hunted) before it escapes completely.

This problem is obviously much more complicated than is the barrier patrol problem, even if the hunt is carried on entirely by aircraft; for here one must take into account the actions of the submarine in a more detailed manner. The simplest way, of course, is to send out enough planes so that the whole area, within which the submarine must be, is kept under continual observation. Naturally the hunt must last long enough so that the submarine will have to surface and will thus be caught. This is called the *hunt to exhaustion* and represents the least amount of cleverness and the greatest amount of effort on the part of the hunter.

A great many hunts to exhaustion were tried in 1942 and 1943, and nearly all of them failed. Group M was assigned to find out why they failed and to devise better hunt plans. Group members were sent to the various air bases which had conducted the hunts and obtained complete details concerning the flying involved, both as to location and time. It soon became apparent that none of the so-called hunts to exhaustion involved a sufficiently continuous search of enough of the ocean to insure the spotting of the resurfacing submarine. In all cases there were enough "holes" in the flying to allow an escape. Such a hunt needed to be continued for about 3 days, over an ever widening area, and almost always, in practice, bad weather intervened, or planes suffered some mishap, or other duties interfered. It became clear that such hunts exhausted the hunter before they exhausted the prey. The problem, therefore, was to devise a means of utilizing aircraft that would have a reasonable chance of success without using an unreasonable amount of flying effort to regain contact with the submarine.

A number of attempts were made on this problem, with varying degrees of success. Nearly every ASWORG member assigned to an operating base was asked by the operations officer from time to time to suggest hunt plans

when the need arose. Thus an empirical body of knowledge grew up as to what plans seemed to succeed and what plans did not. In order to speed up this experience, a battle game was devised by members in the Washington office where one of the members took the part of the escaping submarine and another the part of the plane. Equipment was built by the Special Devices Section of the Bureau of Aeronautics to simulate the search range of the plane and the range of visibility of a submarine at periscope depth and when fully surfaced. It was discovered that a great many hunt plans were ineffective because the submarine had a chance to observe the patrol plane through its periscope for several patrol cycles before it needed to resurface. By this sequence of observations the submarine would learn how to time its escape.

7.2.7 Gambit and Convoy Escort Carrier Plans

One way of avoiding this difficulty had already been suggested. This was a plan that ultimately came to be called the *gambit* and which consisted of flying the aircraft in a course which would be out of visual range of the submarine as long as it stayed at periscope depth. This would lead the submarine personnel to believe that the planes had been withdrawn and would induce them to surface. Once the U-boat had been surfaced, it would cross the path of the patrolling plane if it tried to escape at high speed and would presumably present another opportunity for attack. Detailed plans were devised to obtain the best chance of recontact.

Gambit plans were used in hunts in a number of frontiers and were successful in producing recontacts. Such plans usually have to be made up on the spot to fit the particular situation at hand. ASWORG members at Gulf sea frontier, Caribbean sea frontier, Brazil, and Moroccan sea frontier contributed from time to time in the laying out of hunts after a submarine had been spotted.

Combinations of hunts and barrier patrols are flown from convoy escort carriers [CVE] and much analytical work was done in devising plans for their use. The carriers used planes having characteristics other than those of the usual land-based antisubmarine planes, and consequently, modifications of the usual escort-of-convoy plans were prepared. Carriers of this type turned out to be most useful as offensive weapons by searching out and sinking U-boats rather than waiting for the submarine to come to the convoy. A large number of CVE search plans for different situations were devised and proposed for operational use. Others submitted by commanding officers were evaluated.

Still different situations turned up when the carrier planes began night flying, and when various types of microwave radar equipment began to be installed; so other plans were worked out. Close relations were maintained with many carrier officers, particularly with the air combat intelligence and antisubmarine officers, who had the prime responsibility in laying out hunt plans during a voyage. Several of these officers visited the Washington ASWORG office and discussed various problems of search and tactics.

7.2.8 Surface Vessel Search Plans

The surface vessel search problem is more difficult than the aircraft case in that the speed of the surface vessel is not large compared to the speed of the U-boat. Consequently, the evasive tactics of the submarine affect the search plans very strongly. This disadvantage is offset to some extent by the fact that surface vessels can stay continuously on the spot, and can cooperate more closely in a hunt than can aircraft. It turns out, for instance, that three destroyers hunting in a line abreast are more than three times as effective as one destroyer hunting.

An important property of the surface craft, of course, is its ability to locate the submarine after it has submerged. Consequently, the fundamental theory of visibility here concerns the operational behavior of echo-ranging gear. This problem was studied in great detail by Dr. W. C. Herring and others of the Program Analysis Group of Division 6, NDRC. From

their work it is possible to determine the probability of locating a submerged submarine by a surface vessel under various conditions.

A situation often encountered was that in which one or more destroyers were called on the scene by an aircraft which had made an initial sighting and had forced the submarine to submerge. The destroyers arrived on the scene one or more hours later and then the problem was to devise a search plan for the destroyers to locate the submarine as soon as possible. The same condition obtains when contact has been made and subsequently lost by surface craft. Because of the relative slowness of the destroyers, it appears that some form of search course which spirals out from the contact point is usually the best course (this is known as the retiring search curve). The rate of retirement and the spacing of ships in line, if there are more than one hunting, were matters for analysis. Various types of plans were laid out, the probability of the submarine's escape being computed for each plan, and the best plan was chosen. Like the plans for aircraft, search plans for surface vessels devised by the ASWORG office were incorporated in FTP223.

Additional complications are added when aircraft are available, as with a carrier task force. The aircraft can be used on a gambit hunt, for instance, outside the expanding spiral of the surface vessels. If the submarine should escape the vessels and try to depart at high speed on the surface, the aircraft has a chance of intercepting it.

Each new means of detection or new modification of detection gear has required modification of these various search plans in some way or other. For instance, the introduction of the use of sono buoys by aircraft has enabled the aircraft to keep track of submerged submarines to some extent. This made it possible for the aircraft to keep a certain amount of contact with the submarine after it was forced below, and to call destroyers to it from farther away than was previously considered worth while. Even if the destroyers arrived on the scene several hours later, it was possible for the aircraft still to be in tenuous contact with the submarine. In such cases, extensions of the fundamental theory were worked out and each of the standard search plans was investigated to see if it should be modified.

Thus it is seen that the applications of fundamental sighting theory are endless. Other applications, as World War II drew near an end, were being worked on. These included search plans to rescue air crews forced down and screens to protect large task forces from submarines and aircraft. An exceedingly important study undertaken in the war's closing months involved the re-evaluation of all surface and air search plans to take into account the U-boat use of Schnorchel.

7.3 STATISTICAL ANALYSIS USING PUNCH CARDS

Most of the statistical work carried on by ASWORG involved the abstracting of various details of operations from some standard naval report form. In many cases the report forms had been devised before ASWORG came into existence, and the abstracting of data was already being done by some parts of the COMINCH staff so that ASWORG members took the abstracted data as the basis for their statistical studies. In other cases the report forms had been devised and reports were coming in that had not yet been abstracted; in some of these cases ASWORG members did the abstracting as well as the statistical analysis. In a few cases, ASWORG members assisted in the devising of the report form as well as in the abstracting and the analysis. In all these cases the IBM equipment played a useful role.

The abstracted data from operations reports were used in two different ways. In the first place, the data could be tabulated in an easy-to-read situation summary, to provide the higher command with an up-to-date picture of the status of a given operation. In the second place, the data was combined with other facts to provide a measure of efficiency for a given operation, which might be watched from month to month in order to determine the best tactics for an operation, or to find how much the efficiency of an operation improved as experience was gained, or to determine whether changes in enemy tactics had a deleterious effect on the

efficiency of our own operations. (The effective search rate, computed from sighting reports, is an example of a measure of efficiency.) Group M members were of assistance in producing some situation summaries; they took a more active part in setting up and following various measures of efficiency of operations.

Since the beginning of World War II the abstracting of data from antisubmarine action reports and the preparation of situation summaries came under the cognizance of Commander (later Captain) R. F. Collins (FX-43). Group M went to him for data as soon as they had become established in Washington, and it was his understanding cooperation which saved the group from making many false starts. Captain Collins' office maintained records of Allied shipping sunk or damaged, and a similar detailed record of attacks on enemy submarines, all of which were constantly revised and kept up to date. This material formed the basis of daily situation summaries prepared by Captain Collins and it also formed the basis of a great number of statistical studies made by ASWORG. After working with this material for several months, it was agreed that the needs of both Captain Collins' office and of Group M could be met most efficiently by an IBM machine installation. Later the action reports on other types of naval operations were coded for the other subgroups. Patrol reports of our submarines and AA action reports were thus transcribed for detailed analysis and study.

7.3.1 Punch Cards

The basis of the IBM installation was the punch card, a small cardboard ruled with 80 columns, each having 12 spaces, any of which could be punched. Essentially, therefore, each card could carry an 80-digit number or an 80-letter sentence, since each column stands either for a digit or a letter. By coding the sort of data which were to be reported, a great number of facts could be put on a single card. For instance, in recording ship sinkings, the first 16 columns gave the name of the ship which sank, the next 2 columns the code letters for the nationality. One column gave the code letter for the type of ship, the next 5 columns the tonnage, followed by 4 columns giving the date, 9 columns giving the latitude and longitude, and so on. These cards could be sorted according to any of the columns and therefore could be put in order of date, in order of tonnage, or any other order which was wished. Columns were read off in another machine, the tabulator, and, for instance, totaled in order to give the total tonnage sunk in a day or a month. The tabulator also would print data from properly ordered cards, automatically producing a situation summary. By proper organization of these various machines, a large variety of different operations could be carried out, thus reducing enormously the labor of statistical analysis.

A card punch and verifier, together with a sorter, interpreter, and small tabulator, were ordered and were finally delivered in December 1942. These machines were set up in a room next to Captain Collins' office. Later, in November 1943, additional equipment was obtained. A full-sized tabulator replaced the small one, and a more modern verifier replaced the old type. A reproducing summary machine and a card counting sorter were also added.

7.3.2 Design of Codes

Even before the first equipment had been delivered, preparatory work was under way for placing the data on the cards. A most important part of the use of punch cards is the working out of the code which specifies the order and arrangement of the data on the card. Decisions on the make-up of the code are extremely important, since a badly designed code can make a number of statistical investigations almost impossible. Codes which are best for calculating measures of efficiency are not necessarily good for producing situation summaries and vice versa. Since it is quite difficult to change the code after the system has been in operation for some time, it is important that all future contingencies be thought of when the code is made out. Professor Wilks was of considerable help in this respect, and the details were ably handled by W. L. DeVries, H. H. Hennington,

and P. J. McCarthy, and later by R. R. Seeber, who had been engaged to supervise the actual operation of the machines. The first cards were set up and punched, and a number of runs were made, utilizing IBM machines at Princeton University. By the time, therefore, that the ASWORG machines were delivered, the basic codes were pretty well arranged.

An agreement was made with Captain Collins whereby the time of the machines and the supervisor was used by Captain Collins each afternoon for his special tabulations and other work; the morning was made available for ASWORG work. This arrangement turned out to be quite satisfactory. Two WAVE specialists were obtained to handle the punching of the cards and other mechanical details. By the spring of 1943 it was necessary to obtain the services of one other supervisor, Earl Gardner, and by the end of 1943 an additional WAVE assistant was obtained.

7.3.3 Card Files Used

A large number of card files of operational data were kept in the machine room available for tabulation of situation summaries or for statistical work. Some of those, prepared by Captain Collins' office, of particular interest to ASWORG, comprised the Ship Casualty File, the World Wide Assessment Files, and the File of Details on Attacks on Enemy Submarines. The Ship Casualty Files had reached 3,500 cards by August 1943 and 6,000 cards by August 1944. The World Wide Assessment Files, giving the overall facts on attacks on enemy submarines by any Allied craft, contained 2,500 cards in August 1943 and 5,000 cards in August 1944. Both of these files were primarily designed for situation summary tabulations, but a great deal of general statistical information was also obtained from them. A more detailed file of attacks on enemy submarines by U. S. surface and aircraft gave a great deal of technical information about the attack and was of the utmost importance to ASWORG in working up measures of efficiency. This file reached the size of 8,000 cards by August 1944. Other files giving details on convoys, for instance, were of less use to Group M. All these files were controlled by Captain Collins, and ASWORG obtained permission from Tenth Fleet to utilize them in making its studies.

As Group M expanded its activities, other card files came into existence. For instance, beginning in October 1943, a file was kept on the action reports of our own submarines in the Pacific and contained about 10,000 cards by August 1944. Similarly a file was maintained on air actions in the Pacific for Op-16-V-A (Air Intelligence Group) for statistical studies on air operations. This file was begun in February 1944, and reached a size of 8,000 cards by August 1944. At the beginning of its statistical work, ASWORG felt that it was important to obtain approximate values for a large number of measures of efficiency for various antisubmarine operations. Until approximate operational values of these measures were determined, the group could not be said to know its subject in a quantitative manner. Data were therefore collected on a wide number of related facts and in many cases the results were reported regularly to the interested officers. Later it was found that some of these measures of efficiency remained practically constant and that others were unimportant in tactical studies, so that only a few such measures were eventually continued. Nevertheless, many of them had to be tried at first.

7.4 DATA ON FLYING

An important measure of efficiency in the search problem is the effective search rate for aircraft. In order to obtain this from operational data, one must count all the contacts on surfaced submarines by aircraft in a given area, and at the same time have records of all the flying time in that area spent in searching for submarines. If one is to compare different regions or different types of operation, the time spent in these regions or in these types of patrol (such as convoy or simple patrol or hunt) must be differentiated. If, in addition, the range of first sighting and other related data is reported, a good start is made toward learning the operational "facts of life" as far

as search goes. Arrangements were made with the eastern sea frontier to obtain some of these basic data.

Each plane on returning from an antisubmarine mission filled out a "form mike" which gave the details of the mission, the sightings, visibility, etc. Arrangements were made to have duplicates of all forms mike sent to the ASW unit, eastern sea frontier, where Group M members, aided by yeomen, tabulated the data and sent them to Washington to be put on punch cards. The data were at first recorded in great detail to see which parts were significant. Several interesting conclusions came from this study. One of the results was that the regions which had the greatest amount of patrol flying often gave the least number of sightings per hour flown by the planes. From these data one could determine the advantages and disadvantages of excessive amounts of patrol flying, and could estimate the amount of flying in a given region which would adequately protect the region and would still give a number of sightings which could be converted into attacks. It was also found that flying some distance from the shore (100 miles or more) was much more productive of sightings and attacks than flying closer than 50 miles from shore. It was also shown that the use of radar planes at night was a particularly effective method of obtaining sightings and, eventually, attacks, when proper searchlight equipment made night attacks possible. These results were embodied in reports to eastern sea frontier and had some effect on subsequent distribution of flying.

A similar study of flying time and of operational search rate was made for a time with data from Caribbean sea frontier. When this turned out to give the same general results as the eastern sea frontier data, both of the card files were discontinued, since it did not appear that further results of operational importance could be obtained and since the basic orders of magnitude of search rate had been determined.

Another short-term card file was concerned with convoy statistics, whereby data on convoys were analyzed for a long enough period to obtain the fundamental measures of effectiveness (relation of attacks on convoys to number of escorts and to speed of convoy, etc.). The file on Coastal Command Visual Sightings, mentioned above in connection with the search problem, was another such short-term project.

7.5 IMPORTANCE OF ASSESSMENTS

In obtaining measures of efficiency in attacks on submarines, the official assessments of the individual attacks had particular importance. As a matter of fact, the proper assessment of an action report is of extreme importance to nearly all operational research. If this research is to be of use in deciding the relative effectiveness of various types of tactics, it must know how effective the tactics are when actually tried. In many cases the results of the operations are clearly apparent and the tabulation of the statements on the action reports suffices to obtain a measure of the effectiveness of the action. Cases of this sort were the reports of hours flown on patrol and the reports of sinkings of vessels by U-boats. In both of these cases a reading of the details of the action report sufficed to give the research worker a fairly accurate picture as to what had happened and no careful assessment by a board of experts was needed.

In other cases, however, the results of the action are not at all apparent, and the action reports must be read by experts with a great deal of operational knowledge before arriving at a considered judgment of the result. A considerable amount of operational research of the statistical sort could not have been done in antisubmarine warfare if there had not been a Naval Assessment Committee for Antisubmarine Action. This committee graded attacks in a sequential order: A, being certainly sunk; B, being probably sunk, etc.; down to G, attack probably on a submarine, no damage; H, attack probably not on a submarine; etc. The accuracy with which these assessments conformed to later discovered facts was astonishing and indicative of the experience and skill of the Assessment Committee.

7.5.1 Studies of A/S Attacks

These assessments of antisubmarine action enabled ASWORG to devise a measure of effi-

ciency for various types of attack and therefore to compare the effectiveness of various attack tactics. Since numerical values are the most useful means of comparison, several different weights for the assessment letters were tried, representing the relative probability that the U-boat was sunk; such as 1.0 for A, 0.8 for B, and 0.5 for C. It was finally decided that the percentage of A and B assessments resulting from a given type of attack was an adequate measure of effectiveness.

With this measure as a tool, it was possible to study the attack cards provided by Captain Collins' office to judge the efficacy of various antisubmarine tactics. Several interesting facts soon came to light. In studying the statistics of aircraft attacks, for instance, it was soon discovered that attacks made on submarines that had submerged more than 30 seconds before the plane dropped its depth bombs were very unlikely of success. The results were striking enough to warrant including in the air attack doctrine a phrase forbidding the dropping of depth charges on submarines which had been submerged more than 30 seconds.

Another problem which received early study was the question of the depth setting of the depth bombs carried by aircraft. Early in the war the setting was usually 50 ft, which was too deep to be lethal to surfaced submarines. A statistical analysis of aircraft attacks on submarines showed that about half of the submarines were on the surface at the time of attack. This, combined with the fact that the attacks on submerged U-boats were much less accurate, indicated that the depth setting should be adjusted for lethality against the surfaced submarine.

Consequently doctrine was modified to require a 25-ft setting, and a memorandum was published explaining the reasons. A later comparison on assessments of attacks with the two settings showed that the change in depth setting was equivalent to a doubling of the effective lethality of the depth bomb.

7.6 OTHER PROBLEMS

The IBM machinery was of use in analytic problems as well as in the collection and analysis of operational data. The probability of success in depth-charge patterns is a problem amenable to calculation by punch card methods. A file of 7,500 cards, giving error distributions based on operational statistics, were punched so that all types of patterns could be studied. Many of the results of this study were incorporated in FTP223 as doctrine. In a similar manner a file of 7,000 cards was built up to compute the probability of success (and other details) for surface vessel search plans. In these cases the IBM machines were used as an extremely flexible computing machine. Since the card files can be kept, the problem can be returned to again if further work is needed.

7.7 COUNTERMEASURES

The work on the search problem discussed in Section 7.2 was mostly analytical. The work just discussed in the intermediate sections was primarily statistical. The work to be discussed in this section has had more to do with matériel, although it has had important analytical and statistical aspects. The work carried on by ASWORG in countermeasures in antisubmarine operations had been primarily in two fields, radar and underwater sound, although the work is typical of operational research in countermeasures in other fields. The general problem was as follows. The enemy devises a new piece of equipment or tactic and seems to be in the process of introducing the equipment or perfecting the tactic; it is required to devise equipment or tactics or both to counter the enemy's innovation and to devise criteria to show when these countermethods need to be introduced by our forces. The question of timing the introduction of the countermeasure often turns out to be as important as the devising of the countermeasure itself. There is also the problem of foreseeing possible enemy countermeasures to new equipment or tactics of our own.

7.7.1 Countermeasures in the Bay of Biscay

The radar countermeasure problem in antisubmarine warfare has a longer history than

the acoustic case and provides more examples of Group M activities. In order to obtain a picture of the interplay of events in this field, it is useful to outline the history of the air offensive carried out by Coastal Command against U-boats in the Bay of Biscay. In the early part of the activity, most of the sightings were made by visual means. Flying was done nearly all in the daytime, and the number of sightings and attacks on U-boats had settled down to a relatively constant percentage, which evidently was not large enough seriously to disturb the enemy. In June 1942, however, Coastal Command outfitted a number of squadrons of planes with both long-wave radar sets and searchlights, so that they could find surfaced submarines at night and could carry out attacks against them. The night flying was arduous and the effectiveness of the night attacks was not too high, but the psychological effect more than made up for this. Previously the submarine had been relatively immune in the Bay of Biscay at night, and it was customary practice to travel all night on the surface. The first reaction of the enemy to searchlight radar planes was to reverse their time table, to stay submerged at night and to come to the surface by day. By September 1942, the searchlight planes were making very few attacks but the number of attacks made by day-flying planes in the Bay had risen considerably. Therefore the night flying of two squadrons had increased the effectiveness of more than seven squadrons of day-flying planes.

This increase evidently was too much for the enemy. Within four months after night flying commenced, he had installed search receivers for long-wave radar sets on the majority of his submarines. These receivers picked up the signals from the long-wave radar sets on the planes and warned the submarine in time for it to submerge and escape. Evidence of the installation of these receivers was furnished by an increase in the number of "disappearing contacts," radar contacts which disappeared before the plane obtained visual confirmation of the presence of the submarine. Only a small percentage of disappearing contacts corresponded to submarines with search receivers, but the increase in disappearing contacts corroborated other evidence that search receivers were being installed.

By November 1942, the searchlight planes with long-wave radar had been effectively countered by the German search receiver. The submarines had gone back to surfacing at night, only diving when their receiver warned of a plane's approach. The number of attacks at daytime had subsided to its previous level, and equilibrium appeared to rule again.

The introduction of S-band radar on the British night-flying planes upset this equilibrium all over again. The German search receivers were not designed to pick up the shorter wavelength, and therefore the number of sightings and attacks by night-flying planes rose rapidly. The cycle went through its previous course, the Germans first submerging by night and surfacing by day with a resulting increase in day sightings and attacks. Next, they rushed a search receiver for the short-wave radar. This proved somewhat more difficult to install but eventually a semblance of equilibrium was again reached by October 1943.

This sequence of events was duplicated with some variations on this side of the Atlantic. The variations in the sequence were the special object of study by ASWORG. The Bay of Biscay constituted a special field of activity, and it is important to realize that tactics differed in other localities. Much of the activities of ASWORG in the radar countermeasure field were engaged in showing wherein the problem for American waters differed from the problem in the Bay of Biscay and in suggesting the modifications in tactics and gear required by these differences.

7.7.2 Matériel Countermeasures

The difference between the attitude of a development laboratory and the attitude of an operations research group toward a countermeasure problem is an interesting and important one. Since it takes time to develop and produce equipment, the development laboratory must think up and work out countermeasure equipment for every imagined type of enemy gear in the hope that the right one will be "on the

shelf" when the enemy comes out with his next measure. Thus in the antisubmarine radar field, the development laboratories had to anticipate that the Germans would either use aircraft warning radar on their submarines or else would use search receivers, and equipment had to be devised for both. The proper countermeasure for an early warning radar on a submarine is a search receiver on our own aircraft. Receivers of this sort were devised by NRL and by Division 15, NDRC, and were procured by the Bureau of Ships.

Equipment countermeasures to a German search receiver were more difficult, but one, the Vixen, was devised. This was simply an attenuator in the aircraft radar set which would gradually reduce the strength of signal after the aircraft had picked up a suspicious contact. This attenuation would allow the signal strength received by the submarine to stay constant or even diminish as the aircraft approached, while still maintaining a visible spot on the radar screen. By this means it was hoped the receiving operator on the submarine would be fooled into believing the aircraft was not approaching, for if the receiver were not sensitive the signal might not be detected at all. Equipment of this sort was developed by Division 14, NDRC.

The problem for ASWORG, however, was to decide which of the tactics the Germans were adopting and when the appropriate countermeasure gear should be installed in our own planes. Most countermeasure gear and tactics involve a loss in efficiency in other ways, so that it was important not to commence countermeasures until the Germans had installed gear which required countering on a sufficient number of submarines. For instance it was particularly important not to advise tactics countering German radar if the Germans actually were installing search receivers or vice versa.

X-Ray Plane

Partly at the suggestion of Group M, a plane equipped with a number of radar search receivers was sent to North Africa to fly in waters known to be frequented by submarines. A three months' stay involving a large amount of flying both by day and by night produced no recognizable radar signals from submarines and showed, with reasonable certainty, that radar was not being used by U-boats for aircraft warning.

The problem of the degree of U-boat use of a search receiver was a much more difficult one to solve. The solution depended on the balancing of advantages. If the German search receiver came to have a long enough range and was effective enough of the time, on enough submarines, then it might be advantageous to turn off our antisubmarine radar and go back to visual search. On the other hand, if the receiver range was relatively short or if the receiver was often out of adjustment or was not present on many submarines, then turning off our own radar would be a grave mistake and would lead to a considerable reduction in the number of successful attacks. In order to reach a decision, data from a number of different sources had to be carefully balanced.

Disappearing Contacts

In the first place, there was the operational data which came mainly from reports on disappearing contacts. These data had to be viewed with a great deal of skepticism. Even a large increase in the total number of disappearing contacts in a given region might not indicate that the U-boat was using search receivers in that region. It might only mean that the antisubmarine squadrons in that region had suddenly become upset about the possibility of the U-boats having search receivers and by their own interest happened to be reporting more disappearing contacts than they had previously reported when they had not been interested in the matter. In order to check up on such possibilities, it was necessary to send an expert to the area.

The first example of such a situation occurred in 1943, when a large number of disappearing contacts were reported from the Caribbean region by planes newly equipped with S-band radar (the SCR517, an Army set). The natural reaction of the sea frontier was to order the radar sets to be turned off, thereby preventing the U-boat from hearing the radar if the U-boat actually had a search receiver but also reducing the average search rate by

a factor of two or three. It appeared very unlikely to Group M that the U-boat at that time had S-band search receivers and Dr. Kip, then at Gulf sea frontier headquarters, wrote to Dr. Corson, the expert on Army aircraft radar sets, for suggestions as to other possible explanations of the phenomena. Dr. Corson suggested that "second-time-around echoes" would be more prevalent on the SCR517 set than on other S-band sets and might be the explanation. This effect occurs on sets with rigidly fixed pulse-repetition frequencies, and consists of echoes of the previous pulse from large, distant targets appearing on the screen as smaller near targets (of range equal to the actual range minus the maximum range on the radar screen).

Dr. Kip, and also Dr. Rinehart, then at Caribbean sea frontier headquarters, investigated the reports of disappearing contacts, and found that it was likely that "second-time-around echoes" were the explanation for most, if not all, of them. Dr. Rinehart visited several squadrons which had reported disappearing contacts, and found a pilot who claimed he could obtain a disappearing contact any time he wished by flying in a given region. Dr. Rinehart accompanied this pilot on a flight and sure enough, a disappearing contact was obtained. A little investigation proved that the contact was not on a submarine which dove but was definitely a second-time-around echo from a mountain on an island some 60 miles away.

A further investigation showed that this explanation would account for all of the disappearing contacts then reported. A simple change in the set was suggested which would serve to distinguish between true echoes and second-time-around echoes, and the brief flurry subsided. Radar sets were not turned off in antisubmarine planes, and the effectiveness of the planes in search was therefore not reduced.

By the fall of 1943, however, the U-boats actually had begun using S-band search receivers in the Bay of Biscay in small numbers. At this time again there arose a flurry of reports of disappearing contacts in American waters. In order to estimate the percentage of these reports which actually represented a U-boat with search receiver, Dr. B. L. Havens was borrowed by Group M from Radiation Laboratory of Division 14 and was sent out to a number of bases to interview the crews which had reported the disappearing contacts. After a detailed investigation, Dr. Havens reported that the majority of the reports probably did not represent U-boats with search receivers and that there still was not evidence convincing enough to warrant turning off S-band radar in antisubmarine flying on this side of the Atlantic.

After that time the situation changed slowly. The data on sightings and attacks were watched to see when the effectiveness of the German search receiver would rise to a point which would make a radical change in our tactics necessary. Even at the end of the German war it was not clear whether the search receiver had been an adequate protection to many U-boats.

7.7.3 Tactical Countermeasures

In the meantime, tactical countermeasures had to be investigated. A group member, Dr. M. S. Livingston, kept closely in touch with the development laboratories at NRL and those under Divisions 14 and 15 in order to know the details of the operational characteristics of radar and of search receivers so that the best tactics for various conditions could be worked out. Statements from prisoners of war provided some basis for estimates of the operational properties of the German search receiver and this enabled more definite measures to be suggested.

One important question still to be settled is whether the only answer to an effective search receiver is to turn off our radar completely. A possibility which is still being investigated is some sort of intermittent operation, which preserves some of the range advantage in search given by the radar, but presents to the enemy only irregular bursts of signal which are difficult to detect or to interpret. One technique is to send pulses only in flashes, bursts of a fraction of a second duration. Another possibility is to remove the regularity of spacing between

pulses, so that the signal heard on the search receiver is not a musical note, but sounds like a burst of static. Psychological tests, as well as physical ones, are being carried on to determine the efficacy of such countermeasures.

A property of operations research in countermeasures is the paucity of memoranda and formal reports which are written and the large percentage of personal contacts which are necessary. The data are obtained and the results are reported by personal interviews and conferences with the crews and officers involved. In this work ASWORG played a useful role as a technical intelligence link between operations and development laboratories. For effective liaison, it developed that this link had to be a personal one.

7.7.4 Acoustic Countermeasures

Perhaps more important than the radar countermeasure problem was the acoustic countermeasure problems, particularly the problem of countering the German acoustic homing torpedo.

In the late fall of 1943, the U-boat commenced using a torpedo which steered toward the noise of the ship. Advance information of such a torpedo had been obtained from prisoner of war statements, so that the first few cases of attacks using this torpedo were recognized for what they were.

A number of different measures had already been proposed to counter acoustic torpedoes, and Group M was requested to make recommendations. Dr. E. A. Uehling was placed in charge of this part of the group's work.

The work in this field was voluminous and complicated chiefly because a countermeasure effective against a torpedo of one type may be ineffective against a torpedo with other physical properties and may actually increase the danger from torpedoes of still other properties. The behavior of the torpedo depends very markedly on how it responds to intensity changes, how selective it is in frequency, and whether it can detect sounds from all directions or only from the forward directions. A large number of typical "pursuit curves" were computed for different properties of the homing torpedo. The various Division 6 laboratories were questioned as to the possible properties of the torpedo, and these were combined with prisoner of war statements to narrow the selection down to two or three possible types. An attempt was then made to find a countermeasure which would be good for all or nearly all of these types.

In the meantime, measurements had to be made of ship noise and of the acoustic properties of countermeasure gear in order that the physical background might be known with sufficient detail. Particularly valuable in this respect were the tests and measurements carried on under Commander Hummer of ASDevLant. The group member assigned to Commander Hummer, Dr. Elliot, was quite active in this work. On the basis of the computed curves and of the data from measurements, the necessary tactics and equipment were suggested, worked out, and put in use.

As with the radar countermeasure field, the importance of the acoustic countermeasure investigation, as carried on by Dr. Uehling and his group, was much greater than the small number of formal reports might indicate. Most of the work involved personal liaison between the design laboratories, the groups which were making sound measurements, and the officers responsible for doctrinal decisions. Such liaison is never evidenced by reports.

7.8 WORK AT OPERATIONAL BASES

Work at outlying operational bases provided both a schooling and a proving ground for the ASWORG members assigned there. Nearly all members on base duty were assigned desks in the operations room where they were able to witness the daily round of effort required to protect shipping from the U-boats. They were present occasionally when air crews were briefed or were questioned after flights and thus had a chance to see the multiplicity of small details, all of which have to be correct if an attack on a submarine is to be successful. Nothing is more salutary to an "impractical" scientist who has drawn up a beautifully sym-

metrical search plan than to see the way it actually turns out in practice. Nothing is more sobering than to see a complicated tactical plan rendered unworkable by the simple facts of seamanship or of air navigation.

But if ASWORG members learned the "facts of life" at operational bases, they also turned out to be of some value as teachers. The operations officers who directed the convoy escorting, the patrolling, and the U-boat hunts, were invariably eager to learn more in order to utilize their forces more effectively. Their basic training and the issued doctrine provided the framework for their operations, and issued directives told them the most recent changes in tactics.

Most of them, however, were interested in learning as much as possible of the reasons behind the doctrines and the directives, and were eager to learn as completely as possible the capabilities of the gear which had just been shipped to them. Here the ASWORG member could be of some help. He had only recently come from Washington and had visited various development laboratories. He was acquainted, to some extent, with the basic theory underlying the doctrine and had had a chance to go through some of the operational data from which the measures of efficiency were derived. He could bring to the base officers a little of the overall picture which might not always be necessary but was often helpful.

This combined learning-teaching experience of the members was not limited to their contacts with the operations rooms in frontier headquarters. Most members on base assignment had frequently visited the lower echelons of command, to gain experience and to help in solving problems. Airfields were visited and operational flights were taken; trips were taken on surface craft and local training units were visited. Mention has already been made of the trip on a CVE taken by Dr. Albertson. Dr. Kittel crossed the North Atlantic on a DE which was part of a convoy escort. Pellam traversed the Straits of Gibraltar in a submerged submarine before laying out the MAD patrol plans mentioned earlier.

In many cases, the Group M member was asked to analyze the operational data of the base, in order to provide the operations officer with measures of efficiency for his own forces. These measures could then be applied as tests when new tactics were tried out, and as indications of the level of experience in the different squadrons. In several cases such statistical analysis served to demonstrate to the local forces the advantages of following doctrine, such as using depth-bomb spacings of 50 ft or greater as compared to dropping bombs in salvo. In Brazil and in the Moroccan sea frontier, Group M members were able to show the improvement in sightings arising when patrol flying was directed toward estimated submarine positions shown on the daily COMINCH U-boat plot. In the Trinidad sector of the Caribbean sea frontier, group members were of assistance in preparing a monthly operations summary which showed to the forces operating in the sector what they had been accomplishing.

A very valuable service of the member at an operational base was to collect specialized data to send to Washington for detailed study. To obtain many of the "measures of efficiency" studied by the group, complicated reports of an operation had to be filled out. It was often impractical to ask all operating forces to fill out such forms, and so, the members at bases would be asked to obtain the data for their region for a few months as a sample. Being on the spot, they could obtain the data by questioning, without overworking the crews in filling out forms, thus also obtaining uniformity of the sample.

In many cases the group member was able to assist the operations officer by applying the theory of search in laying out barrier patrols or U-boat hunts. The MAD patrol in the Straits of Gibraltar and the barrier patrol from Brazil have already been mentioned. Dr. Rinehart and Shellard in the Caribbean sea frontier often assisted in laying out barrier patrols to catch submarines coming through one or another of the passages through the Antilles. Dr. Steinhardt, in Brazil, assisted a number of times in laying out air hunt plans involving gambit tactics.

Assistance was also given in getting new equipment effectively into use at the bases. Mention has been made already of the discov-

ery of the second-time-around effect with the Army S-band radar sets in the Caribbean. Shellard, at Trinidad, was of assistance in getting into operation an aircraft search receiver to listen for U-boat radar signals. Mr. Shellard accompanied the crew on a number of the trial flights and was able to assist in working out an effective search technique. The results, as mentioned in the previous section, were negative but were valuable as corroboration that U-boats were not using radar for aircraft warning.

In addition to assigning men to operational bases, ASWORG engaged in a few other investigations involving trips to bases. Mention has been made of the investigations of Dr. Havens on disappearing contacts. A similar project on MAD contacts was undertaken by Dr. Judson Mead, loaned to ASWORG by the Airborne Instruments Laboratory, operating under Division 6, NDRC.

For some time after MAD had come into operationai use, a large proportion of seemingly false contacts on U-boats were reported. This tended to put MAD in disrepute in the operating forces. Dr. Mead was sent to the air fields used by some MAD-equipped squadrons to investigate such contacts. He soon found that the major difficulty was due to lack of understanding of the limitations of the gear by the operators and the aircraft pilots. A discussion of these points with the squadron personnel served to clear up much of the difficulty and the experience gained by Dr. Mead enabled him to be of considerable aid to the Airborne Instruments Laboratory training program when he returned there. False MAD contact reports diminshed considerably in quantity thereafter.

7.9 REFERENCE LIBRARY

An essential part of every scientific laboratory is its reference library. Every scientific work must be checked with the results of other investigators, various sorts of data must be looked up and utilized, and the results must be checked often with experimental measurements made elsewhere. ASWORG had to build up its reference library in order to carry on its investigations.

The treatment of material routed to the group illustrates the difference between its activities and those of the staff officer. The duties of the staff officer are primarily those of an executive and involve action. Reference to past history is seldom needed, and material can usually be read once and deposited permanently in the record files. The activities of ASWORG, however, often involved comparisons, and material a year old might be as valuable as last week's acquisitions.

The necessity for constant reference to past history means not only that material must be kept, but that it must be kept in a way which makes it readily available. This important and difficult task was supervised by Dr. A. C. Olshen beginning November 1, 1942, when the Washington office files were first begun. It is due to his planning and care that the present library of approximately 7,500 technical reports is a useful tool in research.

When the library was begun, it was realized that the filing system would have to be devised to fit the peculiar needs of the group. The system was worked out with great care and has needed only small modifications since. Each piece of material entering the files for permanent retention is abstracted on a card which is placed in the abstract file. Cross index cards are made to file under the various subjects concerned. The report is then inserted in a properly titled folder and placed in the proper section in the file drawers. Ordinarily the subject order in the library is straightforward enough, so that the material can be found without need of recourse to the card index. The index, however, is invaluable when making a thorough investigation of any subject.

7.9.1 Security

A complication not ordinarily present in scientific reference libraries was the matter of security. Material routed to ASWORG was of all kinds of security classification, and the higher classifications had to be kept separate from the lower ones. This was taken into account in the filing system and in the method of keeping track of the material while being used by group members. Since group members,

being civilians, were not under the same legal control as officers and enlisted men, it was felt important for the group to keep the strictest self-imposed control on matters of security. So important was this aspect considered that the equivalent of one group member's time was spent in maintaining security on the reports used. Much of the burden of devising systems of security check also fell on Dr. Olshen.

Material came to the ASWORG via two channels, the Tenth Fleet and OSRD. All reports from naval sources were routed to the group from F-20, Combat Intelligence, via Admiral Low, FX-01, and Captain Fitz, FX-40. The ultimate sources were sometimes the naval laboratories or bureaus, when the material concerned equipment. When the material concerned intelligence matters, the source was often Op16 (Office of Naval Intelligence). Through this same route came reports from British sources: the official Admiralty reports, the Coastal Command reviews, and the British Operations Research Section reports.

By agreement with Admiral Low, reports from OSRD and the various NDRC laboratories were sent direct to Group M. A large library of NDRC reports was built up, the representation being greatest from Division 6 (Subsurface Warfare); but Division 14 (Radar), Division 15 (Countermeasures), and Division 3 (Rockets), were also heavily represented.

7.9.2 Routing

The matter of internal routing was another subject of considerable thought and planning. A large number of the reports received by ASWORG were not for permanent retention but had to be returned within a short time. This material had to be routed rapidly and yet get to the proper persons. Consequently it was made a rule that all items, whether for eventual retention or not, must not be kept by a member for more than 24 hours. If his work required a longer retention, the item was returned to the member after the rest of the routing was completed. Routing sheets were kept in duplicate so as to have available a running record of the location of each report.

An indication of the magnitude of this task and of the necessity for the great care in security which was taken is given by the data on the routing of material during the month of August 1944. About 1,400 different reports were received by the group. Of these, 600 reports received very limited routing and were returned to the senders within 24 hours. The remaining 800 were given more general routing within the group, although 460 of these were eventually returned to FX-40. The balance of approximately 340 reports, after routing, were abstracted, indexed, and filed in the permanent files.

If all this material had to be read by all members of the group, there would have been little other work done. It was felt expedient, therefore, for one experienced group member to spend most of his time in reading over the material and in routing each piece only to those few members whom he was sure needed it for their work. Consequently the average report was read by only 5 men instead of 30, and a great saving of time was obtained without a serious reduction in usefulness of the material.

7.9.3 Distribution to Members at Bases

In addition to maintaining a reference library for the Washington ASWORG office, Dr. Olshen's section had the responsibility of keeping up to date the small working libraries of the men at outlying bases. These libraries were necessary for their work but were, naturally, severely limited in size, which made the problem of choice of material a very serious one. One member (usually one returned recently from a base) was given the responsibility of looking over all the material which came in to see what part of it might be needed badly enough by some one of the outlying members to warrant sending it to him.

7.10 GROUP MEETINGS

An important part of the group activities were the periodic meeting days where all members who could attend gathered together to

hear a series of formal talks in the morning and take part in a series of informal discussions in the afternoon. The talks were given by group members on various aspects of operations research of general interest to the group as a whole; a report by a member recently returned from a base, a preliminary report of the results of an analytical study, a statistical report of the submarine situation, and so on. The agenda for these meetings were approved by Tenth Fleet in advance; following the formation of ORG they were approved by the Readiness Division.

This meeting day provided a chance for the members from nearby bases to bring back to the central group their most recent findings and problems, for the central group to bring the base men up to date on recently developed techniques and ideas, and also for some cross fertilization within the central group.

Early in the history of the group, meetings were held fortnightly, and sometimes were held at Boston, with members of the Atlantic Fleet ASW Unit also attending. After 1943, the meetings were held once a month. Officers of the COMINCH staff, and a few other officers whose duties had a bearing on the work of the group were invited.

PART III

PHYSICAL RESEARCH

FUNDAMENTAL STUDIES OF UNDERWATER SOUND

By *Carl Eckart*

8.1 INTRODUCTION

ALTHOUGH THE FIRST World War stimulated the development and design of devices for detecting and locating submarines and other underwater sound sources, no serious effort was devoted to the scientific investigation of underwater sound phenomena. At the end of World War I, the development of devices dependent for their operation upon underwater sound was continued by the Navy, but fundamental studies of the propagation of sound in the sea were still neglected. General interest in supersonic waves did develop, but security barriers deflected it away from naval problems. Not until the early models of echo-ranging gear were tested did the need for more precise physical knowledge of underwater sound transmission become apparent. Some pioneering work was done by the Naval Research Laboratory [NRL], but the results were difficult to interpret, and therefore did not receive wide recognition.

Why underwater sound should have been the long neglected stepchild of acoustical research is easily understood. The physical theory of sound propagation in both air and water had been developed by early investigations like those of Rayleigh. The study of sound propagation in air was carried forward rapidly because of the continuing interest of architects, radio engineers, and others. It was constantly encouraged by men who wanted to build better theaters, broadcasting studios, or radios, and it was given impetus and focus by the organization of the Acoustical Society of America. But underwater sound seemed to have few commercial applications; its possible importance in navigation has been only recently recognized. Naval laboratories were not in a position to enlist the interest of civilian physicists active in related fields.

The propagation of sound in water is analogous to that of sound in air, but few of the results of the last 40 years of research in air acoustics are directly applicable to the study of underwater sound. The problems are similar, but the answers are different. Though underwater sound is subject to all the seeming vagaries of sound in air, the quantitative aspects require separate determination.

With the increased use of echo-ranging gear under a wide variety of oceanic conditions came the realization that its most effective design and use waited upon data that was not available. In the hope of supplying these data NDRC undertook a broad program of research in acoustics, oceanography, and psychology. Out of this program came results which found a number of immediate applications. They provided information which enabled the Navy to estimate the effectiveness of existing equipment under different operating conditions and to devise doctrine for its most efficient use. They furnished basic engineering data for the development of new sonar equipment. And, finally, they provided information which not only helped the Navy to modify tactical doctrine, but also made valuable contributions to strategic planning.

The NDRC program is now being continued under Navy auspices. There are good reasons for this continuation, since sound provides the only known method for the transfer of energy over any substantial distance under water. Although it is impossible to forecast the future accurately, it seems certain that the Navy will continue to depend upon underwater sound for assistance in many operations.

8.1.1 Scientific Data Available in 1940

When NDRC began its program of research in 1940, its scientists were able to draw upon three important sources of information. First, of course, was the great body of experimental data, mathematical analysis, and working theory which was and is the science of acoustics. Second, there was a small, but very useful and valuable group of observations and measurements on the refraction of underwater

sound, which had been made by naval officers and oceanographers from the Woods Hole Oceanographic Institution [WHOI]. Third, microfilm copies of the reports prepared over a period of years by His Majesty's Anti-Submarine Experimental Establishment, HMA/SEE, at Fairlie, Scotland, were quickly made available. The experimental results of NRL, mentioned above, were also available.

Research carried on for the Army or Navy is like all other research in that it builds on the foundation of pre-existing fundamental scientific knowledge. So it was with the investigations of underwater sound. Though the NDRC scientists found that former investigations of airborne sound had solved disappointingly few of their problems, they naturally began with all the existing theoretical and mathematical analyses of sound transmission that seemed applicable to their work.

The body of special oceanographic information available to them, together with the observations of sound gear performance which had been made by American and British naval personnel, indicated the directions in which their research might go. Thus they knew that sound, unlike light and radio waves, should theoretically travel great distances underwater without great loss of energy. But published experimental results on fresh water and other liquids showed that the attenuation of sound, though not so great as to make the use of sound gear impractical, was frequently far greater than that predicted by theory. The NRL results confirmed this for sea water and in addition showed that the attenuation was extremely variable from day to day, or even from minute to minute. The primary reason for the anomalous behavior of sound in the ocean was recognized by the Woods Hole oceanographers as the refraction of sound by temperature gradients. Finally the HMA/SEE reports contained valuable material on reverberation, theoretical discussions of the acoustic properties of bubbles and of target strength, and data on the variability of echo intensity.

8.1.2 The Research Needed

The sonar gear carried by submarines and surface vessels is required to do many things. It is used to detect the presence of ships, submarines, swimmers, and mines at the longest possible ranges. Ideally, it should locate them accurately, giving their bearing, range, and (for mines and submarines) depth. When used to locate moving targets, sonar gear should show their speed and course, and, when possible, give some indication of the kind of engines and screws that drive them.

At the time of writing this report no gear is available which does all these things. Sonic submarine listening gear, for instance, may detect a surface vessel at ranges greater than 5 miles. At this distance, however, it can give only approximate bearings and no estimate of range. As the range closes, an experienced operator may be able to identify the engines and screws that create the signal to which he listens; he can also get more accurate bearings. But present listening gear cannot give him reliable reports of range.

Echo-ranging gear, similarly, has marked limitations. It cannot be relied upon to detect a submarine at ranges greater than 3,000 yd, and maximum echo ranges on mines have usually been less than 500 yd. Though echo-ranging gear may give the operator clues to target speed and course, it can tell him nothing about the design or construction of a target. Only recently has echo-ranging gear been devised to show the depth of a target and the problem of maintaining contact on a deep target at close range is still being studied.

Nor is this all. Maximum echo and listening ranges are extremely variable. They may be affected by the speed of the searching ship, by the speed, size, and aspect of its target, by sea state, by temperature gradients, by the presence or absence of various forms of marine life, and by the depth of the water. In shallow water, they are affected by the ocean bottom. They are also affected by the skill and ability of the operator, since the detection of a target with any sound gear depends upon recognition of a signal in the presence of background sounds tending to mask it.

Thus maximum listening ranges depend upon four things, most of which are affected by oceanographic conditions:

1. The characteristics of the sound emitted by the target.

2. How much and in what way the signal is weakened by traveling to the listening hydrophone.

3. The nature and strength of the noise tending to mask the signal.

4. The ability of the eye or ear to distinguish the signal from the background noise.

The variables determining maximum echo ranges are similar and more numerous:

1. The characteristics of the transducer (sound source).

2. How much the signal is weakened by traveling to the target.

3. How much sound the target returns to the echo-ranging vessel (target strength).

4. How much the echo is weakened in returning from target to hydrophone.

5. The character and strength of the background noise.

6. The character and strength of the reverberation.

7. The ability of eye or ear to distinguish between echo and background.

Studies of sound transmission are conducted by physicists and recognition is studied by psychologists. But the medium through which sound moves is the sea, and most of the noises tending to mask or obscure a signal originate in the sea or are modified by transmission through it. Consequently the physicist and psychologist must work not only with electrical and acoustical engineers and representatives of the Navy, but with oceanographers, geologists, and marine biologists. Out of their cooperative study has come our present knowledge of the behavior of sound in the sea.

At the beginning of World War II, it would have been practically impossible to have written the paragraphs above. The cooperation of the many specialists listed was necessary in order to formulate the problems to be solved. Civilians, and in some cases even naval authorities, were unaware of the operational problems that sonar gear would be called upon to solve. For example, the development of gear adapted to the location of midget submarines, swimmers, and mines had not even been considered in 1941.

8.2 NDRC PROCEDURES

Woods Hole Contract

When NDRC first undertook to provide for basic research on the transmission of underwater sound, it turned to the Woods Hole Oceanographic Institution. Through continued contacts with the Navy in the years before World War II, the members of the Woods Hole staff had acquired a realistic knowledge of Navy problems. In this, they were unique among civilian scientific organizations. They had also made a good start in the study that NDRC was taking up, for they had collected a substantial quantity of data, not only on underwater sound transmission, but also on oceanographic problems which might prove relevant. They had developed the *bathythermograph* [BT] for the rapid measurement of the temperature of the ocean at various depths, and which could be used from a moving ship. They had shown that this subsurface weather was important in determining sound transmission. They had developed a theory (refraction theory) of this effect, which was necessarily oversimplified, but which has continued to play an important part in the interpretation of later information. In 1940, therefore, NDRC entered into a contract with WHOI.

San Diego Contract

When, in the spring of 1941, NDRC was asked by the Navy for further assistance in the development of underwater sound devices, those responsible for the NDRC program recognized the need for a more intensive investigation of underwater sound phenomena than the Woods Hole staff could prosecute alone. They also recognized that such work could best be done at some location which was near deep water and adjacent to large Navy organizations and units. The shallow continental shelf of the Atlantic coast made deep water relatively inaccessible, so the investigators, in selecting a laboratory site, naturally turned to the Pacific coast. San Diego provided a unique location, since the 600-fathom San Diego Trough is located only 15 miles offshore. Later, the need for experiments in shallow water caused a transfer of some activities back to Woods Hole.

NDRC therefore entered into a contract with the University of California, making provision for the establishment of a new research group at San Diego. Housed at the U. S. Navy Radio and Sound Laboratory (now the U. S. Navy Electronics Laboratory), the University of California Division of War Research [UCDWR] began to supplement the research already under way at Woods Hole. The staff of scientists engaged in this work was assisted by contacts with the staff of the Scripps Institution of Oceanography [SIO], located at La Jolla, some 12 miles away. This institution had accumulated data on oceanographic conditions in the Pacific, and particularly on the conditions off the Southern California coast, and some of its staff transferred to UCDWR.

Sonar Analysis Group

As experimental data began to be accumulated by UCDWR and the WHOI, it became desirable to assign a small group of physicists and mathematicians to its analysis. These men were employed under the Columbia University contract and later became known as the Sonar Analysis Group. Taking experimental data from the two NDRC research organizations and Navy laboratories, as well as from special studies carried on under other contracts, the Sonar Analysis Group conducted analyses to determine the bearing of research findings upon problems of design and operation. Working in very close liaison with interested sections of the Navy, this group was able to interpret and aid in the immediate utilization of the information which was being gradually accumulated.

The slowness of this accumulation was inevitable. Even in peacetime, it would have been slow, for analysis and interpretation of results cannot be carried on hastily even by the best qualified men. There were very few men who had previously given thought to these problems, and they were usually assigned to the development of urgently needed gear. The great number of competing scientific programs during World War II limited the staff of the underwater sound groups, thus reducing the number of problems that could be considered. The qualifications of some of the men engaged in the work were not specifically suited to the research at hand, but they made up for lack of formal training by enthusiasm for the work, and accomplished more than could have been anticipated.

New problems were constantly being uncovered by the operations of the Navy, or raised by the new tactics and weapons of the enemy. Through the mediation of the Sonar Analysis Group, these problems were communicated at once to those actively engaged in the scientific work. All too often, the urgency of the new problems caused the interruption of important but less urgent work. Although the hasty experiments and conclusions (again communicated to the Navy via the Sonar Analysis Group) were valuable, those actually engaged on the work constantly suffered from the fear that their efforts would be "too little and too late."

Navy Observational Program

The Navy also initiated an extensive observational program, installing bathythermographs on an ever increasing number of combat vessels. A farsighted policy initiated this program even before the data obtained could be effectively used in operational planning. The results of the observations in the Atlantic were transmitted to WHOI, and of those in the Pacific, to UCDWR. There, NDRC groups subjected them to analysis and tabulation and worked out methods for the immediate use of new data for operational purposes. The close cooperation between the Forces Afloat, the Bureau of Ships, and the civilian scientists, made this one of the most successful NDRC programs. Its only handicap was lack of time. Had it been initiated some years earlier, even on a small scale, it would have been even more effective.

8.3 SCIENTIFIC DATA SECURED BY NDRC AND THE NAVY

Two methods of approach are possible in a report of extensive scientific studies of closely related phenomena. One is the textbook treatment, the systematic exposition of theory and

supporting data. The other is historical, giving the organization and experimental methods of the scientists, and recording their mistaken assumptions and false starts as well as their progress. The method of this chapter is a kind of hybrid, in so far as it is both and neither; it merely outlines the complexity of the research, the way in which it has been carried on, and some of its most important findings. The history of each NDRC contract is given fully in its completion report, and most of the results of the underwater sound research program have been reported both systematically and fully in other volumes of this series, as well as in special publications of the Sonar Analysis Group and the Bureau of Ships.

8.3.1 Transmission Studies

The chief problem of transmission studies is the measurement of the sound field of any source as a function of oceanographic conditions. When the sound is complex, such measurement requires a number of analyses of intensity and spectrum as functions of range and hydrophone depth. When the source, such as a submarine, can vary in depth, that variation must also be measured. Time variations further complicate transmission studies, since a single pulse may sometimes travel by different paths to arrive at a hydrophone as a series of discrete or interfering pulses. Even when the source emits a steady tone of constant intensity, a hydrophone more than a few yards away receives a sound of fluctuating intensity.

Measuring the effect of oceanographic conditions on sound transmission differs from most laboratory problems in that complete control of experiments is impossible and the separation of independent variables is exceedingly difficult. Experiments must be carefully planned, but the subsurface "weather" cannot be planned. Consequently large quantities of data must be accumulated in the hope that eventually all combinations of variables will occur. It is impossible to bring the sea to the laboratory, so the laboratory must put to sea, collect all the data which may be possibly relevant, and bring it back for analysis. Studies are made in water of varying depth, over bottoms of different character, in dead calms and near gales, at various frequencies, at different times of day and night, and in different seasons. So many variables affect every observation that it required months of experiment to establish the effect of any one variable upon sound transmission.

Transmission studies have been made with many different sound sources. Thus studies have been made of the transmission of ship and screw sounds, of the output of various types of noisemakers used in mine sweeping, of explosions, and of the sound emitted by standard echo-ranging projectors, as well as by specially constructed transducers emitting one or more frequencies. During the progress of the work, greater and greater use has been made of special transducers.

Sound Sources

The behavior of sound in the sea depends considerably on its source. Thus the transmission of the sound beam of a sonar projector is different from that of the sound of submarine screws and machinery. The determination of the characteristics of sound sources was therefore an important part of the NDRC program.

The characteristics of sonar projectors and receivers were studied at calibration stations constructed on piers and barges. Some of these were located in harbors, as at New London and Point Loma. The work at these locations was hampered in two ways by traffic in neighboring waters. Passing ships produced so much noise that special precautions had to be taken to prevent interference with the measurements. Nearby ship-building operations and pile-drivers were other offenders. A second difficulty was experienced when small craft passed near the apparatus. The bubbly water of the wake would drift into the region traversed by the experimental sound and make measurements impossible for a period of minutes.

To obtain more accurate data, calibration stations (see Section 9.3.3) were established in small fresh-water lakes: at Mountain Lake, New Jersey; Orlando, Florida; and at Sweetwater Dam near San Diego. Even these locations were not entirely satisfactory, since the

water was very shallow; Sweetwater station was relatively good, since the artificial lake had been constructed in a deep narrow canyon.

It was found that these stations were indispensable to any development work involving either projectors or hydrophones. Regularly scheduled station wagons and trucks operated between the Sweetwater station and the Point Loma laboratory, and made close cooperation possible.

The characteristics of ships and submarines as sound sources can be measured only in the open sea. This brought other problems with it. The calibration equipment had to be mounted on shipboard. The noise of the laboratory vessel interfered with the operation, so that some attempt was made to work from small rowboats. This was unsatisfactory because of the limited space and electrical power. No one solution was found, but a useful expedient was to suspend the hydrophone from buoys floated out from the laboratory vessel, and cable-connected to the equipment aboard ship.

Hundreds of measurements were made of the sound output of all types of vessels, ranging from submarines to battleships and aircraft carriers. One accidental observation which showed that some carriers had "singing" propellers led to efforts by NDRC and USNRSL to initiate a systematic survey. A relatively minor change in propeller design is said to have eliminated this very undesirable type of sound. But even at the end of the war, some carriers were dangerously noisy. Greater care was given by the Navy to the quieting of submarines and NDRC personnel often cooperated in obtaining necessary data.

These measurements of ship sounds have been collected and summarized in a report. Although some general conclusions of permanent value have been reached, it should be noted that these data are essentially ephemeral. The sound output of a ship is affected by maintenance and by the installation of new auxiliaries. Slight injuries to the propeller, such as can be caused by a bit of driftwood, may raise its sound output many decibels. Consequently an active program of measurements must be maintained at all times and coordinated with a program of corrective measures.

An entirely different set of sound sources—those found in nature—was also studied by NDRC. These background noises interfere with the detection of echoes and other wanted sounds. They have many causes, ranging from marine life (for example, porpoises, snapping shrimp, and croakers) to breaking waves. The levels of background noise, as a function of meteorological and oceanographic conditions were studied. It was found, for example, that certain kinds of biological noise could be predicted with considerable accuracy.

Certain noises heard in sonar gear, originating in the ship which carries it, could not be effectively studied during the war because of the unavailability of combat ships for sufficient periods of time. Some beginning has been made on this problem since the end of World War II, but corrective measures have not yet been considered.

Attenuation Coefficient

Sound traveling outwards from a source always weakens with distance. Even if it travels through a perfect medium, so that none of its energy is scattered or dissipated into heat, the wave front spreads regularly over larger and larger areas. Thus the total energy in the sound wave is spread ever thinner, and the intensity, which is the concentration of energy in any region, decreases regularly with the distance from the source. If the source is assumed to be a point, the intensity of the sound which it radiates should decrease inversely as the square of the range.

Actually, of course, a point source has no real existence, so that the intensity loss caused by spreading of sound from any source will be somewhat different from that predicted by the inverse square law. If, however, the intensity of the sound from any source is measured at a hundred yards and the strength of the source is then expressed in terms of a point source which would be required to produce the same intensity, the inverse square law can usually be used to calculate the losses due to regular spreading.

It cannot be used to calculate all effects, since (1) the ocean is a bounded medium, and sound is reflected by its surface and bottom; (2)

changes in the pressure, temperature, and salinity of the ocean may result in changes in the velocity of sound and so change both the sound path and the way sound spreads; and (3) the ocean is a somewhat less than perfect medium, so that some energy is lost by absorption and scattering. These facts combine to result in observed transmission losses which can depart widely from values predicted by the inverse square law. This discrepancy between the calculated inverse square loss and the measured loss is sometimes called the transmission anomaly.

The transmission anomaly cannot be exactly predicted from oceanographic observations, since even when conditions are seemingly constant, observed transmission losses are highly variable. At the present time, therefore, only average figures can be given for the value of the anomaly under various conditions.

Transmission is best when the water through which sound moves is so well mixed that commonly used measuring devices show no variation of temperature with depth. In the absence of measurable temperature gradients, the water is said to be isothermal, and very little of the transmission anomaly can be attributed to changes in the velocity of sound. When measurements are made with highly directional supersonic transducers in deep water, bottom reflection can also be ignored. Under such conditions, the anomaly is found to be roughly proportional to the range.

This increase of the anomaly with range is called attenuation, and the amount of that increase, measured in decibels per kiloyard, is called the attenuation coefficient. In water which is isothermal from the surface to a depth of 200 ft or more, the attenuation coefficient is relatively constant at any one frequency, and is found to increase with increasing frequency. Thus it is about 3 db per 1,000 yd at 16 kc, 4 db per 1,000 yd at 24 kc, and 15 db at 1,000 yd at 60 kc. At very low frequencies, on the other hand, it seems to be negligible, so that sonic sounds trapped in a "sound channel" may travel for thousands of miles and still be heard.

It has been found that the attenuation of sound in the sea is 40 to 300 times *greater* than it should be on the basis of simple theory. On the other hand, it is 100 to 200 times *less* than would be expected from laboratory measurements at high frequencies in fresh water. This is one of the outstanding scientific problems of underwater sound.

Determination of an attenuation coefficient becomes much more difficult when temperature gradients are present in the top 100 ft of the ocean. When, for instance, there are small gradients within 50 ft of the surface, the average attenuation in the shallow isothermal layer is generally about twice as great as it is when the isothermal layer is deeper, but it is also much more variable. Finally, when there is a strong negative temperature gradient beginning at the surface, transmission anomaly does not show a simple proportionate increase with range. Temperature gradients cause the sound rays to curve, so that the spreading of the sound obeys more complicated laws and obscures the effects of attenuation.

Refraction Theory

Early tests of echo-ranging gear showed that maximum ranges were sometimes dramatically reduced in the afternoons of calm clear days. During the morning a target might return echoes at ranges of more than 3,000 yd; in the afternoon, it might not return echoes even at a range of only 500 yd. Careful observations of this afternoon effect enabled Woods Hole scientists to establish the fact that it was produced by shallow negative temperature gradients in the upper 30 to 50 ft of the ocean.

The explanation was simple. Since the water near the surface was warmer than any below it, that part of a wave front which was nearest the surface traveled faster than the part which was deeper and in colder water. Therefore the whole wave front curved toward the region of lowest temperature, much as a ship turns in the direction of its slowest propeller. The sound beam was "bent" and headed for the bottom.

To put it in another way, all sound rays leaving the projector were bent downward. The one which left the projector at an angle high enough above the axis to become horizontal at the surface was the one which traveled farthest. It was the "limiting ray." Rays leaving at higher angles were reflected or lost at the

surface. Rays leaving at smaller angles never reached the surface, since they were bent toward the bottom before reaching the top. Beyond the limiting ray was the "shadow zone," a region into which no sound could penetrate.

This explanation of afternoon effect led naturally to an extensive theoretical development of refraction theory. As already mentioned, the Woods Hole scientists had developed the bathythermograph, with which a continuous record of temperature as a function of depth could be obtained. Using such a record, they could calculate the velocity gradient (the change in the velocity of sound with depth) and then calculate the path of any sound ray leaving an echo-ranging projector. Given enough ray paths, they could make a "ray diagram."

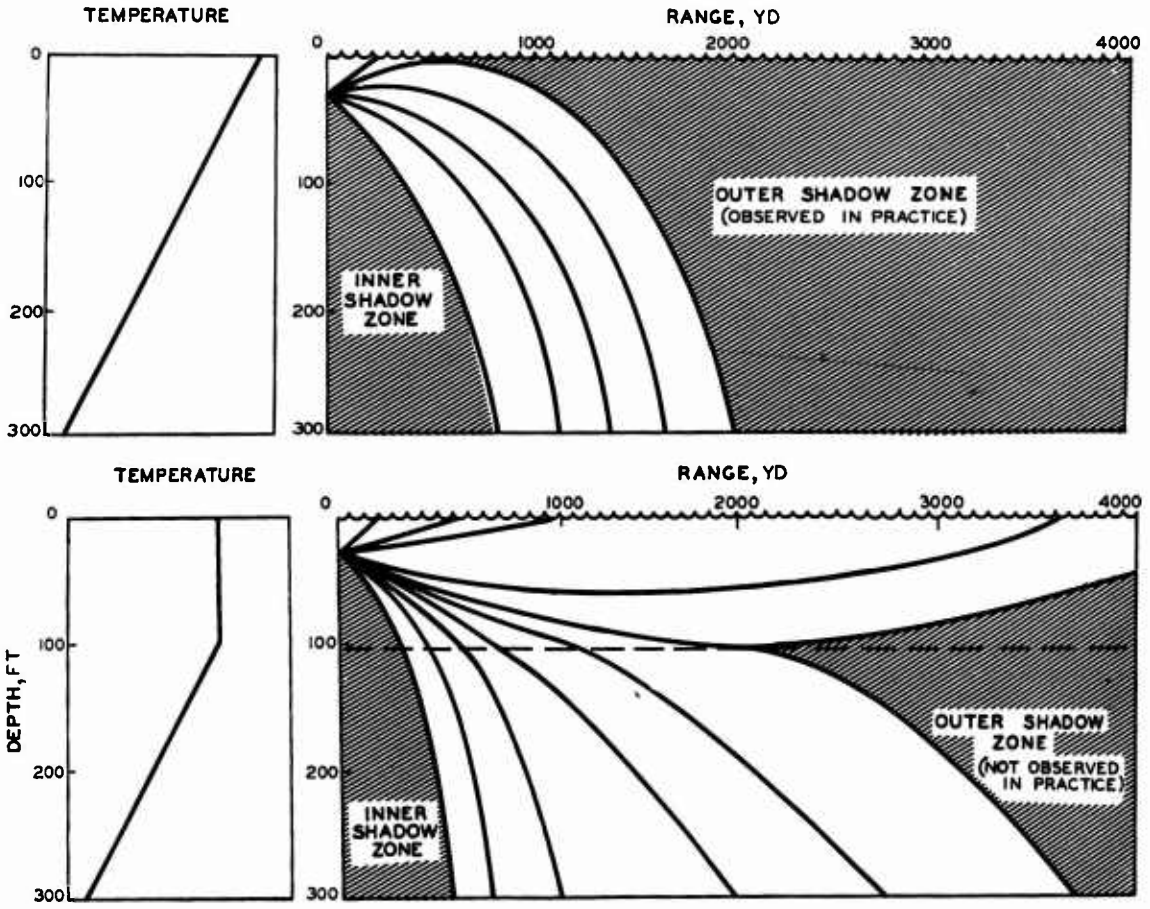


FIGURE 1. Sound ray diagrams: (A) predicted effect of negative gradient beginning at the surface; (B) predicted effect with isothermal layer above negative gradient.

Two ray diagrams are shown in Figure 1. One shows the predicted result of a marked negative gradient beginning at the surface; the other shows the predicted path of a beam projected into isothermal water lying above a layer of sharply decreasing temperature. Because the depth scale is much larger than the range scale, ray bending is exaggerated.

During the early months of research at both WHOI and UCDWR, slide rules and tables for the calculation of ray paths were prepared, and collections of archetypal ray diagrams grew. Two assumptions were implicit in much of this activity. It was assumed that the predicted shadow zone always had a real existence: that transmission was determined completely by the ray diagram, and that the ray diagram could be used to predict sound intensity in all parts of the sound field. Thus, the predictions were: no sound in the shadow zones, weakened sound where rays were widely spread, and little or no

anomaly where normal spreading was not accentuated by bending of the rays.

Although these assumptions were useful, and were supported by some evidence, they were not the whole truth. Transmission studies begun at San Diego in 1943 proved that shadow zones do not always occur when refraction theory predicts them, and that when they do occur they are not utterly soundless. Intensities within the predicted sound field, similarly, are affected by many things, though refraction may be extremely important.

One product of refraction is the commonly observed layer effect, the partial protection from detection by listening or echo ranging which a submarine gains by submerging below a layer of sharp negative gradient. Whenever a beam travels from an isothermal layer into a negative gradient, the sound rays are so turned and spread that there is a marked drop in the intensity of the sound. Consequently the echo range on a submarine below a layer may be less than half the range on one above.

Refraction theory is best borne out by the condition which led to its formulation. A predicted shadow zone materializes only when there is a strong negative gradient starting at the surface. Then the sound within the shadow zone is more than a thousand times weaker than that in the direct sound field. There is some sound in the shadow zone, it is true, but not enough to produce an audible echo from a submarine. What little sound there is probably results from the forward scattering of sound, or perhaps by a deep scattering layer, called the ECR layer. It is discussed in more detail in following text.

Under no other conditions do shadow zones exist. With all other types of temperature distributions, no matter what the ray diagram predicts, sound intensity at any given depth diminishes regularly with range. There is no point beyond which the intensity drops sharply.

Surface and Bottom Reflection

When sound energy reaches the ocean's surface or bottom, any of three things can happen to it. It can be reflected back as from a mirror, with a sharply changed direction but little loss of intensity; it can be scattered back into the medium in all directions; or it can be lost by transmission through the boundary into the air or earth. Ordinarily some of the sound is reflected, some scattered, and the rest lost, in amounts depending on conditions at the boundary.

Ordinarily, about half the sound from any source reaches the surface (unless, of course, a directional source is pointed toward either the surface or bottom: i.e., a fathometer pointed downward, or a Herald tilted toward the surface). Very little of the sound reaching the surface escapes to the air; more than 99 per cent of it is either reflected or scattered back. If the surface is smooth, almost all the sound is reflected. But if the surface is much disturbed by waves, winds, or currents, a large proportion of the incident sound may be scattered.

In echo ranging, the scattering of sound by a disturbed surface results both in high noise and in high reverberation levels, as well as in an increase of attenuation. The reflection of sound by a smooth surface, on the other hand, never shortens echo ranges; sometimes it results in marked extension of ranges when shallow positive temperature gradients warp the sound beam toward the surface.

In listening, high sea states frequently reduce ranges by increasing both the attenuation and the loudness of the background noise over which the signal must be heard. With low sea states, ranges are ordinarily longer, though sometimes the intensity of audible sounds may be reduced by interference between direct and surface-reflected sound. This interference tends to cut down the intensity of audible sound at intermediate ranges and to cause irregular changes in intensity at short ranges.

At long ranges, almost all of the sound received from a shallow nondirectional source has been reflected from the bottom. The importance of reflection and scattering by the bottom depends both on the nature of the sound source and on the depth of the water. Thus a noisy ship, which is a powerful sound source emitting sounds of many frequencies in all directions, may be heard at great distances even in deep water. This is true under all thermal conditions. At these ranges, the higher frequencies have been so weakened by attenuation that only

the low-frequency components are heard. In echo ranging, on the other hand, the sound source is a highly directional supersonic projector which beams most of its output horizontally. Consequently, little sound reaches a deep bottom, and the little that does is so weakened by attenuation that its reflection has no effect upon maximum echo ranges in deep water.

In shallow water, however, bottom effects are important. Experiment has shown that the amount of sound scattered or reflected by the bottom depends roughly upon the "hardness" and "smoothness" of the bottom. Thus soft mud absorbs much of the sound striking it; although it may scatter enough sound from an echo-ranging ping to raise reverberation levels, it reflects very little sound. Sonar ranges over mud, therefore, are much like those in deep water.

Harder bottoms reflect more sound, so that listening ranges over sand, rock, and stony bottoms are frequently lengthened by bottom reflection. Echo ranges over sand may be similarly extended, but over rock another effect more than compensates for the reflection, for the ranges are usually shortened by the roar of reverberation caused by the scattering of sound by the rough, irregular bottom.

Accurate prediction of sonar ranges and transmission losses in shallow water waits upon more extensive studies and careful classifications of bottom character. Enough was discovered during the war to show that such research can be extremely valuable; submariners, for instance, are particularly interested in finding the ocean areas with the best "natural cover." Operating in such areas, they are least likely to be detected with sonar gear.

Fluctuation

Many months of experiment and analysis have been required to establish the effect of temperature gradients, sea state, and bottom type upon sound transmission. Today, however, the findings of the NDRC program have enabled us to explain and even to predict the average transmission loss under known conditions. The explanations are not complete, and the predictions are less accurate than they should be, but average transmission losses seem explicable and calculable.

The joker is hidden in the word "average." With standard echo-ranging gear, for instance, which has a nearly constant output, and with carefully measured oceanographic conditions (bottom character, temperature gradients, sea surface), only the average intensity of a series of pings received by a distant hydrophone is calculable. Though all conditions may seem to be constant, the intensity of one ping may differ from that of the next by as much as 20 db. The intensity of most pings, it is true, will lie somewhat closer to a median value, but about one in ten will be more than 10 db below the median.

A similar fluctuation may be observed in the character or "envelope" of successive pings. Thus the short "square" pulse of sustained intensity put into the water by an echo-ranging projector may be received by a distant hydrophone as a signal of fluctuating intensity, or as a short crescendo or diminuendo. When this distortion is considered together with the ping-to-ping fluctuation of intensity, the problem of predicting the range at which a submarine can be certain of getting an audible echo from a single ping becomes extremely knotty.

The causes of fluctuation can be guessed at but they have not yet been established by experiment. It may be, for instance, that the signal travels by several paths; when sounds which have traveled different ways reach the hydrophone, the intensity of the signal depends upon their phase relationship. If they are in phase, they reinforce each other to produce a strong signal. If they are out of phase, they interfere with each other to produce a weak signal.

Another cause of ping-to-ping fluctuation may be small variations in the vertical and horizontal temperature structure of the ocean. Although a single bathythermograph record shows the gross vertical temperature structure of the ocean at the point where it was made, records taken at various points along the transmission path may show variations in that structure. Then, too, the structure in any one place may change from ping to ping; internal waves, for instance, may regularly raise and lower the thermocline. Finally, the temperature micro-

structure of the ocean is almost completely unknown; small, local changes in temperature are omnipresent, and their effect is unknown.

Fluctuation, in other words, stands near the top of the list of problems marked for further study.

Echo Formation and Target Strength

Echo ranges depend not only upon the initial sound level and the transmission loss, but also upon what might be called the "acoustic size" of the target. This is merely another way of saying that the more sound a target intercepts and returns to an echo-ranging vessel, the louder will be its echo.

Generally speaking, a large target returns a louder echo than a smaller target at the same range and depth, and the echo from any particular target is louder at beam aspect than at bow or stern aspect. To compare various targets and aspects, the "target strength" is a useful number; it is measured in decibels.

The target strength of a ship or submarine depends on both its size and its aspect, but presumably not on its range nor on oceanographic conditions. Thus the target strength of any ship at given aspect is a constant. The experimental measurement of target strength, however, is not an easy matter. There are many sources of error, and since the measurements must be made in deep water, it is difficult to control them. Difficult problems of seamanship also arise in these operations.

Theoretically, target strength is not a simple function of target size. The processes of echo formation are complicated, and target strength depends not only upon the amount of sound intercepted, but also upon the nature and shape of the reflecting or scattering surfaces. A 6-ft triplane, for instance, which is a structure so designed that most of the sound incident upon it is reflected back toward its source, theoretically has the target strength (for 24-kc sound) of a sphere about 100 ft in diameter. Practically, it has a target strength somewhat, but not much, less than a submarine.

Wake Studies

Interest in the acoustical properties of surface wakes was first stimulated by reports that they returned echoes several hours after they had been laid. Interest in submarine wakes arose from reports that submarines could sometimes confuse echo-ranging pursuit by creating "knuckles" during evasive maneuvers. The study of wakes became imperative when necessary to design countermeasures against acoustic torpedoes, and their effect on our own acoustic torpedoes then became a matter of concern.

Few of the phenomena involved in underwater sound transmission studies are so difficult to study. Among other things, many experiments involve some danger, even when conducted with excellent seamanship. Once, for instance, when the UCDWR laboratory was working with destroyer wakes, a new commodore came on the bridge of his flagship just in time to see that it was bearing down rapidly on a yacht lying dead in the water while a small boat was apparently intending to ram the destroyer. It was with difficulty that he was dissuaded from giving a number of anxious orders. As it turned out, his fears were almost justified, for the force exerted by the moving vessel on the nearby stationary vessel (Bernoulli effect) was great enough to draw the yacht into the destroyer's wake less than 100 ft behind the destroyer's stern.

Skillful seamanship and careful coordination prevented any serious accidents, even when submarines operated very near surface vessels. But the work was frequently unrewarded by results, since the failure of a single part of the program could vitiate all others.

Consequently it is felt that the problem should be approached indirectly, through laboratory work and theoretical calculations, and through studies of related problems like turbulence.

During the war, the rapidly planned and executed empirical studies produced useful information on transmission loss through wakes, reflection from wakes, and the intensity of propeller sounds in wakes, but much remains to be done.

8.3.2 Noise Studies

Whatever the signal level, detection of the

signal depends upon its relationship to the unwanted sounds which are being received at the same time. A signal which is easily detected at one time may be masked by high background noise at another. This is, of course, what common experience might lead anyone to suspect; a sneeze, for instance, is clearly audible in a library reading room, but goes unremarked in a boiler factory. In much the same way, a loud echo may be unmistakable when an echo-ranging ship is making less than 15 knots in deep, quiet water; the same echo might never be heard if the ship were speeding through a rough, shallow sea, with its pings reverberating from a rocky bottom and mixing with the sound produced by large and noisy settlements of snapping shrimp. Therefore the study of echo ranging and listening necessarily involves the measurement and analysis of background sounds, as well as of the ability of operators to distinguish between signals and masking sounds.

Types of Noise

If a ship is alone in the open sea, drifting with wind and current, and with engines stopped, noise can still be heard in a hydrophone. This is called the ambient noise, since it surrounds, but is independent of, the listening vessel. If the ship starts its engines and begins to move through the water, the loudness of the noise increases. To the sea sounds is added the self noise produced by the engines and propellers, and by the movement of hull and hydrophone through the water.

All these noises pass through the same receiver that amplifies the signal. They may, consequently, be called the amplified noise, and are so distinguished from the airborne noise such as orders, explosions, bells, and aircraft sounds, which can distract an operator even though they are not amplified by his equipment. Unamplified airborne sounds should not ordinarily limit sonar ranges, since the sonar ought to be located in a reasonably quiet part of the ship and in a sound-conditioned room. During World War II, however, such a location was not always possible. The masking of signals by the sounds which are not airborne is a more difficut problem, since any amplification of the signal also amplifies the noise; no matter how high the gain, the relationship between signal and amplified noise remains constant.

Self-noise levels vary from ship to ship, since they are affected by the design and maintenance of the engines, hull, and propellers, as well as by the housing and location of the hydrophone. Certain generalizations, however, can be made on the basis of data taken by the Navy and NDRC scientists. Sonic self-noise increases so rapidly with increasing ship speed that Allied antisubmarine vessels during World War II seldom attempted to detect or track submarines with sonic listening gear. Echo-ranging gear can be used more successfully at high speeds, since the intensity of self noise is lower in supersonic frequencies than in the sonic, and since the high directivity of an echo-ranging transducer enables it to discriminate against much of the ambient noise. Even so, high noise levels at speeds of 20 knots or more make effective echo ranging almost impossible with earlier gear, not streamlined. Newer gear, with the hydrophone housed in a streamline dome, can be used at 20 knots, but echo ranges at such speeds are much reduced.

Ambient noise is unaffected by the speed or design of the ship, being determined by oceanographic conditions. Because much of it is caused by wave motion, it increases with increasing sea states. In shallow water, the ambient noise level may be raised by snapping shrimp, which produce a steady clatter of sound in both sonic and supersonic frequency bands. Cooperative studies, made by UCDWR, CUDWR, and the Naval Ordnance Laboratory, have shown that shrimp noise can always be expected in tropical and subtropical areas whenever the water is less than 30 fathoms deep and the bottom is rock, coral, or stony. Shrimp noise is only one of many sounds of biological origin, but it is uniquely important because it is omnipresent in certain areas. Other biological sounds come and go, continue for seconds or minutes and stop, but the shrimps snap on through day and night. Their clicking claws are consequently important not only to submariners who like noisy areas, but also to the designers of acoustic mines and other sonar devices which are triggered by sound.

Almost all noises are "white"; they are, that is, spread over a wide frequency band. Some, like the sound of shrimp, have spectra with predictable slope, but they are rarely peaked at any one frequency or narrow-band frequencies. Noise concentrated in a few frequencies is ordinarily caused only by the activity of other ships, or by industries or other human activities in harbors.

Masking by Noise

As has been remarked, the masking, or "drowning out" of one sound by another is a matter of common experience. Some of the laws governing it were known before the war, but specific data and even some general studies were needed.

The recognition of one sound in the presence of another depends not only upon the intensity of the two sounds, but also upon their spectra. If their spectra are identical, only the louder will be heard; if it is to be distinguished from the other, it must be appreciably louder. But if one sound has a definite pitch, while the other has a wide spectrum, the one may be heard even when its intensity is lower than that of the other. The use of bugles to transmit signals above the roar of battle was based on this fact.

This is an example of what may be called the filter property of the ear. It is capable of hearing many simultaneous sounds of widely differing intensities, and of distinguishing one from the other. So long as the sounds are markedly different in frequency, they will not mask one another unless one has a deafening intensity. Only when two or more are concentrated within a narrow band of frequencies (about 40 c) will they interfere with one another.

In echo ranging, consequently, recognition of an echo (a relatively pure tone) depends upon the intensity of the background sound in a 40-c band centered at the echo frequency. If the echo is louder than other sounds in that band, it will be heard. If it is fainter, it will be masked. Shifts in echo frequency caused by movement of a target toward or away from the echo-ranging vessel will not affect the ease with which it can be recognized against a background of noise, for noise has such a relatively smooth spectrum that its intensity in any series of adjacent 40-c bands is approximately the same. When the echo length is that commonly used (about 200 msec), the echo can just be heard if it is equal to the noise in a 40-c band. Shorter echoes must be louder in order to be heard.

In listening, even when the signal is spread over a band of frequencies as broad as that of the noise, recognition usually depends upon perception of those signal frequencies which are louder than the noise within 25 c of them. It follows, then, that if the slope of the signal spectrum closely parallels that of the noise spectrum, detection of weak signals will be difficult. But if the signal spectrum is peaked at some particular frequency, the signal may be recognized at long ranges because of a squeak, whistle, or groan which rises clearly above the background. It is interesting to note that detailed study of these phenomena has verified many of the common phrases used to describe them.

It is the filter property of the ear which makes possible the aural detection of signals which could never be recognized if they were presented visually (with cathode-ray oscilloscope, range recorder, etc.). With all methods of visual presentation thus far devised, every sound admitted to the receiver is equally effective in masking the signal. If the signal is always of the same frequency or frequencies, the efficiency of visual presentation can approach or even exceed that of aural presentation, since it is then possible to filter out mechanically all background noise except that at or very near signal frequency. But the spectra of ships and submarines are extremely broad, or else peak at varying frequencies. Even the echoes heard in echo-ranging receivers change in frequency as the target moves toward or away from the echo-ranging vessel. Consequently the ear, which is able to ignore virtually all sounds except those within 25 c of the signal to which it listens, no matter what the signal frequency, is ordinarily more effective in detecting faint signals than is the eye or any recording device. The range recorder is an exception, since the study of its permanent record of previous pings often reveals details that were overlooked at the time. This study can be made by the operator as he listens to the later pings.

8.3.3

Reverberation Studies

In listening, the background over which the signal must be heard is always noise. In echo ranging, the dominant background may be either noise or reverberation.

Reverberation is the sound of many small echoes returned by myriads of small sound scatterers at the surface, in the volume of the water, and at the bottom. It differs from noise because it is an almost pure tone (if the ping is of constant frequency), and because it is generally strongest immediately after the ping is emitted and therefore diminishes with time (range).

This diminution is always observed, but it is not regular. Reverberation intensities fluctuate widely and rapidly, and though the decay of average reverberation intensity may sometimes be plotted as a smooth curve, the slope of that curve depends on many things and varies markedly from time to time. Usually the curve is far from smooth, being marked by humps and peaks at various ranges. But always, since the reverberation weakens with range, it must sooner or later fall below the constant level of the background noise. So long as the reverberation is louder than the noise, it is said to be dominant, since it is then the sound which tends to mask weak echoes. When the reverberation is weaker than the noise, the noise is dominant and the reverberation becomes unimportant.

Since reverberation may frequently mask echoes at short and intermediate ranges, one of the first programs undertaken by NDRC scientists was a study of the variation of reverberation. In this study, many kinds of transducers, operating at frequencies of from 10 to 80 kc, and transmitting pings of varying length, were used. Some work was initiated with frequency-modulated pings and with ping lengths as short as 1 msec. Most of the routine work, however, was done with longer pings at 24 kc. Although virtually nothing was known about reverberation at the outset of these investigations, enough was discovered during the war to permit improvement of many operational procedures and to indicate possible solutions for some design problems. Most of the work was done at the San Diego laboratory, although it was guided both by the earlier research of the British and by valuable assistance and suggestions from the Bureau of Ships, the Sonar Analysis Group, and the publications of other laboratories interested in the development and improvement of sonar gear.

It is difficult, and perhaps impossible, to write a brief description of the reverberation studies without oversimplification. Reverberation levels depend upon even more variables than echo levels; they are affected by the directivity of the gear, the length and frequency of the ping, and by all of the oceanographic factors known to affect sound transmission. Their analysis has led to such disparate activities as photographing the ocean bottom, calculating the target strength of fish, and studying the daily life of plankton.

Types of Reverberation

It has been possible to identify reverberation originating at the surface, in the volume of the water, and at the sea bottom. When an echo-ranging projector is near the surface, the first crash of reverberation comes from the surface. The average intensity of surface reverberation decreases rapidly with range and soon sinks below that of volume reverberation. Bottom reverberation is not heard in deep water but in shallow water it is returned as a burst of sound from the range at which the beam hits the bottom. Thereafter the strength of the bottom reverberation falls off fairly rapidly.

To a sonar operator, of course, the various kinds of reverberation are one, since they all sound much the same and are mixed together in the rolling, ringing sound that he hears in the first few seconds after the ping. But their separation in the laboratory has led to a better understanding of the causes of reverberation. Thus, surface reverberation has been found to increase with sea state and to be influenced by the vertical temperature structure of the ocean. Bottom reverberation depends upon the character of the bottom, being weakest over mud and strongest over rock. It, too, is affected by temperature gradients.

Volume reverberation is not so well understood. Surface reverberation is probably the product of scattering by entrapped air bubbles

and by the irregularities (waves) of the surface itself. Bottom scattering, similarly, is caused by irregularities of structure and composition at the bottom: the greater the irregularity, the louder the reverberation. But how to account for volume reverberation? Some of it comes from fish and seaweed, certainly, but these are neither so abundant nor so evenly distributed as to account for all the observed volume reverberation. It may be produced by the scattering action of small organisms, but this hypothesis encounters difficulties.

Out of reverberation studies has come one important scientific discovery. Even in deep water, the volume reverberation does not always decrease regularly with range, but may have a crescendo at relatively long ranges. It has been found that this is caused by a deep oceanic layer, in which the population of small organisms, called plankton, is very much higher than in shallower or deeper layers. These organisms perform a daily migration, so that during daylight hours, the layer is at a depth of 900 to 1,200 ft. In the evening they move toward the surface, only to return to depth in the morning. This ECR-layer, as it has been called, has been traced over a wide area of ocean off the coast of California, though its boundaries have not been definitely located. Scattered reports indicate that it is also found in other parts of the ocean.

The precise mechanism connecting the plankton and the reverberation is not known. The simplest idea, that the small organisms themselves scatter sound, may be correct, but this is not very probable. It may be that fish feed on the plankton, and that they are the immediate cause of the scattering, but this hypothesis again encounters difficulties. Finally, it may be that the plankton generate gas bubbles. A great deal of work remains to be done on the ECR-layer, which may result in conclusions important not only to the Navy, but also to marine biology and the fishing industry.

Some very important conclusions about reverberation levels have been established definitely. Other things being equal, reverberation decreases with increased projector directivity. It increases with increased power output and with increased ping length. This knowledge has been important in the design of echo-ranging equipment. Its application is not simple, however, for any decrease in power output lowers not only the reverberation level but also the echo level. The relationship between the two remains unchanged. Second, the only known way to increase directivity without building impractically large projectors is to raise the ping frequency. And since the attenuation increases rapidly with increase of frequency, the maximum range may not increase. Other difficulties multiply if the directivity is greatly increased. Finally, although it is possible to reduce ping lengths to extremely small values without affecting echo levels, a short ping is more difficult to hear. Over a considerable range of ping lengths, these two effects just about balance each other. Very long pings are disadvantageous because the increase in audibility stops at about 200 msec. Very short pings are also disadvantageous because their audibility decreases more rapidly than the reverberation level.

These questions of audibility are discussed in greater detail in following text.

Masking by Reverberation

Reverberation is important for two reasons. First, it provides a sonar operator with a kind of acoustic reference for the detection of doppler effect in echoes. Since it is composed of many small echoes from scatterers which are practically stationary, the operator who hears an echo of a different pitch knows that his target is moving. If the echo pitch is higher than that of the reverberation, the target is moving toward him; lower pitch means that the target is moving away from him. If the pitch is the same, the target is either motionless or is moving in a direction that neither opens nor closes the range. Serving as an omnipresent reference, reverberation makes the detection of slight pitch changes possible.

The second reason for reverberation's importance is on the opposite side of the ledger: it may make detection of the echo completely impossible. It is the dominant background at short and intermediate ranges in deep water, and is frequently the dominant background at all ranges in shallow water. Or, to put it in an-

other way, it then is louder than the amplified noise, so that if anything masks the echo, reverberation will be that thing.

Unless the target is moving, the frequency of the reverberation will be the same as that of the echo. This means that the filter property of the ear cannot help to distinguish the echo of a stationary target from the reverberation. To be heard, the echo must have an intensity much greater than the average intensity of the fluctuating reverberation background; a weak echo is masked. If the target is a floating mine case, for instance, its target strength is low and its echo is weak. Even with no reverberation at all, the echo would usually be masked by noise at ranges greater than a few hundred yards; with the reverberation heard in a constant frequency echo-ranging receiver in the first second after a 100-msec ping, the echo cannot be heard at all.

For any kind of mine detection, therefore, the reverberation must be reduced. With constant frequency gear, only three methods, previously mentioned, are possible. The first of these, reducing the power output, is futile, since echo strength will suffer as much as reverberation. The second, increasing the frequency (and so the directivity) of the gear, is only slightly more practicable. An increase of attenuation accompanies increase of frequency, and since present mine-detection gear cannot hope to detect targets at ranges greater than 1,000 yd, some increase of attenuation can be tolerated. But unless the sonar is mounted on a pier or similar steady platform, too much increase in directivity will make it virtually impossible to maintain the projector on the bearing of the target. Operating such a sonar on a ship is like trying to use a high-power telescope without a tripod. Finally, an extremely short pulse can be used. Since very short pulses have wide spectra, the filter property of the ear is of no advantage in their detection. Therefore, a visual presentation of the echo can be used effectively. This enables the operator to see extremely short echoes which he could never hear. Extreme reduction of ping length produces a great reduction in reverberation levels.

Target motion makes easier the detection of echoes over reverberation. When a target is moving toward or away from an echo-ranging vessel, its echo has a frequency higher or lower than that of the reverberation. This doppler effect can shift the echo 50 c or more away from the reverberation frequency, and then the echo may be heard even if its intensity is less than that of the reverberation. The ear is again able to center its attention on the echo, and high reverberation is not necessarily masking. This can be described in terms of the operator's sensations. The echo from a stationary target is heard as an unusually loud part of the reverberation. The echo from a rapidly moving target is heard as a separate sound of different pitch. This fact has obvious operational importance to submariners. When they are operating in shallow water over a rocky bottom, or under any conditions of high reverberation, they know that they may be undetected by echo ranging so long as they stop, or at least avoid moving rapidly toward or away from the searching vessel. If, however, they turn directly toward the enemy and increase their speed, they know that they may betray themselves with echoes that shriek through the reverberation like a police whistle through traffic noise. If they turn directly away from the enemy and increase their speed, their echoes are even more audible, since down doppler is more easily heard than up doppler.

Many of the phenomena described in this section on masking were not generally recognized at the beginning of World War II, although the use of doppler to determine target motion had already become part of Navy doctrine. The work of NDRC groups at UCDWR and BTL was not only directed toward the analysis of this complex problem, but toward the acquisition of numerical data. This was used in attempting to strike a balance in evaluating the importance of the different aspects of the problem.

8.3.4 Application of Data to Gear

Basic research expenditures are a capital investment subject to amortization over a long period of time, rather than overhead entirely chargeable to current operations. During World War II, this economic fact was some-

times obscured, for there was no time to realize full returns on the investment. Lack of time also affected the conduct of research programs, since they were necessarily planned to give the earliest results, rather than the most valuable results.

It is to be anticipated that the underwater sound data accumulated during the war will ultimately exert a considerable influence on the design of sonar gear and may lead to the development of new types. Even during the war, although many operations, both naval and industrial, had to be based on existing types and designs of gear, some applications to the design of new gear were made.

Thus, when the development of countermeasures for the enemy's acoustic torpedoes became urgent, it was obvious that the acoustic properties of wakes would determine the success or failure of these devices. Knowing the sound output of ship screws was also essential. Therefore basic research on the properties of wakes became a high-priority task assigned to UCDWR. The urgency of the task is illustrated by the fact that, on orders from CNO, the departure of a fully loaded carrier [CV] was delayed so that its wake and sound output could be studied. The data accumulated by these studies were used not only for countermeasures, but also in the design of our own acoustic torpedoes. These measurements were among the most difficult that NDRC was called upon to make and the haste with which they had to be carried out makes it highly desirable to initiate a program to study the same problem more carefully.

Data on biological noise were used by the Bureau of Ordnance in the design of acoustic mines. Development of prosubmarine devices (NAC and NAD beacons, described later) was based on data concerning the sound output of submarines, and on the results of psychoacoustic research. NDRC studies of reverberation affected the design of small-object detection gear and studies of refraction were important in devising a system for correcting the readings of depth-determination gear under varying temperature conditions.

Harbor defense was also aided by NDRC scientists who made a number of expeditions to various harbors of the continental United States and the Hawaiian Islands for the purpose of studying background noise, transmission conditions, currents, and bottom topography and character. On the basis of these studies, NDRC was able to assist the Navy in preparing recommendations for the location and operation of underwater sound equipment. Some of the men who had been engaged in the expeditions later cooperated with the UCDWR Publications Group in preparing the first draft of an official Navy manual explaining the effects of oceanographic conditions on the operation of harbor defense echo-ranging and listening devices.

This is certainly not a complete list of the effects of basic research on equipment design during the war. But it is true that the major use of the data was in the modification of doctrine concerning existing types of gear. Both tactical and strategic plans were affected.

8.3.5 Prediction of Maximum Ranges

As soon as tests had shown that maximum echo ranges were extremely variable and that they were influenced by the vertical temperature structure of the ocean, work was begun on the development of a range-prediction method.

The need for some method was evident. Without some way of forecasting the maximum range on a submerged submarine, echo-ranging screens were greatly handicapped in their work of protecting convoys. With such an estimate, they could space available antisubmarine vessels most effectively for the defense of a convoy, for the detection of an escaping submarine, or for the establishment of a patrol across a narrow strait or channel. Knowledge of seasonal and local variations could be utilized in planning the safest routes for convoys.

As anyone familiar with experimental studies of sound transmission might guess, it was impossible to work out a perfect method of range forecasting immediately. Even now the prediction system has many shortcomings which can be remedied only as more is learned. Some margin of error must be expected to con-

tinue indefinitely, since the problem is very similar to that of weather forecasting. But the present range-prediction methods are a great improvement over the first fumbling efforts, which frequently were grossly inaccurate, overly complicated, or both.

Prediction Methods

The first method of range prediction was simple enough—too simple, in fact. Based on the assumption that ranges always extended just to the shadow boundary shown on ray diagrams, the first official manual which NDRC helped to prepare for the Navy predicted only the assured range (maximum range on a submarine at the depth where the maximum range is shortest), and that for only three types of temperature structure. Simple tables were used, together with specific instructions for determining from a bathythermograph slide the proper table to be used.

Many slides, unfortunately, did not fit these simple rules, and in these cases no prediction could be made. Even when the slides did seem to fit, a further disadvantage of the method was that only the assured range could be estimated. Therefore this first method was modified, and a special refraction slide rule was issued to antisubmarine vessels. The use of the slide rule permitted somewhat more accurate predictions but a considerable amount of training was needed before an operator could calculate a ray diagram showing the theoretical extent of the sound field and the maximum range for various target depths. The calculations were time-consuming and liable to mistakes. They required concentration, and it was expecting too much of the sound operator or sound officer to ask him to perform them at sea.

Finally, as experimental data accumulated, it became evident that even this complicated prediction method was less accurate than it should be. It was based solely on the limits of the sound field as determined by refraction theory and so failed to take into account many of the factors now known to have a profound influence on the maximum echo range. Predicted ranges were usually too long because it was assumed that the intensity of sound from an echo-ranging projector would drop 80 or 90 db (as calculated from the ray diagram) before the echo became too weak to be detected. This last assumption is almost never justified. The effects of reverberation and ambient and self noise were ignored in the method.

The present prediction method contains two different procedures, one for deep water, and one for shallow water. Under certain conditions, the method used in deep water may be used in shallow water as well. When these conditions are not found, however, the problem of range prediction in shallow water is so complicated by bottom reflection and reverberation that it must be solved by entirely different means.

The present system of prediction used in deep water differs radically from previous ones in that it attempts to predict the range at which the intensity of the signal has dropped to the point where a returning echo will just be detected (i.e., heard 50 per cent of the time) through the noise tending to mask it. Thus the range tables now in use are based not only upon transmission measurements but also upon studies of noise, reverberation, and recognition. Even so, they give only approximate values; there can be little doubt that the systematic study of sound transmission will produce new methods which will be both more accurate and less difficult to use.

The present system of prediction used in shallow water is already obsolete. When the method was first formulated, very little was known of transmission losses in shallow water and not very much was known about bottom reverberation. Since March 1944, when the last official manual for antisubmarine vessels was published, much more work has been done in shallow water. Consequently, it is now possible to make rough generalizations about transmission over different kinds of bottoms. These have been used in the preparation of manuals for submariners, who are acutely interested in areas of poor sound conditions. Since the end of World War II, additional progress has been made by UCDWR operating under a direct contract with the Bureau of Ships, and there is some hope that future methods of forecasting for shallow water may be even more reliable than those for deep water.

8.3.6 Bathythermograph Data Applications

When it became apparent in 1944 that enough accurate information had become available to permit extensive operational use of predicted ranges, drafts of tactical rules for using range predictions in antisubmarine warfare were formulated by the Sonar Design Section of the Bureau of Ships, in collaboration with NDRC groups and the officers responsible for tactical doctrine.

During the last 18 months of World War II, consequently, dial settings of sonar gear were determined in part by sound ranging conditions. Both the keying interval (time between successive pulses) and the ping length, for instance, were based on the local conditions revealed by the bathythermogram. Escort, search, and scouting plans for antisubmarine vessels were also based on the predicted maximum range, with ship spacing and choice of search procedure being subject to carefully formulated official doctrines. Since not all escort vessels are equipped with bathythermographs, signals were devised for sending information on sound conditions from one ship so equipped to all the others operating with it.

Submarines also made increasing use of oceanographic information, and particularly of BT observations. Since lowering a small instrument overboard from a submarine was not feasible, a special submarine BT was developed by WHOI. With a temperature-measuring element fastened rigidly to the outside of the boat and connected to a recording element inside the pressure hull, the submarine BT made a continuous record of the temperature of the water at all depths through which the submarine moved. This record had many uses, many of which were suggested by submarine personnel after bathythermographs had become standard gear.

First of all, of course, the BT record is one of the submariner's best guides to sound conditions at all depths. Using tables and charts similar to those published for antisubmarine vessels, he can determine the areas and depths at which he is least likely to be detected by sonar gear and can use this knowledge in determining tactics of approach, attack, and evasion. Equally important, however, is his use of the submarine BT as a hydrometer. Since the density of sea water varies markedly only with changes of temperature and salinity, and since there are great areas of the oceans in which salinity changes are so slight as to be unimportant, the BT record is usually a reliable indication of the change of density with depth. Even when marked salinity gradients are present, they are frequently accompanied by distinctive temperature distributions which reveal their presence. Toward the end of World War II, improved instruments were developed that measured salinity as well as temperature and automatically computed the density.

Using the BT, submariners found that they could dive more quickly, quietly, and safely; they also found that the BT detects and records sharp negative gradients (layers of water in which the density increases so rapidly with depth that a properly trimmed submarine can float on them with motors stopped). This kind of density layer is easily illustrated by an extreme example: when water floats on mercury, a stone which sinks through the water will float lightly on the mercury. Though the density changes in the ocean are never so dramatic or so abrupt, they can sometimes be used in the same way.

8.3.7 Publications

Both surface vessels and submarines took ever increasing numbers of BT observations as World War II continued. These records had an immediate value in the estimation of spot conditions, but they were also valuable in extending naval and scientific understanding of conditions in the Atlantic and Pacific Oceans. Consequently, all records were saved by forces afloat and forwarded to the Hydrographic Office for interpretation and filing. As has already been remarked, a farsighted policy had initiated this program of observation by naval vessels even before the BT had developed into an operational necessity.

NDRC was concerned with the taking and interpretation of all BT data. To instruct men in the use of the BT and the information

it provides, scientists from both WHOI and UCDWR were attached to submarine and antisubmarine forces. These men aided naval officers in supervising the installation and maintenance of BT gear; they were able to explain seemingly anomalous sound and diving conditions by making the most recent scientific information available to the Navy; and they were able to conduct many valuable tests of ship and submarine performance under a wide variety of operating conditions.

Navy Manuals

The training activities of these scientists were facilitated by the publication of new official Navy manuals. Although the preparation of these manuals was properly a part of the NDRC training program, the technical nature of the material made it essential that the manuscripts be written and edited by personnel intimately connected with the scientific program. The operational nature of the material made close liaison with the operating forces similarly essential.

For the preparation of these manuals and their illustrations, the Bureau of Ships requested NDRC to establish a publications group. This was done, and the UCDWR employed a staff of artists and writers who worked in the same laboratory with the scientific staff. Liaison with the operating forces was made possible by the close cooperation of the Sonar Analysis Group and the Bureau of Ships. Conferences between all concerned in this complex project were frequent, and required much travel. Groups of San Diego personnel sometimes worked for periods of several weeks in Washington, so that they could have the benefit of frequent conferences with naval officers stationed there. The published manuals contained the simplest explanations (consistent with correctness) of the factors determining sound and diving conditions, as well as the most recent tables and instructions for interpreting BT observations and various Hydrographic Office charts.

Hydrographic Charts

Many of these charts were themselves prepared by NDRC scientists working in close cooperation with officers attached to the Hydrographic Office. Since all BT records (or copies) were forwarded to NDRC laboratories—slides from the Atlantic and Mediterranean to WHOI, slides from the Pacific and Indian Oceans to UCDWR—great quantities of new data on the temperature distribution in the oceans were made available. By the end of December 1944, more than 40,000 slides had been returned from the Pacific and about as many from the Atlantic. When this new information was added to that accumulated before World War II, both by the Allies and our enemies, a number of valuable aids could be prepared for the Navy.

Sound Ranging Charts. Among these aids were the sound ranging charts, which combined the most recent findings of underwater sound research with all available oceanographic information to show predicted sonar conditions in many areas of active submarine and antisubmarine warfare. These charts went through several editions as knowledge of the effect of temperature conditions on maximum echo ranges became more precise. They were disseminated widely through the Navy, and were used in the routing of convoys and in the planning of antisubmarine activities. The two sound schools included lectures on these charts in their curricula. These lectures were sometimes delivered by NDRC personnel, and were always planned in close consultation with it.

Bottom Sediment Charts. Equally important were the bottom sediment charts, which were rushed into production when German submarine activity along the Atlantic and Gulf coasts demonstrated forcefully the importance and variability of sound conditions in shallow coastal waters. The dependence of echo ranges on bottom type in shallow water was determined by the only available method—theory. NDRC engaged marine geologists (members of a very specialized profession) who brought together all available charts and studies of each area, collated all notations of bottom type, and prepared new bottom sediment charts for publication by the Hydrographic Office. Later, as American submarines pushed nearer Japan, similar charts were prepared for the most important and active areas of the Pacific. Other charts, requested in connection with amphibi-

ous operations, were also prepared. Cooperation with the Joint Army-Navy Intelligence Service was an essential element in the success of this work.

Submarine Supplements. For submariners, in addition to official BT manuals and bottom sediment charts, a series of Submarine Supplements to the Sailing Directions was prepared by a separate NDRC group and published by the Hydrographic Office. These supplements included not only information on sound and diving conditions, but also charts and descriptions of wind and water currents, of bottom topography and character, of salinity gradients, and of transparency conditions. Three NDRC groups at WHOI, SIO, and UCDWR cooperated with the Hydrographic Office and the Sonar Analysis Section in their preparation. A special group of writers and cartographers was established at UCDWR under the supervision of a geologist on leave from the Geological Survey of the Department of the Interior. They maintained close contact with all the scientists whose research had made possible the preparation of these very comprehensive atlases of the ocean areas most important during World War II.

The reception accorded these supplements by the submarine forces indicates that all ocean areas should ultimately be described in a similar manner. This is a major peacetime project for the Hydrographic Office, and will require an expansion of its staff and facilities.

8.4 A PEACETIME RESEARCH PROGRAM

Research has been defined as the production of something whose specifications cannot be written in advance of completion. Provided it is recognized that ideas are usually the most valuable product of research, this definition is not bad. It is obvious, however, that it refers primarily to the construction of apparatus whose function is predetermined, although its construction and capabilities are indeterminate.

The activities described as research are so varied that many definitions are possible. Another definition asserts that pure research is an activity without visible practical objective. This definition is unpalatable to many administrators, but embodies certain well-established truths, for it has been found by experience that the most valuable practical results often arise out of work that was done without consciousness of the practical objective.

This can be illustrated by two well-authenticated instances. Oliver Lodge was very active in the early study of radio waves, and made valuable contributions to knowledge of their properties and means for his generation. He later stated that he had no thought of their use for communication purposes, and that news of Marconi's application of them came to him as a complete surprise.

In other cases, the general objective may be visible to the research worker, but appear visionary to the layman. Thus, during World War I, Ernest Rutherford was asked to help develop underwater sound gear. He refused, saying that his work on atomic disintegration was much more important. At that time, few scientists could have foreseen that Rutherford's work would lead to military application within a generation and the layman's incredulity would have occasioned no surprise.

These definitions and anecdotes could be multiplied. They serve only to vivify an abstract truism: research is an exploration of new and unknown areas. The task of Division 6 of NDRC at the beginning of World War II was the development of an organization for the exploration of underwater sound. A similar problem confronts the Navy at the present time. The NDRC organization is now scattered. The work begun by it is incomplete, and the conditions under which the work is to be completed are different. It is appropriate to conclude this chapter on wartime research with suggestions as to an organization that can continue permanently.

At least three kinds or levels of research can be distinguished. They are:

1. The *development* of gear to perform specified functions. The projects of this program have definite objectives and definite lines of progress toward them.

2. The research *supporting* the development program, by exploring other objectives, other lines of progress, and by systematically ac-

cumulating basic data on the factors limiting the performance of gear already constructed or under development.

3. The *pure* research, whose objectives may be difficult to define, but out of which the objectives of the other two levels will evolve.

Each of these three levels of research in underwater sound should receive support from the Navy, but not all in the same manner.

8.4.1 The Development Program

It is fairly clear that the development program is of interest only to the Navy and of such vital interest that its administration must be kept within the Navy's immediate jurisdiction. In accordance with established policy, this program will consist of two parts: one entrusted to naval laboratories staffed by civilian scientists, and the other entrusted to industrial organizations operating under contract with the Navy.

The objectives of this organization must be determined jointly by the cognizant bureaus and the senior civilian staff of the naval laboratories. The objectives will change as the situation develops, necessitating an organization that will be responsive to such changes of objective. On the other hand, the administration must naturally guard against the confusion resulting from too-frequent changes of objective.

Each of the smaller parts of the organization must clearly understand its mission and its relation to the major objective. Freedom of decision must be allowed, and initiative in accomplishing the mission must be encouraged. Communication between parts of the organization must be possible without congesting the higher administrative offices.

It may not be superfluous to remark that this organization will be staffed largely by engineers, rather than by scientists in the academic sense of the title. It is important that liaison between this engineering development program and the supporting program of scientific research be close. This can be best accomplished by obtaining the services of engineers whose professional training is such that they can, on occasion, participate actively in the scientific phases of research. The present trend in the engineering profession is such that this should become increasingly possible in the future.

8.4.2 Supporting Research

Although the broad objective of this program is to support and assist the engineering program just described, it must not be organized as a service at the command of the development organization. The immediate missions are scientific rather than engineering. The activities of this organization should therefore be directed entirely by the senior scientific staff of the naval laboratories. Frequent changes of objectives must be avoided, for the scientific process is time-consuming. Frequent changes in objective are thus likely to prevent all progress.

The supporting research will frequently require facilities beyond the means of the naval laboratories. Examples are the BT, wake, and ship sound programs mentioned in the earlier pages of this report. Although refraining from participation in directing such work, the cognizant bureaus and even the Navy must be sufficiently informed of its nature and value so that they will freely make available the necessary facilities. The fact that such facilities were provided by the Navy even in time of war indicates that this information and willingness to participate is already widespread. It cannot be too strongly emphasized, however, that such a policy of participation in scientific programs on the part of the bureaus and the Navy is dictated by self-interest.

As has been said, the objectives of these programs are such that the layman cannot properly assess their value to the Navy, and hence should not participate in their direction. Nonetheless, the values involved are so specifically naval that outside organizations cannot be expected to support them financially. This is true even of some of the programs that do not require facilities beyond the means of the naval laboratories.

The calibration stations furnish one example of such an activity. Since their mission is one of careful measurement, unbiased by any per-

sonal interest in the result, they must be maintained and supported entirely by the Navy.

Another example is a consulting and fact-finding organization, which will assist in the preparation of operational plans and doctrine. Although this is traditionally a function of the commissioned personnel, the technical nature of modern warfare makes some of the problems scientific rather than military or even engineering. The limitations imposed by natural laws on the performance of gear and its operation so as to obtain optimum results—these are problems on the level of the supporting research program.

Although all such activities must receive their financial support from the Navy, it is possible that universities or other scientific organizations can be induced to direct them under contracts with the Navy Department. In general, however, the reluctance of civilian organizations to assume such responsibilities will increase in direct proportion to the value of the work to the Navy. This should not be considered a reproach to these organizations: in many cases their charters are specific in formulating their objectives in such terms that a wide interpretation is necessary before they can justifiably engage in specifically naval enterprises. It should be added that almost all of the research performed by universities during the war, under NDRC auspices, was of this nature. It was justified by the emergency, but in peacetime, the universities cannot continue to carry this work.

The Navy must therefore be prepared to secure the services of men with high professional standing. The difficulty of competing with academic institutions in this field has often been stressed, but until now, these latter have not faced serious competition.

8.4.3 Pure Research

The social and economic value of pure research is no longer a subject of argument. The names of many of the great men in this field have entered so basically into our technological language that they are no longer even capitalized: e.g., volt (Alessandro Volta), ohm (George Simon Ohm), farad (Michael Faraday), henry (Joseph Henry). The objectives toward which these men were working were quite incomprehensible to contemporary laymen. Often they remain so today, even though the layman has had to learn their names in order to purchase household appliances. The engineer has somewhat greater comprehension for these past achievements, but his professional necessities prevent him from being fully aware that the same process is continuing today, and at an accelerated pace.

Traditionally, the universities are the home of pure research. Their financial endowment, according to this same tradition, comes as a gift from private individuals. These traditions, together with that of academic freedom, have insured the continuation of pure research, no matter how unclear its objectives might be. The only necessity was that someone find the problems sufficiently interesting to work on them despite the small financial return to himself.

The traditions of the industrial research laboratory were largely established by Thomas A. Edison. He found such a large accumulation of the results of pure research that there seemed no need for more. In fact, his work and that of his associates was almost entirely development. Edison was the first to undertake the systematic exploitation of scientific results, and worked under conditions that may be compared to those in a virgin forest. By comparison, present-day development work is the harvesting of plantations; hence the necessity for scientific research directly supporting every development program. The research conducted in academic organizations may be compared to the spontaneous growth in previously unforested areas—an obviously uncertain process. The analogy should not be labored, however.

These traditions are changing. The large industrial laboratories have found it advisable to encourage pure research, as well as to establish development organizations and their supporting research. The achievements of Irving Langmuir at the General Electric Research Laboratory and of C. J. Davison at the Bell Telephone Laboratories have been recognized by the award of the Nobel Prize.

The reasons for the support of pure research

by industrial concerns are various; altruistic motives should not be excluded, but there are others. The professional reputation of both laboratory and staff depends in large measure on its publications, and security problems exist even in industry. The publication of pure research presents fewer problems than does that of results having more immediate objectives. The professional reputation of the laboratory is important, not merely for prestige and advertising, but because of the professional channels of communication which it opens. The influx of intelligence through these channels is of extreme value. Moreover, it is very difficult to obtain first-class scientific personnel for a laboratory whose professional reputation is small. The professional scientist is accustomed to place a very considerable financial value on such matters, as well as on an environment in which pure research flourishes. Finally, although the financial return on investment in pure research is speculative, it is occasionally unexpectedly large.

Many of these reasons are equally cogent in fixing the policy of a government agency, and the altruistic motives should be given greater weight. It cannot be too strongly emphasized that, while the objectives of pure research are obscure, experience shows that its value is enormous. It is no exaggeration to say that our present technological civilization would be impossible had it not been for the mathematical and astronomical researches of Newton. Fifteen years ago, many people were inclined to say that the work of Einstein would never affect everyday life. Today it would seem very rash to make that assertion, and 15 years from now, the effects may be appreciable.

In other words, while the return to the investor in pure research may be highly speculative, the return to society is certain and large. This is the reason that has influenced the individual donors of the past to endow universities for this purpose. The changing economic state of the world is reducing the funds thus made available for this important social function; the obligation of state and federal governments to provide the necessary support is clear. The present arguments in Congress and elsewhere concern the mechanism of checks and balances necessary to make government funds available without placing the research under the handicap of a bureaucratic supervision which might stifle initiative. The early obscurity of the objective of the most valuable work is such that not even the most competent scientist can be entrusted with too much authority over the work of others. This is the reason for the tradition of academic freedom in determining what problems each man will pursue.

8.4.4 Summary

To summarize this rather general discussion as it applies to the research policy of the Navy:

1. It is essential that a certain amount of pure research by the staffs of naval laboratories be encouraged and adequately supported.
2. It is essential that professional contacts be maintained with research workers in the universities and other private laboratories.
3. It is entirely proper for the Navy to provide financial support for pure research in academic institutions and it may reasonably anticipate such an investment to be profitable in the long run.
4. In thus supporting academic institutions, the Navy will acquire power over them, and thus also the responsibility not to misuse this power.

If and when a general Federal agency for the support of research is established, the Navy will undoubtedly wish to work through it, and delegate the responsibility mentioned in point 4. This should not affect the conclusions formulated in points 1, 2, and 3.

Specific Fields of Underwater Research

Any specific proposals for naval research programs must presuppose the existence of organizations capable of performing the functions outlined above. In the following, no attempt will be made to discuss the development program. The reasons for this omission will be clear from the previous discussion. The amount of work that might be done in the way of supporting research and pure research is very large, and some selection must undoubtedly be made by the scientific administration

of the naval laboratories and by those other agencies within the Navy Department whose responsibility is the liaison with academic research.

The following list in Table 1 makes some pretense at completeness, but it cannot be hoped that there are no omissions. However, it includes only research[a] that specifically supports the probable program for the development of underwater sound gear and closely allied problems. The possibilities for pure research are only implicit in the outline. The projects are not all of the same kind—some are very detailed, some very broad; some will require only a small staff and few facilities, some can only be carried out with the cooperation of the Navy. Because of this heterogeneous character of the projects, no attempt has been made to arrange them in any order of importance.

[a] More specific suggestions as to needed research will be found in Division 6, Volume 7, entitled, "Principles and Applications of Underwater Sound."

TABLE 1. Research specifically supporting the development program.

Data programs	Laboratory and theoretical problems	Forecasting and planning problems
Calibration stations.	Electromechanical properties of crystals, etc.	Forecasting of oceanographic conditions.
Sound ranges for measuring the sound output of ships.	Theory of electromechanical systems.	Prediction of maximum echo and listening ranges.
Self-noise measurements.	Generation of underwater sounds —wanted and unwanted.	Plans for search and attack using underwater sound gear.
Target strength measurements.	Cavitation.	Plans of installation of gear on shipboard and in harbors.
Ambient noise surveys.	Theory of beam patterns and hydrophone arrays.	Plans for evasive maneuvers and use of countermeasures.
Transmission and scattering of sound in the sea.	Sound absorbing properties of materials, including sea water and other fluids.	
Acoustic properties of wakes.	Velocity of sound in sea water as a function of temperature, pressure, and salinity.	
Bathythermograph program.	Theory of the propagation of sound in nonideal media.	
Marine geology.	The formation of echoes by large objects.	
Marine biology.	The scattering of sound by bubbles and small objects.	
Diving characteristics of submarines.	Theory of and experimental work on the physical characteristics of noise.	
Surface waves at sea.	The masking of one sound by another.	
	Laws of hearing in general.	

Chapter 9

TRANSDUCER RESEARCH AND CALIBRATION

By *Robert S. Shankland, Frederick V. Hunt, and Franz N. D. Kurie*

9.1 MAGNETOSTRICTION TRANSDUCERS

MOST OF THE scientific work devoted to the production of new tools for subsurface warfare involved the type of work commonly called development rather than research. Development work usually involves the modification and application of known scientific principles and techniques to produce new and useful results. Research work, on the other hand, is directed toward the establishment of scientific principles and increasing the scope and store of fundamental knowledge.

The wholesale concentration of scientific manpower during World War II on the development of weapons of war made serious inroads on the unexploited stock of fundamental knowledge. It is to the credit of the academic scientists that they were able so effectively to translate basic science into practice but, to borrow a term from oil conservation, the depletion of our proved reserves of fundamental scientific knowledge is a matter for national concern. This impairment was aggravated by the almost total diversion of academic scientists from their normal peacetime research to weapon development.

In the face of this situation the study of the science and art of designing and constructing magnetostriction transducers provided an exception to the rule. A substantial program of basic physical research in magnetostriction was conducted by three of the Division 6 contractors in parallel with a program for the development of transducers for experimental and Service use. These agencies included Bell Telephone Laboratories [BTL], Harvard Underwater Sound Laboratory [HUSL], and Columbia University Division of War Research at the U. S. Navy Underwater Sound Laboratory at New London [CUDWR-NLL]. As a result of this research effort, the fundamental scientific base for further development work in magnetostriction has been broadened and strengthened rather than restricted by the work devoted to subsurface warfare.

The principle of magnetostriction is very old but its technological utilization dates from the middle 1920's. In the period following that marked by the pioneer work of G. W. Pierce, the development of magnetostriction transducers as underwater sound projectors was carried forward by the staff of the Naval Research Laboratory [NRL]. The development lacked, however, the impetus that would have been provided by a widespread demand for industrial use and restricted resources prevented NRL from exploiting the development fully. The lack of an industrial demand arose in part from restrictions on the dissemination of information imposed in the interest of military security and also in part from a lack of sufficient scientific personnel in industry trained to handle the experimental work required "to prove in" the potential industrial applications of high-frequency sound. It may be remarked, incidentally, that the postwar redeployment of scientific personnel engaged in these problems during World War II may go a long way toward increasing the industrial use of ultrasonics provided the postwar requirements of military security permit a rather free dissemination of the results of these scientific studies.

Magnetostrictive materials, such as nickel and nickel-bearing iron alloys, are intrinsically stiff and are, therefore, exceptionally suitable for the generation of sound waves in liquid media, such as water, which are also stiff. Magnetostriction transducers are well adapted for use in the frequency range extending from 10 to 100 kc (and perhaps higher) and can easily produce sustained sound waves of intensities sufficient to cause cavitation in all ordinary liquids. Transducers, or sound projectors, for echo-ranging equipment were available and in wide use at the beginning of World War II but the conversion efficiency of such transducers was low, techniques were not available for determining their electroacoustic performance accurately, and control of uniformity in production was extremely difficult. There was little control over the shape of the radiated sound

beam, and the design of the projector itself was a matter of experimental trial and intuition rather than a result of accurate quantitative analysis.

The Harvard Underwater Sound Laboratory carried on throughout the war a research program devoted to elucidating the fundamental factors affecting the performance of magnetostriction transducers. As a result of the studies of the HUSL group and the collateral investigations of the other laboratories engaged in similar work, it not only became possible to construct improved transducers for sonar and ordnance purposes but also to put the problem of designing such transducers on a sound engineering basis permitting calculation of performance in advance of construction.

Analysis of Electromagnetic Coupling

The fundamental research program on magnetostriction transducers carried out by HUSL can be described under three broad headings. First of all it was necessary to make a careful theoretical analysis of the electromagnetic conversion process. Special emphasis was placed upon a mathematical analysis of the magnetostrictive coupling between the electrical driving circuit and the active material of the transducer so that this fundamental characteristic of the transducer could be described quantitatively in terms of the magnetic properties of the active material and the configuration of the electric and magnetic circuits. This study made it possible to draw equivalent electrical circuits which would represent the performance of the electroacoustical system not only in a qualitative way but with quantitative precision.

These equivalent circuits made it possible to apply to the transducer design problem the wealth of technical information concerning the behavior and design of electric transmission networks. By computing the performance of the equivalent electrical circuit it was possible to propose useful alterations in the electric, magnetic, mechanical, or geometrical characteristics of the transducer. This work is closely related to the analyses of mechanical vibrating systems discussed in following text. It provided, however, an independent method of dealing quantitatively with the vibrating system of the transducer, placing special emphasis on the evaluation of the magnetostrictive coupling and the corresponding electromechanical conversion efficiency.

An example of the utility of the foregoing analysis arose in connection with the consideration of a novel magnetostriction transducer utilizing flexural vibrations. In this case it was possible to compute the resonant vibration frequencies of the system, the electroacoustic coupling coefficient and the expected efficiency of the device in several modes of vibration, all in advance of constructing the first model.

Properties of Materials

It was also necessary to conduct investigations and make extensive measurements of the magnetic properties of the magnetostrictive materials available for use in transducer construction. Pure nickel remains one of the most useful of the magnetostrictive materials for transducer construction but its behavior can be influenced remarkably by heat treatment and mechanical working. In addition to studies of nickel of commercial purity, measurements were made of the magnetic properties of various alloys including in particular vanadium-Permendur (2% vanadium, 49% cobalt, remainder iron) which proved to have properties especially useful in transducers operating without benefit of an external source of magnetic polarization.

The magnetic measurements made by HUSL included initial magnetization curves and accurate delineation of complete hysteresis loops for carefully prepared small samples. In addition, special experimental arrangements were made for determining accurately the variational permeability observed for various steady conditions of magnetic polarization. The background of experimentation with sample transducers, utilizing magnetostrictive materials which had received various heat treatments, made it possible to confine the magnetic studies conducted by HUSL to those materials which showed the most promise.

An extensive investigation was also conducted by engineers of BTL who used their metallurgical facilities to provide specimens of many alloys having a wide range of composi-

tion. These measurements, which included both static and dynamic studies of magnetostrictive activity, eliminated many alloys from further consideration and provided a very useful body of fundamental data on magnetostriction research. The BTL studies also covered a wide variety of heat treatments for the materials showing the most favorable magnetostrictive properties and provided a guide for establishing the specifications for magnetostrictive materials.

It may be said that these studies did not indicate that any single material is universally "best" for the construction of magnetostriction transducers. The requirements for an ideal material for transducer construction are inherently contradictory. High reversible permeability and high coercive force are both desirable but they usually increase and decrease in opposite directions as the composition and treatment of the material are varied. Fortunately, useful compromise values may be obtained.

It is usually desirable to emphasize the high reversible permeability of the magnetostrictive material and then to compensate for the corresponding low coercive force by providing polarization by permanent magnets suitably disposed. This suggests that composite materials might be used for the magnetic circuit and some preliminary experiments were carried out to explore this possibility. However, until improved methods of utilizing composite magnetic circuits become available, it will continue to be necessary to apply engineering judgment in the choice of the magnetostrictive material best suited for a specific application.

Analysis of Vibrating System

The third major phase of fundamental research in magnetostriction transducer design concerned the analysis of the complex vibrating system by which magnetostrictive strains are converted into the vibration of a radiating surface in contact with the water medium. This activity offered many opportunities for ingenuity and invention and, as often as not, the detailed analysis followed, rather than preceded, the suggestion of a basic design scheme. Both the New London Laboratory and HUSL conducted active programs of transducer design in which various configurations of the magnetostrictive material were employed in the attempt to secure desirable performance in the final transducer.

Eddy currents constitute one of the most serious sources of internal dissipation in magnetostriction transducers. In units employing radial or longitudinal vibration of nickel tubes, this effect is especially prominent and led to many schemes, some practical and some impractical, for reducing the eddy currents by lamination. Proposals for the use of stacks of flat laminations by which the eddy currents could be minimized were also made and tests of experimental laminated stacks revealed the soundness of this conception. Quantitative analysis of the vibration of asymmetrical laminations made it possible to compute the efficiency of electroacoustical conversion and also to choose the configuration of the lamination in such a way as to provide a desirable sharpness of resonance for bandwidth coverage and to produce a useful degree of preferred radiation from the face of the stack in contact with the water. Similar analysis was extended to laminated stacks of thin rings which proved to offer a desirable range of acoustical performance characteristics.

9.1.1 Types of Transducers

The principal types of magnetostriction transducers made available by this research program may be classified as follows:

Radially Vibrating Tubes. In one arrangement the driving coil and polarizing magnet are contained inside the magnetostrictive tube leading to a transducer which is convenient to mount and handle. Units of this type were employed in the sound gear monitor for sonar testing. Several thousand units were procured by the Navy during World War II.

Asymmetrical Laminated Stacks. Two forms of the asymmetrical laminated stack received wide usage. One of these provided a 60-kc transducer having unusually good directional characteristics for use in echo-ranging types of homing ordnance. Another type of asymmetrical stack was used in the multielement cylin-

drical transducers required in scanning sonar systems.

Laminated Ring Stacks. The laminated ring stacks were usually provided with a toroidal winding and the entire unit encased in a molded plastic shell. Altering the diameter of the rings controlled the resonance frequency whereas the radial thickness of the lamination controlled the sharpness of resonance over a wide range. Transducers could be made in this way to have substantially uniform response over a wide frequency range. In this respect the ring stacks had a frequency response comparable with the tubular units (first type described) but operated at a considerably higher efficiency.

Tube and Plate Transducers. This type of unit was employed in the sound projectors widely used in sonar equipment at the beginning of World War II. As a result of studies by HUSL and BTL, the efficiency of such units was markedly increased and design factors were elucidated so that the characteristics were controllable. One unit of this type received wide usage in underwater homing ordnance devices.

Miscellaneous Forms. These included units employing flexural vibrations and some novel forms which revealed interesting possibilities for development not fully exploited by this program.

9.1.2 Directivity Theory

Almost every laboratory engaged in applications of subsurface sound gave some attention to analysis of the directional patterns of sound radiators. The primary objective of the studies was to provide a means for eliminating the spurious sound radiation characterized by minor lobes in the directivity pattern. Methods for control of the directivity patterns were found through variation of the spacing of uniformly excited transducer elements, variation of the vibration amplitude of uniformly spaced transducer elements, and variation of configuration of arrays of uniformly vibrating elements. Specifications were established for producing directivity patterns of any degree of sharpness and freedom from minor lobes, provided the surface of the radiator could be excited according to any prescribed pattern of phase and amplitude. These mathematical conditions had a physical counterpart in the construction of transducers as arrays of small stacks of thin laminations whose individual excitation could be controlled in accordance with the theoretical requirements. One typical transducer constructed on this basis was designated SPEP and exhibited an excellent directivity pattern as well as the high efficiency characteristic of the laminated stack construction.

Theoretical consideration was also given to the formation of sharply directive sound beams by multielement cylindrical arrays of transducer elements. Proper specifications for the distribution of amplitude and phase among the elements of the array were found and relations were established for the conditions under which the directive patterns so formed could be caused to rotate about the axis of the array without distortion by suitably modulating the amplitude and phase of the excitation of the individual elements. In order to solve the mathematical problems involved in these analyses, several mathematical functions were tabulated over extended ranges and new results were obtained for the behavior of a radiating line element located in a pressure-release baffle. These results were utilized in the design and construction of magnetostriction transducers for use in scanning sonar systems.

9.1.3 Pilot Plant Facilities

One element of research work in magnetostriction transducer design which became apparent during the wartime research program is the fact that a sizable pilot plant must be provided to build the experimental models required for test purposes. In some cases this need arises from the fact that units must be constructed at substantially full scale in order to duplicate the conditions of water loading, while in other cases a significant factor in the performance of the final model is represented by the incidental elements such as bonding cements whose characteristics cannot be adequately represented in small-scale models. For transducers of the type encountered in these

investigations such pilot plant facilities must include punch press equipment for handling nickel laminations, rolls for strip stock, annealing, impregnating and baking ovens, and equipment for casting plastics. In addition the electrical measurement equipment for observing the performance of transducer models demands the highest order of experimental skill in order to obtain reproducible results. For these reasons, a program of research in magnetostriction is not to be entered into lightly or without adequate resources. It may be that this feature would merit special consideration in connection with Federal support of further fundamental research in this field.

9.1.4 Remaining Problems

In spite of the gratifying results of the Division 6 research program on magnetostriction transducers, a great deal of work remains to be done in this field. Like all research programs, this one uncovered many new problems for each one solved. A few of the possibilities for further development in this field may be mentioned. Most of the transducer designs that have been studied relate to vibrating systems of a single degree of freedom. In electric transmission networks and in other electroacoustic problems, it has been possible to improve the performance of the system by introducing, in a helpful way, additional degrees of freedom. The additional parameters afforded by such systems make it possible to provide for extending the frequency range of uniform response. Further study could profitably be devoted to such wide-range transducers.

In the field of magnetostrictive materials there is still room for improvement of the factors which increase the tightness of the coupling between the electrical and mechanical circuits and for further reduction of the eddy current losses. In other applications of iron-nickel alloys, eddy current losses have been drastically reduced by using the material in a finely powdered form embedded in a suitable binder. It was only possible to try one experiment involving magnetostrictive materials in powdered form. This experiment gave negative results for unknown reasons but it would seem worth while to pursue the matter further. Additional progress in improving the magnetostrictive properties of available materials must wait for improved understanding of the fundamental physics of the ferromagnetic alloys.



FIGURE 1. Partially assembled HP-35 magnetostriction transducer showing use of preassembled laminated-type elements and wiring.

9.2 PIEZOELECTRIC TRANSDUCERS

The very diversified uses to which sonar was put during World War II have required the development of wide varieties of transducers. Thus sonar devices have been made for listening, where their function is to make possible the perception of noisemaking objects such as a ship's propellers or the enemy's sonar gear; for echo ranging, to detect the presence of submarines and other objects; for sounding, to measure the depth of the water; for mask-

ing, to interfere with the performance of the enemy's sonar; for decoying, to make sounds and noises which will mislead the enemy. A transducer is needed in every such device to convert electrical impulses into sound waves. With sonar devices ranging from large permanent installations on ASW ships and submarines to small expendable countermeasure devices, it is clear that a considerable variety of transducer designs are needed. These designs are frequently circumscribed by factors other than electromechanical efficiency and call for much ingenuity in their conception. Such ingenuity naturally must rest on a strong body of fundamental physical knowledge of the factors influencing the performance of all components of a transducer.

Although the word, transducer, by its Latin derivation may properly be used to describe any device which converts energy of one type into some other type, we shall here limit out attention to the conversion from electrical to acoustical energy and vice versa. The reasons for doing this relate to the great flexibility with which an immense variety of controlled signals may be made by electrical means, together with the analytical ability of electrical receiving circuits. Every transducer must contain as an element of its structure one part, called the motor, which can convert electrical energy into acoustical (mechanical) energy and back again. This conversion has been accomplished in several ways: electrodynamically, as in the conventional radio loudspeaker; by the magnetostriction effect as described in the previous section; and by the piezoelectric effect.

9.2.1 Piezoelectric Materials

It was toward the end of World War I that Professor Langevin in France suggested the use of piezoelectric crystals for the motors of receivers and generators of supersonic waves. This marked the first commercial application of piezoelectric materials and was followed shortly by the development of crystal frequency-control devices, crystal filters, etc. Most of the research in the period of peace was devoted to these latter and only a little to the Langevin oscillator.

Piezoelectric materials are crystals which, when compressed in particular directions, accumulate electrical charges on certain of their surfaces. When an electrical field is established across these latter, the crystal expands or contracts in certain directions. The most common of these substances are quartz, Rochelle salt, and ammonium dihydrogen phosphate ($NH_4H_2PO_4$). The first occurs naturally in certain parts of the world while the last two may be grown synthetically. The properties of a crystal are different in different directions. Consequently, to describe them, one must refer to certain natural directions in the crystal, which are called axes. For the crystals just mentioned only three axes, called X, Y, and Z, are needed.

Quartz Crystal

Imagine a slab cut from a quartz crystal so that the X direction is perpendicular to two flat parallel faces. If electrodes, such as pieces of tin foil, are attached to these faces, we should find that positive and negative charges would accumulate on the electrodes when the crystal was compressed by a force in the X direction.

Langevin made the first sonar transducer by cementing a mosaic of X-cut quartz crystals between two heavy steel plates which also acted as electrodes. On impressing an oscillatory voltage to the plates, the alternate extension and contraction of the quartz caused them to move in unison. By choosing the frequency of the oscillatory voltage to be equal to the natural frequency of the mechanical vibration of the quartz-steel sandwich, the mechanical oscillation could be made great enough to radiate an intense beam of sound when placed in water.

Rochelle Salt Crystals

Langevin's sandwich became the prototype for the very successful ASDIC transducer developed by the British Admiralty. A similar unit was developed for the U. S. Navy by the Naval Research Laboratory, but since the demand for quartz in the communication field was so great and since most quartz must be imported into the United States, an early effort was made to design American transducers around a more readily available material. The

success of the Brush Development Company in growing large flawless crystals of Rochelle salt soon suggested the use of this material in place of the rarer quartz.

Rochelle salt has a number of usable "cuts." If a slab is cut from a crystal so that the faces to which electrodes are to be applied are perpendicular to the X axis and the other edges are parallel to the Y and Z axes, we shall find that the application of an electric field in the X direction causes the slabs to distort so that one diagonal of the rectangular plate shortens while the other lengthens. This type of motion is of little use in sonar so the plate is cut at 45 degrees to the Y and Z axes. In this case the motion will be either extension or contraction. A similar piezoelectric bar may be cut perpendicular to the Y axis giving a 45-degree Y-cut unit. A cut which makes equal angles to all three axes is known as an L cut and has a thickness vibration characteristic similar to X-cut quartz though little use has been made of it so far.

ADP Crystals

Rochelle salt has many disadvantages. It contains water of crystallization which makes it difficult to handle and also seems to limit the amount of power which may be applied to it. At about 55 C it decomposes. In 1943, the Brush Development Company introduced a new piezoelectric crystal which came to be called ADP (ammonium dihydrogen phosphate). ADP is usable as a 45-degree Z-cut crystal. It has no water of crystallization, decomposes at 190 C, and is usable up to about 130 C. In very short time, this material was available in sufficient quantity to replace Rochelle salt, so that now, with a few exceptions, all new transducers are being designed around the better properties of ADP.

By 1940 only a few actual crystal transducers had been developed. The best of these was the Navy's JK listening hydrophone and its QB echo-ranging transducer. These were designed by NRL and the Submarine Signal Company. These units employed crystal arrays composed of 45-degree X-cut Rochelle salt. They were good transducers and served as examples of skillful design practice for some time.

9.2.2 Need for NDRC Program

When NDRC first began to work in the field of underwater sound it was not immediately realized that basic transducer engineering had yet to be established. A contract was entered into with BTL to design and build transducers for calibration uses. The Brush Development Company had also developed a series of useful calibration hydrophones. It was not until the principal central laboratories came to recognize that the commercial companies were not in a position to design transducers quickly to meet definite specifications that transducer research groups were built up. These groups learned that the closely related fields of piezoelectricity and elasticity had not been adequately developed, in an engineering sense, to meet the requirements of war.

All the three central laboratories set up transducer groups and apportioned work among them. Thus HUSL and CUDWR did much work with magnetostriction units but very little with piezoelectric units. UCDWR on the other hand dealt mainly with piezoelectric transducers. Operating principally under direct Navy contract, both the Brush Development Company and the Bell Telephone Laboratories [BTL] also did notable work and the OSRD laboratories profited by the free exchange of information with them.

9.2.3 UCDWR Program

As an example of the type of research which was carried out in this field during World War II, the following description of the work done by the group at UCDWR is given. The transducer laboratory at UCDWR had its genesis in the need for transducers with which to carry on its work. At the beginning, several standard Navy units (magnetostriction) and a number of crystal units made by Brush were available, but it was soon realized that the limited performance inherent in these transducers was seriously handicapping progress and the need for hydrophones and projectors with particular characteristics became more acute.

Because of the shortage of qualified personnel in the field of crystal physics and its offspring, transducer engineering, a cut-and-try method of design was used not only by UCDWR but by most other workers in this field. The practice at UCDWR was to design a transducer as well as experience and empirical data would permit and after making measurements on it, modify the design to bring its performance closer to that desired. This method of design is still being generally followed but design approximations now come much closer to specifications.

Analysis of Vibrating System

A piezoelectric transducer is a very complicated vibrating system. A thorough realization of this is essential to the development of engineering practices. It had always tacitly been assumed that the crystal bars vibrated longitudinally with a frequency which depended only on the crystal length and the thickness of the backing plate to which the crystals are often cemented. This is only true when all dimensions perpendicular to the vibrating dimension are vanishingly small. This means that such a simple assumption would apply to a needle-like crystal attached to a needle-like backing plate. A single crystal of finite dimensions will actually have many other modes of vibration in addition to this simple one and the coupling between such modes has great influence on the output of the crystal at different frequencies. One of the most useful properties of crystals is the fact that they are not sharply resonant and a single crystal will radiate an appreciable amount of energy at frequencies far away from its resonance. However, when the frequency is close to the resonant frequency of some other mode of motion, this mode may be excited and the energy may not be radiated. In addition to coupling between many vibrational modes within the crystal itself, there is similar coupling with the backing plate, the case, various cavities, etc.

The multiplicity and complexity of these often make it seem as though a devilish intelligence were at work seeking malevolently to introduce irregularities in the performance of the transducer. Remedies for such irregularities within the operating band are often tantalizingly difficult to obtain, since the offending vibrational modes are often flexural and torsional. However, as one's understanding of the ways in which such parasitic vibrations are stimulated grows, one's ability to diagnose them and apply design remedies increases.

This problem was attacked by UCDWR in two ways. A thorough study was made of the complex vibrations of a crystal and mathematical methods capable of dealing with them were developed. These studies have enhanced our understanding to a point where fairly accurate predictions of vibrational characteristics may be made. A further study was made experimentally in a search for an answer to the question of why the directional patterns of transducers often failed to agree with theory. A small probe microphone with which one could explore the variation of velocity over the vibrating face of a crystal array showed that such an array does not move back and forth like a piston but has great irregularities. These are particularly bad in the case where the crystals are cemented to a backing plate. Moreover, a single crystal is shown to vibrate in very complicated ways, depending on its dimensions and the amplitude of the driving force. Applying this method to a backing plate or bar has led to a better understanding of the torsional and flexural vibrations of these driven components. A backing plate is simply a slab of some material, usually with parallel faces. To it are cemented the array of crystals so that the composite becomes the vibrating motor of the transducer. It is usually assumed that the backing plate stretches and contracts only in the vibrating direction. Actually it bends and twists and writhes as though possessed. These parasitic motions sap energy from the desired motion and thus impair the efficiency of a transducer and spoil its beam pattern.

Although these studies have served to expose many of the pitfalls which a design may experience, they do not point uniquely to methods of avoiding them. In practice such "design adjustment," as it has been called, leading to complete or partial elimination of undesirable properties is still a matter of educated guesswork. The latter benefits greatly from experience and a body of empirical knowledge. Fre-

quently slotting the backing plate, breaking it up into a number of isolated sections, or altering the location of the crystals on the plate will serve to change the frequency of parasitic oscillations so that they cease to be troublesome.

The simple theory developed for slender crystals did not take account of frictional loads on faces other than the radiating ends. Thus an array of crystals is imagined as moving back and forth like a piston. In an actual transducer, since crystals are soluble in water, the motor is usually in a box filled with some liquid such as castor oil, which serves to transmit the sound to the sound window (usually rubber) and also to insulate the electrodes from each other. The motion of the crystals is such that the radiating ends must push the viscous castor oil aside while the sides slip through it. Both of these actions absorb energy and, since they contribute nothing to the radiated sound, tend to reduce the efficiency of the transducer. When the spaces between the crystal are too small, the energy absorbed in moving the oil in and out of such narrow crevices can be very large. Many of these matters are not obvious at first glance because of the minuteness of the motions which we are discussing. Actually the motion of a crystal in a transducer is not much greater than a wavelength of light and one's failure to recognize many obscurities in transducer performance are traceable to this fact.

Equivalent Circuits

The timely publication of, "Electromechanical Transducers and Wave Filters," by W. P. Mason of BTL in the spring of 1942 has been of inestimable value to workers in this field. Mason developed and treated an equivalent circuit for a piezoelectric transducer which aids and simplifies the task of dealing with a practical design. The idea of an equivalent circuit is old and useful in applied acoustics; this is particularly so in the case of electromechanical transducers where a mechanoacoustic circuit is connected to an electronic circuit. In practice the two influence each other, and in all treatments the circuit and the mechanical portion must be considered together. Use is here made of the formal mathematical similarity between the rôle played by masses, springs (compliances), and friction in mechanical systems to those played by inductances, capacities, and resistance in electrical circuits. Mason gave a circuit for piezoelectric crystal which is accurate for a long slender crystal, either free or on a similar backing plate and which is loaded only on the ends. The load considered is normal and no account is taken of tangential or rubbing loads. The Mason circuit is one to which all more complicated circuits must reduce when applied to this particular case. It is, therefore, a check to be applied to other circuits. Dr. Glen Camp of the UCDWR group sought to extend this to practical transducers and evolved a circuit which successfully takes into account the finite size of actual crystals, loading on all crystal faces, tangential as well as normal, and the coupling between various modes of vibration in so far as they are practically important. As it must, Camp's circuit includes Mason's as a limiting case.

Even though an equivalent circuit is of very considerable aid in simplifying design calculations, it still involves long and tedious work. A small group of computers was set up at UCDWR to make such calculations. In addition it has been possible in many cases, by suitable juggling, to devise equivalent circuits whose components are real. It is then possible to construct the circuit from resistances, condensers, and inductances which may be found in the stock room. By making electrical measurements on such a circuit, one may quickly make design adjustments, simply by turning knobs. One has then a computing machine of great flexibility and convenience. This device, which has been called the LCR simulator, has proved its usefulness as a design aid.

9.2.4 Construction Techniques

Techniques used in the construction of transducers have undergone considerable development. This was partially the result of the need for standardization in order that some control of quality could be exercised in production. The diversity of sizes and shapes of transducers also required great flexibility in assembly which in turn required variety in technique. Much work

has been done on cemented joints, on the type of cement, and the baking and conditioning procedure. An interesting case arose when it was noticed that ADP would tolerate the temperatures required to use the Chrysler Cycle-Weld process. It was thus possible to bond crystals to rubber so that either the rubber or the crystal ruptured before the bond failed. This technique permits one to attach crystals directly to the rubber sound window and elimi-

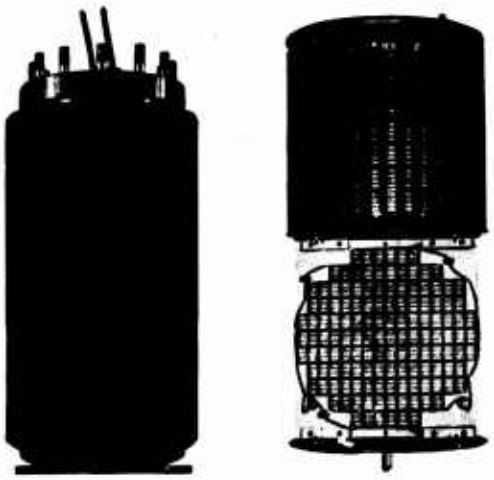


FIGURE 2. The CJJ 78256 QLA transducer showing the crystal motor assembly.

nates the need for the castor oil which usually permits the transfer of sound from the motor to the water. Such transducers obey theoretical predictions much better than those of conventional design. Methods have been found for strengthening the rubber windows so that such Cycle-Welded units give promise of being as rugged as those made otherwise.

9.2.5 Contributions by Other Groups

Much very excellent work has been done during World War II by other agencies in addition to OSRD. Most particularly, those responsible for the continued availability of crystals have contributed indispensably to the furtherance of transducer engineering. The Brush Development Company had, before World War II, designed and built a number of plants for growing Rochelle salt crystals and had set aside a large stockpile of crystal bars. The patriotic and progressive attitude of A. L. Williams and W. R. Burwell of that company gave the country the reserve of crystals needed for the heavily increased demands occasioned by war. Their continued support of fundamental research in crystal physics and physical chemistry led to the introduction in 1943 of ammonium dihydrogen phosphate (ADP) by Dr. H. Jaffe and his associates. The realization of the usefulness of this new material led to a rapid development of growing methods so that before the end of World War II, plants at the Brush Development Company and BTL were in adequate production. A pilot plant for further study and control of ADP was constructed and put into operation by NRL.

In addition to their work on transducers for calibration work, BTL entered into contract with the Navy for the development of improved sonar systems. During the course of this work they designed many excellent transducers and supplemented them with studies of a fundamental nature. A BTL group did valuable work on crystals, cements, electrodes, oils, rubbers, and nearly every other phase of transducer engineering. The excellence of their work is nowhere better shown than in performance of their Navy projectors.

The Sound Division of NRL under Dr. H. C. Hayes was very active both before and during World War II. Their attention was particularly focused on the design of new gear and on the basic study of crystal vibrations. NRL has differed from UCDWR in the philosophy of this latter work, preferring the direct solution of the differential equations, with suitable boundary conditions, to the representation of the problem by an equivalent circuit. It is highly desirable that both methods be followed, the one to act as a check on the other. The direct method is somewhat more cumbersome to use but, when aided by the comprehensive charts recently published by W. J. Fry, J. M. Taylor, and B. W. Henvis ("The Design of Crystal Vibrating Systems") of NRL, can probably compete for accuracy and speed with calculations based on the equivalent circuit. They lack, however, the convenience of the LCR simulator.

9.2.6

Summary

A number of related lessons have been learned from the concentration of work on piezoelectric transducers during World War II. The full appreciation of the position occupied by calibration stations in transducer engineering has come somewhat slowly. Before World War II there was no centralized reference station. Everyone calibrated his own transducers. In 1942, Division 6, NDRC, established the Underwater Sound Reference Laboratories [USRL], described in Section 9.3. The USRL undertook the task of making frequent checks on the standard hydrophones and projectors used by all other activities, and there was frequent exchange of other transducers so that some idea was gained as to the reproducibility of the results of one station by another. This open and friendly self-criticism served to evaluate the state of the art of transducer calibration. It is clear to all who have had much contact with transducers and their calibration that there is much room for improvement in this direction, and a very healthy step would seem to be the proposed establishment of the U. S. Navy Underwater Sound Reference Laboratory under the Office of Research and Inventions.

A second lesson relates to the missionary work which transducer engineers have found it necessary to perform among their colleagues, the electronic engineers. A piezoelectric transducer is a most unusual circuit element, by ordinary standards. The problem of matching a circuit to its transducer is complicated by the fact that it is not yet possible to design a transducer with definite specifications. It is necessary that the specifications be established early in the development of a system and that the transducer engineer come as close as he can to meeting them. If, as often happens, some of the elements of the specifications are incompatible with others, it may be necessary to make compensations in the electronic circuit. Thus the systems engineer may ask for a certain beam pattern (fairly easy to predict), a certain impedance (less easy), a certain response over a wide frequency band (still less easy), and the whole thing to be within certain dimensions and weight (usually too small!). The transducer engineer finds that he can, in a finite time, satisfy all the conditions except, say, the frequency response. The systems engineer will then try to equalize the output of his power amplifier to compensate for the slope of the frequency response of the transducer. Such hand-in-hand work has proved its value and an electronics engineer who has been indoctrinated into the vagaries of the transducer can usually greatly assist the transducer engineer in producing the desired end result.

The final lesson is derived from experience with the manufacture of transducers. Such apparently minor changes in technique materially affect the performance of a unit, that significant differences are often found between laboratory-built and manufactured transducers. It is important, then to assign a transducer engineer to liaison work with a manufacturer who is setting up to produce a particular unit and to follow this with periodic examinations of his product.

Taking stock of the accomplishments of piezoelectric research and its offspring transducer engineering, it is seen that the war period has led to a great improvement in the realization of the great complexity of the couplings between various modes of vibration, not only of the crystals themselves, but of the backing plates, cases, and all other components of the transducer. Improved methods of treating the elastic problems mathematically have eliminated much of the guesswork from design. This elimination is not complete and the final stages of a design are still empirical. A better understanding of the nature and origin of parasitic vibrations, together with a similar comprehension of the factors contributing to energy dissipation, have materially raised the overall efficiency of transducers. The accuracy of current calibration methods does not permit very good measurement of efficiency but in many specific models it apparently approaches a value of 100 per cent. Many small developments in cements and other attachments to the crystals have improved construction methods and reduced variability between "identical" units. The transducer engineer may proceed more surely toward the design of a new and unique unit with greater promise that he will

succeed in meeting its specifications. A large measure of these improvements came at a sufficiently early date so that transducers which were used in combat were greatly improved over the prewar units.

9.3 STANDARDS AND CALIBRATION MEASUREMENTS

Whenever a surface vessel detects a submerged submarine and destroys it, whenever an acoustic mine functions properly, whenever an acoustic torpedo strikes its target, part of the success is due to a great mass of precise and detailed measurements of underwater sound.

During an actual attack, these measurements are completely forgotten. This is quite proper. When a destroyer suddenly makes contact with an unidentified submerged target, the sonar officer rarely has time to consider the exact number of decibels emitted by his projector. But without these data, obtained many weeks or months or even years before, it is doubtful that his attack could be made and it is almost impossible that it could succeed.

These measurements, carefully standardized and intelligently applied, have been found essential in almost every phase of sonar work from the very first stage of development through the training of operators and on to the time of actual attacks. They have been used effectively during the research stage and during the development of preproduction models. Here experience has proved that significant progress is greatly accelerated when quantitative measuring techniques are available and when reliable physical data, expressed in the terms and units standard for the art, can be obtained. They have been useful in full-scale production and in installation. They have been particularly valuable in testing and monitoring sonar equipment, in order to determine whether or not the gear is functioning properly.

The groups of workers who coordinated their efforts in the field of sonar have found that these measurements, calibrated and presented in terms which are standard for all underwater sound studies, offered not only a yardstick but a language of comparison. Without this material, they found, it was difficult to use existing equipment at its maximum efficiency or to design better equipment.

At the outset of World War II, it was apparent that these measurements would be needed and that facilities, equipment, techniques, and men would be required to obtain them. In 1941, when NDRC undertook to cooperate with the Navy in underwater sound research and development, these requirements were promptly and carefully considered. In view of the urgent needs which were already evident, the rapidity with which subsurface warfare operations were expanding, and the probable directions of this expansion, an intensive program was clearly indicated. It was impossible then to forecast all the types of acoustical devices that would be needed in the constantly changing military situation, and accordingly the scope of the program was made as broad as possible. NDRC decided to make full use of peacetime developments in acoustics and electronics, of the current practices in industry, and especially of the experience gained by U. S. and British Navy laboratories during the years between the two World Wars.

The overall objective was obvious: Means and methods must be provided so that the scientists and the engineers could make quantitative measurements and make them with sufficient accuracy to fit the needs that were certain to arise.

By the end of the war, not only had this broad objective been attained, but in addition, other significant goals had been reached. Instruments and techniques required for precision measurements had been developed. Standard terms, basic units, and reference points had been established and accepted so that the results of all quantitative measurements could be accurately and conveniently expressed. Accuracy had been improved to the stage at which sound in water could be measured at least as precisely as it heretofore could be measured in air.

In short, it had become possible for the scientist and engineer to make quantitative studies of underwater sound phenomena, to measure the performance of underwater acoustical

vices, and to express the results in terms that both could understand. Thus, in this field of research and development the mission had been accomplished.

9.3.1 Major Objectives

When NDRC began its work, the acoustic gear used by the Navy consisted principally of listening hydrophones and simple types of echo-ranging sonar. Even with this early equipment, there were no satisfactory devices or methods to measure their operation. No single type of underwater acoustical device was sufficiently reliable to serve either as a standard hydrophone or as a source of sound. In fact, in many instances, microphones or loudspeakers designed for air acoustics were hastily adapted to subsurface applications, applications for which they were wholly unsuited. To complicate this problem still further, radically new types of gear were rapidly developed by the Navy and NDRC and these required testing facilities which had hitherto been totally nonexistent.

It was necessary, therefore, that an entirely new array of testing devices and techniques be developed and that they be placed in service so quickly that the development and testing of sonar equipment would not be delayed.

Even though a rapid expansion in sonar had been expected, the speed of this expansion and the directions it followed were almost startling. At the close of World War II, acoustic systems of the greatest versatility and efficiency had been developed and put into use, and still others were under development. At each stage in the evolution of these devices, corresponding improvements were urgently required in both the standardizing techniques and the instrumentalities needed for precision measurements.

The introduction of new enemy weapons made this problem even more acute. For example, the sudden appearance of the German acoustic torpedo made it imperative to develop and improve acoustical countermeasures. These countermeasures required improved methods for their measurement and evaluation, including the introduction and development of methods for the accurate measurement of very short acoustical pulses.

When it became apparent that newly designed German submarines were able to dive to very great depths in their escape tactics, changes were required in sonar detection gear. The resultant development of new depth determining sonars had to be paralleled and occasionally preceded by corresponding improvements and extensions in calibration methods suitable for their study.

As a consequence of these and many other events, the operations of NDRC had to be as elastic as possible. In 1941, the initial requirements for the program were written in terms of the equipment the Navy was using and developing at that time. Laboratories were organized, measuring equipment was designed, and investigations were laid out accordingly. But, as this equipment was changed or replaced by newer and different gear, the work of NDRC had to be modified. These modifications were so extensive and the need for them so great that it was necessary for NDRC's measuring and standardizing facilities to be altered and enlarged continually. The development program for the testing equipment and improved standards had to be planned so that the Underwater Sound Reference Laboratories would not merely be ready to work on new types of equipment soon after they had been developed but would actually be prepared in advance to make measurements on these radically new types as they appeared. Only in this way could NDRC meet Service needs and properly serve the war effort.

9.3.2 Procedures

Guided to a considerable extent by the experience that had been built up by the Navy in underwater sound and by the work of universities and industry in air acoustics, NDRC attempted to reach its various objectives by research and development work along both theoretical and experimental lines. By keeping in constant touch with the Services and with industrial laboratories which were developing new equipment, NDRC and its contractors were always able to anticipate well in advance the kind of precision measurements which they would be called upon to make on short notice.

The theoretical program was directed in part toward the definition and adoption of standard terms and units for expressing the results of underwater sound measurements. The terms and units were chosen with the aid of the Hydrophone Advisory Committee appointed for this purpose by the Coordinator of Research and Development of the Navy. In formulating its recommendations, this committee made use of whatever definitions and terminology of air acoustics were applicable to subsurface sound. Particular attention was paid to terms and definitions that had been adopted by the American Standards Association. In keeping with the general trend of terminology in air acoustics, units referring to a decibel scale were expressed in terms of a pressure level rather than an energy level. The opinions of those actively engaged in this work during the war were ascertained before decisions were reached. The definitions and terms finally adopted by the committee have been recommended by the Navy for formal adoption by the American Standards Association.

Theoretical work together with necessary experimental investigation was also directed toward the specification of optimum testing depths and distances and toward a schedule of computation procedures so that the test data could be accurately and rapidly prepared in report form.

9.3.3 Facilities

The experimental work in this field was conducted largely by USRL, which operated during World War II on a contract between OSRD and CUDWR, and BTL, which operated on the basis of a contract negotiated between OSRD and the Western Electric Company.

A great deal of valuable assistance was obtained from the Brush Development Company, the RCA Laboratories, the Submarine Signal Company, the Massachusetts Institute of Technology Underwater Sound Laboratory, HUSL, and UCDWR. With the cooperation of these and other groups, work began immediately on the development of standard hydrophonic instruments and measuring equipment and on the improvement of all experimental techniques. To a considerable extent NDRC looked to BTL to develop instrument standards and measuring equipment for the program. This work continued throughout World War II, with a continual evolution of instruments and measuring equipment and finally reached the development of instruments superior even to those previously used in air acoustics. As these improved devices were developed and accepted, every effort was made to obtain them in sufficient quantities for use by other NDRC facilities and by Navy ships and shore installations.

It has been emphasized that this general program of precise measurement was constantly faced with changing and ever increasing requirements. To meet this challenge, it was found necessary to make available four complete calibration systems, two at Mountain Lakes, New Jersey and two at Orlando, Florida, each of which could cover the frequency range from 20 to 150,000 c. In addition, powerful amplifiers able to deliver more than 1 kw of undistorted power were provided for testing work at each station in order to handle the more powerful subsurface acoustic gear which soon appeared.

Mountain Lakes Station

At the Mountain Lakes station, three additional test systems were provided for special work. One of these was a low-frequency system which operated over the range from 2 to 100 c and which was used to calibrate small hydrophones for use in acoustic mines. These units were calibrated in a testing tank in which variations of temperature and pressure could simulate those which would be met in actual operational use. The second was a large pressure tank and calibration system designed and constructed for calibrations up to a water pressure of 300 psi on complete submarine sonar systems. It made possible the evaluation of the acoustical performance of submarine sonars under operating conditions corresponding to deep submergence. The third was a high-frequency system for calibrations up to 2.2 mc and was designed for use either in the open water of the lake or in a specially constructed acoustical tank. This high-frequency system

was valuable not only in the calibration of small object locators operating in the megacycle frequency range but also in model studies on the echoes reflected from submarines. In this latter work, the wavelength of the sound was scaled down by a factor of 60/1 and the model of the submarine was built to the same reduced scale. It is felt that, for use in the study of models, this system presents exceptional opportunities for further Navy investigations.

The frequency range over which these various calibrations were made is in itself an indication of how vastly the measurement program expanded. One of the first decisions made by the Navy and NDRC was the choice of this frequency range. In the beginning, it extended only from 100 to 50,000 c. At the close of World War II, it extended from 2 to 2,200,000 c.

During this period, the powers of the sound sources and the sensitivities of the hydrophones were continually increased. In general, the guiding principle for the design of calibration instruments was that the acoustic power projected into the water for test purposes should equal the power used in actual operations; in the same way, hydrophone sensitivities and efficiencies should be increased to the point at which their effectiveness was limited only by the background noise encountered in their tactical use.

Simultaneously, provisions were made for studying the effect of temperature and pressure conditions and other pertinent physical factors actually encountered by sonar gear operating in the ocean. Thus, facilities were available for testing equipment at any temperature from arctic to tropical and at any pressure from that at the surface of the water to that at hundreds of feet below it.

Perhaps the most important decision underlying basic procedures at the various test stations was the original one to conduct routine measurements in small fresh water lakes where freedom from tides, waves, and currents prevented interruption of regular work schedules and the low background noise minimized inter-

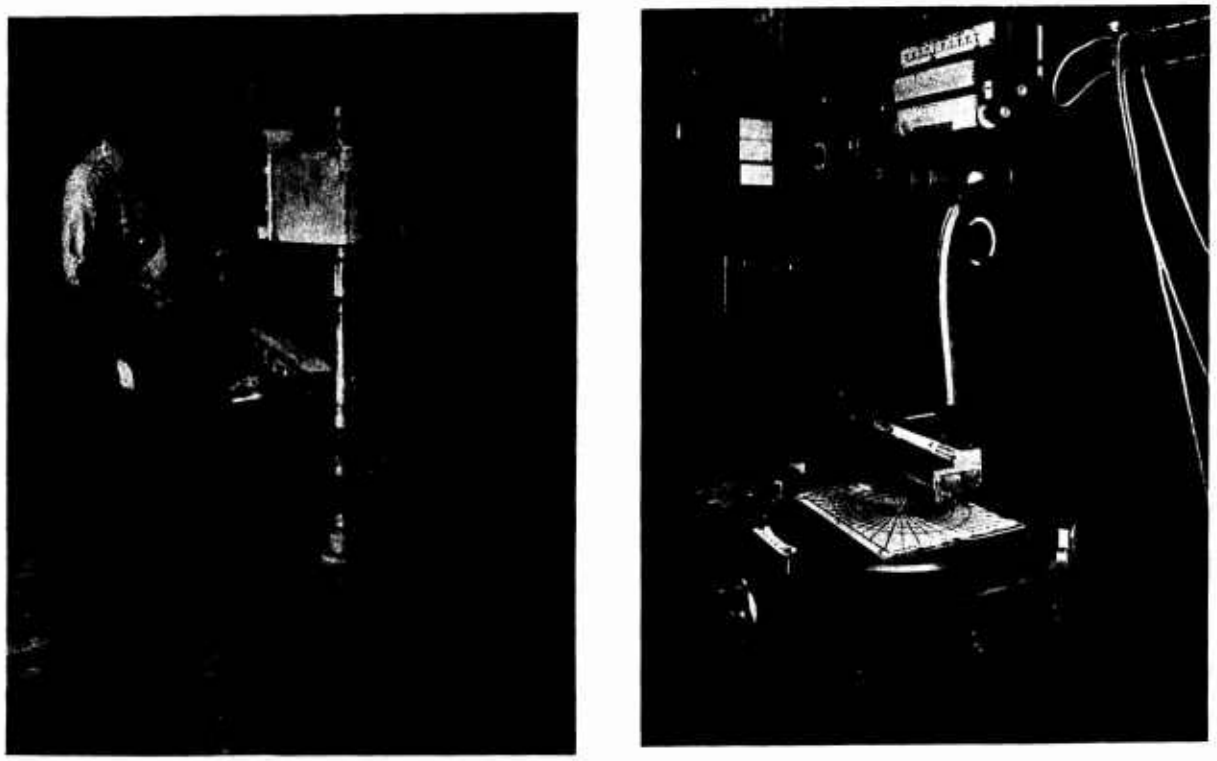


FIGURE 3. Transducer mounting assembly and polar recorder used for making the transducer directivity response measurements.

ference with the most delicate calibrations. Once this decision had been reached and the frequency range selected for the tests, it was then relatively simple to set up the requirements for the first standard hydrophones and procedures, the specifications for the auxiliary electrical and mechanical test equipment, and the techniques and routines for measurement and calculation.

9.3.4 Results

From all this work has come a wealth of information and new equipment which not only had a significant effect on the outcome of World War II but also may confidently be expected to benefit science and industry in the future.

The improvements in quantitative measuring and standardizing techniques, forwarded at once to all authorized organizations, made possible the production and use of greatly improved sonar equipment. Production testing methods were applied in sonar factories and made possible the control of quality to an extent never before realized on acoustical gear. With the newest and best techniques made available quickly to Navy groups, a high degree of accuracy was installed into practically all acoustical measurements made at sea and this was reflected in the increased efficiency of sonar equipment in combat. With the aid of CUDWR and USRL, acoustical measuring sets were supplied to measure and help in the control of noise produced by American submarines when operating in combat areas. The acoustic monitor developed at HUSL made it possible to check the acoustic operation of the sonar on every destroyer while it was at sea.

High on the list of the classes of acoustical gear which were calibrated and tested by USRL were echo-ranging and scanning sonars, shipboard and submarine listening systems, acoustic elements for the radio sono buoy, harbor defense installations, acoustic torpedoes, acoustic decoys and other countermeasures, and instruments for quality control. The wide applicability of this standardization work may be indicated by the fact that the measurement methods developed here were useful not only in developing these improved instruments, but were also suitable for important checks on their operation at sea.

In addition to these purely military applications, the work of the various NDRC groups may well find many important uses in industry and in the peacetime Navy. These include both instruments and techniques which have been made available for precision measurements.

Many types of acoustical work will benefit by the use of such new piezoelectric crystals as ammonium dihydrogen phosphate [ADP], which were brought to the fore during wartime research. As a by-product in the development of better standard instruments, better methods were found for the utilization of the older piezoelectric materials such as quartz and Rochelle salts.

Similarly, the increased efficiency of magnetostriction devices and electromagnetic instruments, which resulted from the full utilization of new materials and from fundamental improvements in the theory and practice of magnetic circuit design, will contribute to many lines of peacetime acoustical engineering and other related fields.

Many other general applications will be found for acoustic gear with greater power-handling capacity, for equipment with wider frequency responses, and equipment which responds with high fidelity when used with very short pulses and other special signals.

Among the wide variety of new acoustical techniques perfected during World War II and available for future use may be cited the application of enclosed testing tanks in which sidewall reflections were eliminated by the use of short pulsing techniques, a method which was aided by parallel developments in the field of radar. Without such methods, a large number of calibration and factory production test procedures would have been completely impractical; with them, many future and apparently impossible goals may be achieved.

Further advances in this field will be stimulated by the inevitable improvements in sonar equipment itself. As sonar gear is changed and developed along still uncharted courses, improvements in precise measuring and standardizing will be essential. Measurements must be still more precise and standardization tech-

niques still more stringent. More complete laboratory facilities must be provided to include not only deeper fresh-water testing lakes, but also larger indoor tanks able to withstand higher pressures and to operate over wider temperature ranges. Continual improvements will be required in the standard hydrophonic instruments themselves and in the associated electrical equipment to provide higher testing powers, wider frequency ranges, and greater sensitivity.

So long as the Navy develops and expands its use of underwater sound in subsurface operations, the related field of measurement and standardization must develop and expand with it.

Chapter 10

TORPEDOES AND FLUID DYNAMICS

WORLD WAR II brought to those responsible for our naval preparedness the realization that the development of improved torpedoes was essential if we were to defeat the Nazi U-boats in the Atlantic and the Japanese Navy and merchant fleet in the Pacific. The task of providing fundamental design information leading to better and more efficient torpedoes was assigned by Division 6 to the Special Studies Group of Columbia University Division of War Research [CUDWR].

The study of the travel of projectiles in fluid media, both in the water and air, and during the critical transition from an air to a water path had already been launched by a group at California Institute of Technology [CIT] concerned with the development of a fast-sinking depth charge.

These two research programs, although independently administered, had considerable areas of mutual interest. The fluid dynamics research work soon became concerned with many types of projectiles including torpedoes, with special emphasis on the development of an aircraft torpedo which could be launched from high altitudes and at high speeds. And as the torpedo research work developed, the Special Studies Group was able to concentrate on the theoretical phases, depending on the CIT group for proving and testing.

10.1 TORPEDO RESEARCH

World War I had stimulated the development and design of self-propelled, self-steered underwater torpedoes. Although research and development were continued after that war, no extensive improvements had been made in the methods of torpedo launching, propulsion, steering, and charge-exploding. Torpedo development had not kept pace with the improvements in the defenses of naval and merchant vessels. At the beginning of World War II, it became apparent that a more effective and more efficient torpedo was required to fight surface and subsurface warfare.

The overall problem of improving torpedoes was assigned to Division 6, but the most pressing demand was for improvement in the performance of torpedoes launched from aircraft. Since little seemed to be known in a quantitative way about the stresses at water entry, and about the necessary characteristics of such torpedoes, it was decided to carry out fundamental research in parallel with the design and construction of experimental torpedoes.

This work involved research in problems of torpedo air flight, water entry, and underwater travel. Research was also conducted on propulsion systems and steering control.

10.1.1 Propulsion

When the division took up the problem of improving torpedo propulsion, there were three systems of power to be considered: (1) electric power from a primary or storage battery; (2) burning of fuel to drive a turbine or engine; (3) utilization of some form of jet propulsion.

The division was not primarily responsible for any substantial research or development of jet propulsion, although it did to some degree advise and furnish test facilities to organizations other than its contractors. Therefore, jet propulsion will not be discussed in this volume.

In investigating the other two systems, theoretical studies were combined with practical engineering skill to work out the best combinations.

An analysis and assessment of electric and turbine propulsion showed that electric propulsion offers certain advantages. An electrically driven torpedo leaves no wake of surface bubbles which might be detected during approach by the target ship and offers a much reduced maintenance problem. It was found that electric propulsion had previously been restricted to certain types of torpedoes because the battery weight limited the running time or range, and the problem was to develop an electric system which would provide for longer

running time or greater range by means of a lighter battery.

The Bell Telephone Laboratories [BTL] worked on this problem and developed a primary sea-water battery, which provides a much longer range with a given battery weight. At the same time, the division designed a counterrotating motor and demonstrated its possibilities. This design not only reduced the weight necessary for providing the required power, but eliminated the troublesome system of gears necessary to drive the counterrotating propellers. With this advantage was combined the automatic balancing of the torques applied to the propellers and the consequent elimination of the necessity for careful balancing of the propellers. An analysis of the properties of the sea-water battery and the counterrotating motor indicated that this combination promises to be a highly useful solution of the battery propulsion problem. In addition to the advantages of ease of maintenance it provides an energy per unit weight equal to that of the best turbine-driven torpedoes in use during World War II. However, this system has not yet been tried operationally.

The division also conducted substantial research in the problems of engine or turbine propulsion. An investigation of existing propulsion mechanisms showed that this portion of a torpedo occupies the major part of the torpedo both in volume and in weight, and that the overall size of a torpedo is largely determined by the requirements for speed and range. Therefore to achieve maximum speed and range, with a given weight, the power plant must be as light, compact, and efficient as possible. Unlike a surface ship, a torpedo must carry not only its fuel, but also its oxidant. Therefore, the problem was to improve the efficiency of torpedo operation by designing a highly efficient engine that uses the lightest fuel and oxidant possible.

Investigation of various oxidants, such as air and oxygen, showed that they are most efficient in the form of a liquid. A liquid oxidant reduces the weight of the fuel and container by 60 per cent merely by reason of being liquid rather than gaseous. The most highly developed system was found to be one which uses liquid hydrogen peroxide as an oxidant. The investigations showed that any further improvement in the weight of fuel and its container can be translated directly into increased torpedo range, increased running time, or increased explosive charge, depending on the torpedo characteristics desired.

An extensive study of propulsion mechanisms was also made by the Navy Department and these data provide the basis for future torpedo propulsion development.

10.1.2 Air Flight

In order to improve the efficiency and effectiveness of aircraft-launched torpedoes, the division undertook a program of research and theoretical study concerning the behavior of torpedoes in the air, at water entry, and during underwater travel. These studies indicated numerous necessary improvements in design.

An investigation of aircraft torpedo tactics and the conditions under which an aircraft torpedo is launched indicated the desirable specifications. When a torpedo is launched, it usually can be observed by the target, and the target may have time to take proper evasive action. A study was made of means to make evasive action difficult or ineffective and it was found that the most difficult way would be to try to increase the underwater speed. Since the speed of travel in air is so much greater than any possible underwater speed, it was concluded that most of the distance between the point of release and the target should be covered by air travel. Advantage could then be taken of the speed of the plane and the altitude from which the torpedo could be dropped.

The problem, then, was to develop a weapon which could be launched from very high-speed planes, from high altitudes, equipped with a sufficient power plant to travel a short distance under water at moderate speed, and which would pursue the proper course at proper depth to reach its target.

Theoretical study as well as experiments emphasized that not only should the torpedo be rugged in construction to withstand the shock of water entry, but also that the torpedo must end its air travel in such a way as to make a

clean and smooth entry into the water. Experiments showed that a 15-ft horizontal drop of a torpedo might be more damaging than a clean entry from high altitude at speeds of over 200 knots. Thus, it was found that serious damage to the torpedo could only be minimized by providing for a clean water entry.

Investigations of means of achieving clean water entry showed that the torpedo must be traveling parallel to its axis at the time of the impact with the water, but this could be accomplished only by proper stabilization of the torpedo in the air.

Before the division undertook this work, the Navy had started using air stabilizers that break off on water entry. Experiments were conducted with torpedoes using no control surfaces and with torpedoes using various kinds of stabilizers. A simple cylindrical body tends to set itself perpendicular to its direction of travel. But when a large tail is added, this tendency is overcome and the torpedo then tends to travel parallel to its axis. The large tail is undesirable during the underwater run, and to solve this problem a tail of light wood was constructed, which breaks off on water entry.

In addition to the tail, other stabilizers are required to overcome certain forces working on the torpedo during its air flight, which tend to prevent it from entering the water smoothly and cleanly. A wide variety of stabilizers were tried but the most satisfactory was found to be the Mark 2-1 stabilizer combined with a drag ring, or pickle barrel on the nose. The Mark 2-1 stabilizer is a simple wooden box that is slipped over the torpedo fins and the drag ring is a short wooden cylinder that slips over the nose. According to the experiments, the combined effect of these two devices is to cause the torpedo to be stable when traveling parallel to its air trajectory.

Investigations also proved that there are initial disturbances caused by release conditions, which require some time to be damped out. Thus, it was indicated that by increasing the launching altitude, the time in which this damping action can be effected is also increased. Also, this damping effect increases with speed, so that a high-speed launching may tend to be cleaner than a low-speed launching.

While working with stabilizing appendages it was found that they are effective only in causing the torpedo axis to remain parallel to its trajectory with respect to air. If there is a wind, the trajectory with respect to air will not be identical with the trajectory as seen from the ground (or water) and it is the trajectory as seen from the ground that determines water-entry conditions.

Analysis showed that a torpedo stabilized on its trajectory and traveling with a tail wind tends to enter the water nose-down, or traveling in a head wind, it tends to enter nose-up. A torpedo traveling in a crosswind will enter with a certain amount of yaw. Although the effects of wind cannot be overcome by simple air stabilizers, these effects cannot be neglected because they affect the underwater behavior of the torpedo. The division recognized and recorded these effects, so that proper allowance can be made for them in tactical methods.

10.1.3 Water Entry

The water-entry phase of an aircraft torpedo was found to be less subject to theoretical analysis than either the air travel or underwater travel. When the division began to study the problem, almost no information was available as to the torpedo's behavior during this phase. Water-entry study is greatly complicated because of the vastly different properties of air and water, so that it was possible to establish only a more or less phenomenological description of torpedo behavior during this phase.

Tests and studies were conducted to determine the magnitude and duration of forces acting on the torpedo when it strikes the water and how these forces determine its underwater behavior. Calculations and tests were also made to determine how to control the water-impact phase by properly shaping the nose of the torpedo and to determine what effect, if any, certain torpedo appendages have on the initial underwater trajectory.

Although it was not possible to determine the exact magnitude or duration of the impact force, it was possible to calculate the total impulse associated with this force. Theoretical

analysis and tests showed that the impact force produces both a sudden change of longitudinal velocity and a sudden access to angular velocity about a horizontal axis. The change in longitudinal velocity apparently plays no significant part in determining subsequent behavior but the sudden access to angular velocity causes the nose to rise and the tail to fall, and determines whether the subsequent trajectory turns upward or downward.

It was found that after initial impact, the torpedo creates a cavity, roughly conical in shape, so that only the nose is in contact with the water. This continues until the torpedo is several lengths under the surface and during this time the torpedo is subject to a decelerating force which tends to turn the torpedo more nose-down if the torpedo is nose down to its trajectory, and therefore tends to overcome the initially produced nose-up angular velocity. If the torpedo is nose up to its trajectory, the drag force adds to the initially produced upward angular velocity. Therefore, the torpedo tail will eventually strike either the top or the bottom of the cavity. If it strikes the top, the torpedo will travel in a roughly circular path concave-downward. If it strikes the bottom, it will travel in a path concave-upward. Which path is followed depends upon the magnitude of the initially acquired angular velocity and the later angular acceleration that either adds to or subtracts from the initially acquired angular velocity. This depends on the pitch and trajectory angles at entry.

The forces producing the suddenly acquired angular velocity and the dependence of these forces on the entry conditions depend on the shape of the torpedo nose. Most nose shapes give the torpedo an upward impulse but sufficiently blunt noses give it a downward impulse. Blunt noses are rarely used on aircraft torpedoes because of the large drag associated with them, so the investigations dealt with finer shaped noses. Since the angular velocity acquired at impact depends on the nose shape, the critical pitch angle varies with the nose shape.

According to the studies, the major features of the initial underwater trajectory are apparently determined before the cavity closes, so that these features are not influenced by movement of rudders or elevators and consequently are not dependent on the depth-control mechanism or the steering device. Of course, these mechanisms are important in determining trajectory after the cavity closes, when the normal hydrodynamic forces begin to act. The hooks to the right or left, as well as the maximum depth of dive, are influenced by the behavior of the depth mechanism, the extent to which the elevators are reduced in effectiveness by a shroud ring, and the extent to which the torpedo heels over.

Investigation and analytical studies showed that if the steady-state hydrodynamic constants of the torpedo are known, the trajectory after collapse may be roughly calculated.

On the basis of such a study it was possible to predict with some degree of certainty the initial underwater behavior of the Mark 13 torpedo. It was thought desirable to find some shape of torpedo less sensitive than that of the Mark 13 to pitch angle and yaw angle at entry, and analysis indicated that it is quite possible that a proper combination of nose shape and large tail structure may overcome this sensitivity. However, at the present time there is no convincing evidence that any shape is significantly better than that of the Mark 13 or Mark 25 torpedo as a compromise between the requirements for water entry and those for underwater travel. If tail and nose appendages could be discarded after water entry, better characteristics could be secured.

10.1.4 Underwater Run

A torpedo is equipped with a steering and depth-control mechanism to enable it to travel on a prescribed course at a fixed depth. Since it may have to travel for a considerable distance underwater, the steering performance is of importance in determining whether or not the torpedo hits the target. Depth-keeping performance is important because it is necessary to set the torpedo to strike a ship below the armor belt. For these reasons, it was necessary for the division to investigate and study the behavior of a torpedo underwater, and to design

steering and depth-control mechanisms which would function effectively.

The division's studies led to a fairly satisfactory theory of torpedo control. It was found that the behavior of a torpedo is the result not only of the control mechanism, but also of the hydrodynamic characteristics of the torpedo body. These two things can be modified more or less separately, and the theory shows that the necessary properties of the control mechanism can be fairly well specified when the hydrodynamic behavior of the torpedo is known.

The division studied torpedo models in water and wind tunnels, and full-scale bodies in towing tanks, in order to determine torpedo properties. The result of these experiments and studies was the development of a theory of dynamic and static stability. It was found that most torpedoes are statically unstable. That is, if water is pumped past a torpedo, or if a torpedo is towed by an attachment at its center of mass, it will not continue to travel with its axis parallel to the direction of motion. Instead, it will turn one way or another, and set itself at a considerable angle. Addition of tail fins and shroud ring tend to reduce the angle to which it turns. Although this type of static instability is striking, it is of relatively little significance to the running behavior of the torpedo.

In studying torpedo behavior, it was possible to set up a criterion of dynamic stability. A body is dynamically stable, if, when it is displaced from its straight course, it takes up another relatively straight-line course in a direction slightly different from the original. On the other hand, if a body is unstable dynamically, and is displaced slightly from its course, it will go into a circle and continue to turn with a definite radius of curvature.

A body that is dynamically stable can be steered but it imposes a very considerable load on the steering mechanism. A body that is dynamically unstable can be steered with much less anticipation in the rudder correction.

A body that is statically stable will need very little steering, but it will be very difficult to turn. Therefore, because of simple shapes of conventional torpedo bodies, it was possible to set up a scale of stability in terms of hydrodynamic constants of the body. At one end of this scale is a region of dynamic instability, and at the other end is a region of static stability. Between these is a region of static instability but of dynamic stability, in which a steering device can turn the torpedo in a reasonable circle and also keep it on a straight course without too great limitations being imposed on the steering mechanism itself. To make careful hydrodynamic studies of any torpedo body, it was found to be important to study its behavior in straight-line motion, in curved motion, without propellers, and with propellers—both driven and free.

10.1.5 Steering Mechanisms

On the basis of the hydrodynamic studies of torpedo behavior, it was possible to specify the necessary properties of a control mechanism. The division considered two types of control, two-position mechanisms and proportional mechanisms.

A proportional mechanism works in such a way that the rudder displacement of the torpedo is proportional to the amount by which the torpedo axis departs from its prescribed direction. In a two-position mechanism, the rudder is thrown hard over to one side or the other as soon as the torpedo departs more than a prescribed amount from its proper direction. Other types, which may be described as intermediate, were also considered.

Experiments showed that a proportional mechanism may result in unstable oscillations of increasing magnitude if it is applied to a torpedo without consideration of the hydrodynamic properties. This happened when the control was too stiff. Such an unstable system is, of course, unsatisfactory because the torpedo wanders widely from side to side. Instability of this kind was corrected by reducing the amount of rudder throw, or by reducing the rudder area, but such a remedy reduced the curvature of the torpedo path, making it more difficult to turn the torpedo in a prescribed direction. It also slowed the correction of the course. It was found, therefore, that in designing a steering mechanism, proper balance must be struck between the necessity for stability and the neces-

sity for a sensitive control, or for quick restoration after disturbance.

Experiments showed that the two-position control always results in oscillation of the torpedo about its course. However, studies proved that if this oscillation can be made of high enough frequency and of low enough amplitude, it is not serious. Therefore, if a two-position control is properly designed and built, it will steer just as well as a proportional control although its specifications will be somewhat more severe than those of a proportional control.

10.1.6 Depth-Control Mechanisms

In assessing depth-control mechanisms, the division considered types that operate in the same two ways as the steering mechanism. A depth-control mechanism may produce an elevator deflection that is proportional to a given signal or combination of signals, or it may put the elevator either hard up or hard down.

Experience proved that in order to get adequate depth-keeping, it is necessary to have some kind of an anticipatory device which will recognize any attempt to turn up or down and restore the body to proper level even before the body has changed its depth.

Many kinds of anticipatory devices were suggested and considered, but the one given the most attention was the pendulum and it is the one in most common use. Experience indicates that this is also the simplest device. Nevertheless, it was found that the pendulum has numerous disadvantages. It has a natural period of its own and it is important that this period does not come too near to the natural period of depth oscillation of the torpedo. Also the torpedo can oscillate at a certain frequency at which the pendulum will not indicate any oscillation at all. Study showed that these two disadvantages can be taken care of to a large extent in design and location of the pendulum, but only by imposing certain limitations upon the kind of pendulum that can be used. The most serious objection to the pendulum is its response to acceleration. When the torpedo is launched it accelerates, throwing the pendulum back, and hence the elevator down and when the torpedo hits the water, it decelerates, throwing the pendulum forward and hence, the elevator up. Despite these objections, however, no other mechanism was found which performed better, and it may well be that the pendulum, because of its simplicity, will always be the most satisfactory, and that its disadvantages can be minimized by suitable design.

Studies were also made to improve the pendulum depth-keeping system. Analyses of various proposed systems showed that a device sensitive to the time rate of change of depth can be constructed to assist in stable depth-keeping. If used with a pendulum, stability can be guaranteed and the disadvantages of using a pendulum alone can be minimized. However, it remains to be determined whether the additional complication is justified.

The gyroscope was also studied for use in indicating the vertical, but it was not given extensive service trial. The principal result of the studies of depth-keeping was the development of a theory by which it is possible to predict the performance of any projected mechanism. A mechanism already constructed can be examined in the laboratory but if the mechanism is only projected, its expected characteristics can be used to determine the behavior of a torpedo under its action. Tests showed that the theory gives a close and fairly detailed description of torpedo behavior. Therefore, there is no longer any excuse for the laborious production of depth mechanisms that cannot be expected to operate at all.

10.1.7 Sound Control Mechanism

A major part of the division's research and development program concerned the application of sound control to torpedoes and mines. Before sound control mechanisms could be developed, it was necessary to study the behavior of sound in the sea and to combine this knowledge with the theoretical studies and research on torpedo behavior in its three phases of travel, and then adapt the sound control mechanism to the hydrodynamic properties of the torpedo.

Extensive research was carried out in the

field of underwater sound. Experiments showed that maximum listening ranges are extremely variable, and may be affected by the speed of the torpedo, by the speed, size, and aspect of the target, by sea conditions, and by depth of water.

Two basically different sound control systems were investigated. In one system, the controlling sound source is the target itself; hence, the designation of listening or acoustic controlled torpedoes. This system received the most attention and proved to be very effective. In the second sound control method, the torpedo itself projects a sound pulse in the supersonic range and is guided or directed to the target by the echo received from the target. This was designated as echo-ranging control. The first method was more fully developed. A sound control device was needed that could be incorporated in the existing body already being used. In order to get a working device in the shortest possible time, compromises had to be made to avoid discarding something already developed and taking the time necessary to go back and re-engineer parts of systems which were found unsatisfactory. Therefore, there is need for continuing research to improve the effectiveness of listening and echo-ranging control systems.

10.2 FLUID DYNAMICS

The concern of Division 6 with the development of various types of projectiles dates back to 1941. The need for knowledge concerning specific projectile characteristics arose first in connection with the attempt of the division to develop more effective antisubmarine weapons. Thus the first projectile to be studied was the depth charge. As the needs of the division developed, the list of projectiles grew until it included rockets of many types, bombs, shells, and torpedoes. In addition to the individual specific requirements, all of these projectiles were expected to have adequately accurate travel to the target and to utilize efficiently the applied propulsive force. As will be seen from the enumeration of projectile types, the method of propulsion varied over wide ranges, from simple fall under the action of gravity to continuous propulsion by means of propellers or jets. Whether or not these requirements of accuracy and propulsive efficiency are met depends largely upon the interaction between the external forces resulting from the motion of the body through the surrounding air or water and the dynamic properties of the projectile itself, such as the mass, moment of inertia, and center of gravity. The external forces resulting from the motion of the projectile through the surrounding fluid are determined by the shape or form of the projectile, its orientation, and velocity. Early in the life of the division, a brief investigation showed that comparatively few reliable data were available concerning the fluid dynamic forces acting on a projectile of a given shape. Therefore, laboratory research was indicated to obtain such information to guide the design engineer.

It should be understood that the forces acting on projectiles in flight represent only one very small subdivision in the field of fluid dynamics. Many other structures employed in warfare fall within the same field. For example, submarines, surface ships, and airplanes all have to be designed primarily on the basis of the fluid dynamic forces that act upon them. Consequently, during the war years, an enormous volume of research and development has been carried out in this field. Progress reported here concerns merely this small segment of the field and in itself is but a portion of the total research that was carried on in the fluid dynamics of projectiles. In this restricted segment, however, the division has sponsored the development of certain new laboratory methods for determining the dynamic forces acting on projectiles in flight and the utilization of these methods to obtain data that could be used in the design of new projectiles and in the modification of existing ones.

It may have been noted that in this discussion the term *fluid dynamics* is used rather than aerodynamics or hydrodynamics. The reason for this has its origin in the projectiles with which Division 6 has been concerned. To reach the target, many of these projectiles have the first part of their travel path in air and the second part in water. To insure acceptable per-

formance, such projectiles must travel stably through each of these very dissimilar fluids. Of course, some of the projectile types, such as submarine torpedoes, have their entire travel wholly under water. On the other hand, certain of the rockets were designed for surface attack, and hence, their path involved air travel only. Thus, the relative amount of effort which had to be devoted to securing correct air travel and correct water travel varied with the specific projectile. It was soon found that to regard the travel of a projectile having a combined path as being simply divided between a period of air travel and a period of water travel unduly simplified the problem. Very frequently, in such cases, the transition period of water entry is of major importance. During this period there are obvious possibilities of mechanical damage to the projectile. Moreover, completely apart from the risk of damage, the fluid forces applied to the projectile during the entry period may also cause it to emerge from the water, to change direction sharply, or to get out of control and assume an erratic path in its subsequent underwater travel. As these facts were realized, they clearly demonstrated the need for special studies of the dynamics of water entry.

10.2.1 Development of the Laboratory

The first studies of projectile dynamics undertaken by the division were carried on by CUDWR for the purpose of supplying information concerning the design of certain depth charge ordnance. This work, while rather limited in scope, produced valuable results which clearly indicated the desirability of providing more adequate facilities and plans for research and testing in this field. To provide a portion of these needed facilities, a contract was entered into in 1941 with the California Institute of Technology, which provided for the extension of the facilities of the Hydrodynamics Laboratory of that institute and for the initiation of a program of research on projectile dynamics. The first research equipment constructed under this contract became known as the high speed water tunnel. The available equipment in the Hydraulic Machinery Laboratory served as a nucleus for this new construction. By making the fullest possible use of the existing instruments and equipment, the laboratory was enabled to complete the water tunnel and start taking measurements within 4 months of the signing of the contract. The polarized light flume used for visual study of the flow patterns around projectiles was developed at the same time as an accessory to the main tunnel. At a considerably later date the design and construction of a controlled atmosphere launching tank and a free surface water tunnel were undertaken.

From the foregoing description of the apparatus constructed, it will be noted that the fluid medium chosen for the experimental measurements of the dynamic forces on the projectiles was water. There were several reasons for this choice. In the first place, at the time of the initiation of this work, the projectiles under consideration were largely those having only underwater paths. In the second place, the phenomenon of cavitation was frequently involved in the underwater behavior of projectiles, and since cavitation is a phenomenon that is peculiar to motion in a liquid, there is no very satisfactory way of studying it in a wind tunnel. In the third place, the equipment available as a nucleus for the work was adaptable to use with water and not with air. Finally, it can be shown that over a wide range of conditions, the results obtained by study of a projectile in a water tunnel are almost equally applicable to the projectile in air travel. The only serious limitation is that when the results are applied to air travel, they must be restricted to cases in which the projectile velocities are sufficiently low so that the air can be treated as an incompressible fluid. This means, in general, that the results obtained in the water tunnel can be applied with acceptable accuracy to the air flight of projectiles having velocities of less than 700 fps.

10.2.2 Experimental Facilities

High Speed Water Tunnel

The high speed water tunnel is a vertical, closed circuit tunnel in which water is circu-

lated continuously by means of a propeller pump driven by a variable speed motor. The working section, which is 14 in. in diameter and 6 ft long, is located in the upper horizontal run of the circuit. It has the smallest cross section and consequently, the highest velocity and the lowest pressure in the circuit. The flow of velocity in this section can be maintained at any desired value up to 70 fps. The models of the projectiles or other devices to be tested are mounted on the spindle of a three-component balance of the National Physical Laboratory type. Figure 1 shows a group of stainless steel components for the 2-in. diameter models. This group illustrates the type of model construction developed by the laboratory. Measurements of the drag force, the cross force, and the moment can be made with a projectile aligned parallel to the direction of flow, or rotated in the horizontal plane to any desired yaw angle between plus and minus 20 degrees. The absolute pressure in the working section can be controlled independent of the velocity and can be held at any desired value from five atmospheres down to the vapor pressure of the water. The working section is provided with large Lucite windows for visual and photographic observation purposes. Cameras with synchronized flash lamps of the Edgerton high-speed type are a regular part of the equipment. Although the propeller pump and drive motor produce considerable noise in the audible range, it has been found that the tunnel is comparatively quiet in the sound range above 6,000 c. Therefore, microphones mounted at the focal points of spherical and ellipsoidal reflectors have been developed for investigating the sound produced by the flow in passing the projectile, both under



FIGURE 1. Group of stainless steel components for 2-inch diameter models.

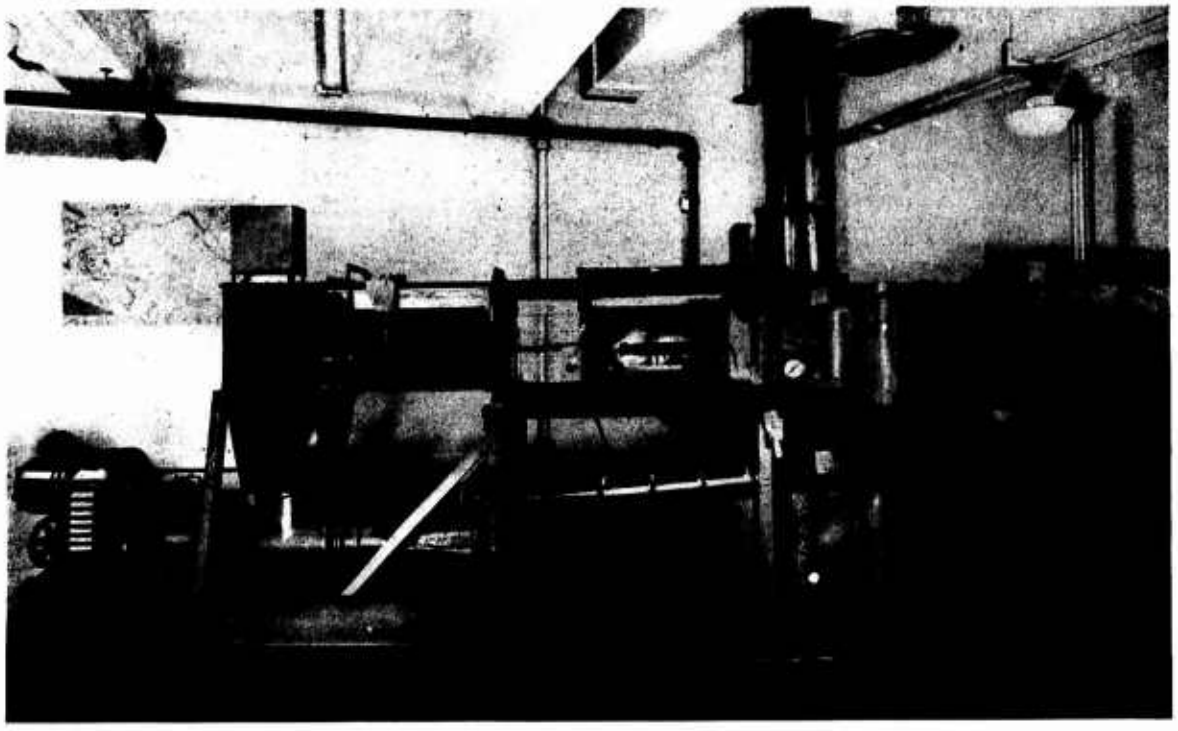


FIGURE 2. The polarized light flume.

cavitating and noncavitating conditions. These reflectors have double walls enclosing an air space and are installed in a water-filled tank attached to one of the Lucite windows directly opposite the model under test. Sound measurements with this equipment were made in the range of from 10,000 to 100,000 c. In order to study the effect of the propeller drive on projectiles, small electric motors were developed that could be mounted within the model. These motors proved to be capable of driving the propellers at correct model speeds and thrusts. The actual operating speeds of the propellers were as high as 18,000 rpm.

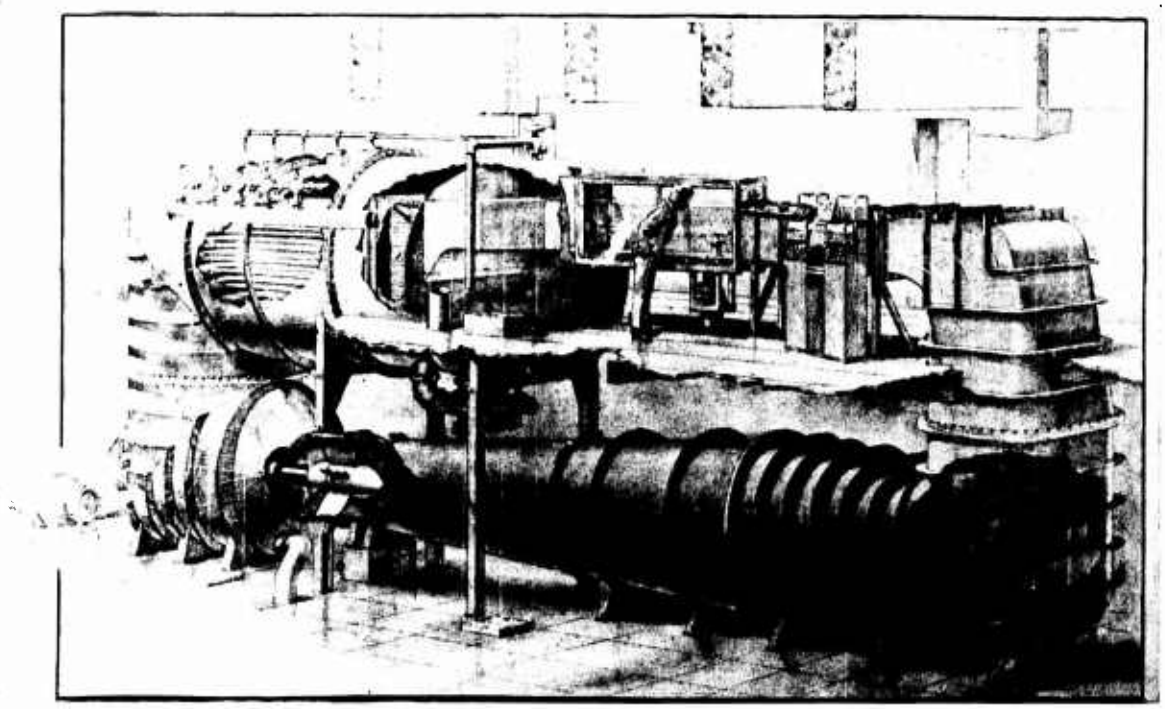


FIGURE 3. Free surface water tunnel. Hydrodynamics Laboratory, California Institute of Technology.

POLARIZED LIGHT FLUME

This piece of equipment was constructed to make possible visual studies of the flow patterns around various types of projectiles. The polarized light flume shown in Figure 2 is essentially similar to the high speed water tunnel in principle, but it is constructed on a much smaller scale. It has a working section 6 in. wide, 12 in. deep, and 4 ft long, and operates only at low velocities, the maximum being in the neighborhood of 5 or 6 fps. In order to make the flow lines visible, a suspension of M. S. Eyrite was employed as a circulating medium in place of clear water. This material, a species of Bentonite, has strong properties of streaming double refraction. When the flow is observed with transmitted polarized light, the shear pattern, and by analogy, the velocity pattern, become visible. Although the results from this flume are purely qualitative, they have proved to be very useful not only in delineating the general flow patterns, but also in locating various sources of disturbance which might cause an increase in resistance or loss in stability. The concentration of the suspended material is only a few tenths of 1 per cent, which has practically no effect on the other physical properties of the water.

CONTROLLED ATMOSPHERE LAUNCHING TANK

A more ambitious structure is the controlled atmosphere launching tank, which, with its associated apparatus, was constructed for the specific purpose of studying the water-entry problem. As the name implies, it differs from most launching tanks in that provision is made for control of the atmospheric pressure above

the water surface. This control is necessary when working with scale models of projectiles, because the phenomenon of water entry is essentially one that involves the interaction between the air and the water. Hence, in the model study, to simulate conditions which exist when full-sized projectiles are launched from the air into the ocean, it is necessary to reduce the air pressure in the same ratio as the linear scale of the model projectile. This tank, with its accessory equipment, was completed only a short time before research under the Office of Scientific Research and Development contract terminated.

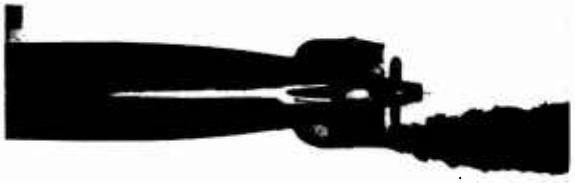


FIGURE 4. Interference of exhaust gases with propellers, stabilizing and control surfaces.

FREE SURFACE WATER TUNNEL

During the course of the fluid dynamics research project, several problems arose in connection with the underwater travel of projectiles which could not be investigated satisfactorily in the high speed water tunnel or other equipment available in the laboratory. One of these concerned the study of the behavior of projectiles such as torpedoes, when they are traveling so close to the surface that the flow of the surrounding water loses its symmetry. Another such problem involved the effects of underwater jet propulsion, a study of which necessitates the introduction of comparatively large quantities of gas into the flowing water in the test section. The free surface water tunnel was designed so that these and similar important sets of conditions might be studied. Although quite similar to the high speed water tunnel, it has a larger working cross section (20 in. square as compared to 14 in. in diameter). The upper surface of the stream is in contact with the air. The air pressure is controlled for the same reason that was discussed in the preceding paragraph. Figure 3 shows a sketch of this equipment as it will appear when completed. It was still in the course of construction at the termination of the OSRD contract.

10.2.3 Laboratory Program

As has been seen, the laboratory program was developed primarily to meet the needs of the war research program. The main objective was to assist in the development of specific projectiles. From time to time, however, the accumulated data have been studied and evaluated with a view to formulating more general conclusions. The reports of the laboratory, therefore, can be divided into these two classes: first, the presentation of characteristics of specific projectiles and second, general conclusions concerning some phases of the projectile problem.

SPECIFIC INVESTIGATIONS

In carrying out the investigations of the characteristics of specific projectiles, the high speed water tunnel has been used in the same manner as wind tunnels are used for testing airplane models. This means that accurately made scale models of the projectiles were constructed and tested in the water tunnel to furnish information that could further the design and development of the projectile. Nearly all of these tests included the measurement of the drag, i.e., the resistance to forward motion; the cross force normal to the direction of motion, and the turning moment about an axis passing through the center of gravity. These quantities were measured for a series of angles of yaw of the projectile axis with respect to the line of motion. The drag forces are useful in calculating the range and trajectory of the projectile and the amount of propulsion required to maintain a constant velocity. The cross force gives an indication of the deviations from the normal trajectory which may be expected, and the moment about the center of gravity gives one measure of the stability. Many other special types of measurements were made to suit the needs of the individual projects.

Torpedoes

A large part of the work of the laboratory was concerned with the hydrodynamic behavior of torpedoes. In addition to the normal measurements previously described, many determinations were made of the pressure distribution over the entire body of the torpedo. The resultant data were useful in evaluating various specific characteristics such as the operation of the depth-control mechanism and arming devices. Extensive tests were made on the speed and submergence at which cavitation would develop on various portions of the body, and on the effect of cavitation on the drag of the torpedo, the control characteristics, and the production of noise.

In the case of the aircraft torpedo, studies were extended to include the characteristics during water entry. One outcome of these investigations was the proposal by the laboratory that a shroud ring be added to the tail structure. This modification was thoroughly tested under operating conditions by other NDRC groups and later by the Navy, and it was later adopted and used successfully. Another special study connected with the aircraft torpedo investigated the effects of the exhaust pipe location on the interference by the exhaust gases with the operation of the propellers and the stabilizing and control surfaces. Figure 4 is a view of one such test.

Bombs and Depth Charges

Depth charges, like aircraft torpedoes, have both air and water flights. Several different designs of this type of projectile were studied chiefly to determine their drag and stability, with a view to improving their accuracy and increasing their fall velocity. Such studies were also made on a group of aircraft bombs which have quite similar characteristics, although they were designed for air flight only.

Rockets

Although this laboratory had no direct connection with the development of rockets, it carried out a rather extensive program of tests on rocket characteristics. This was due to the fact that many of the troubles encountered in rocket behavior developed during the burning of the propellent charge. It was found that water tunnel measurements of the forces acting on the rocket body could be correlated with the behavior of the rocket during this initial period and could be used to develop shapes that would have the desired performance characteristics. The rockets, for which model studies were made, ranged in size from the Bazooka projectile to the "Tiny Tim" aircraft rocket with a diameter of nearly 12 inches.

Some cavitation studies were made in conjunction with these rockets since some of them were designed for use against underwater targets. Though most of the rockets studied were of the fin-stabilized type, it was found that the water tunnel measurements were also of use in the design of spin-stabilized rockets. As a result, the properties of several types of spinner-rocket projectiles were investigated in the tunnel.

10.2.4 General Investigations

Projectile Components

Though the hydrodynamic characteristics of a given body shape cannot be predicted accurately from a knowledge of the properties of the component parts, this does not mean that a knowledge of the characteristics of the components is of no use. On the contrary, a compilation of such knowledge is of great value to the designer in guiding him in his work. Therefore, whenever possible, the laboratory has attempted to systematize the information it has collected on the various projectiles studied. For example, an extensive series of diagrams of the flow around noses, afterbodies, and tail structures of widely varying projectile shapes was published. In a few cases in which the results seemed to warrant it, the laboratory has gone a step further and made additional tests to obtain semiquantitative correlations. An example of this is the study conducted on the general characteristics of ring tails and fins as stabilizing surfaces for one given class of rocket projectiles.

Cavitation

More work of general significance was done

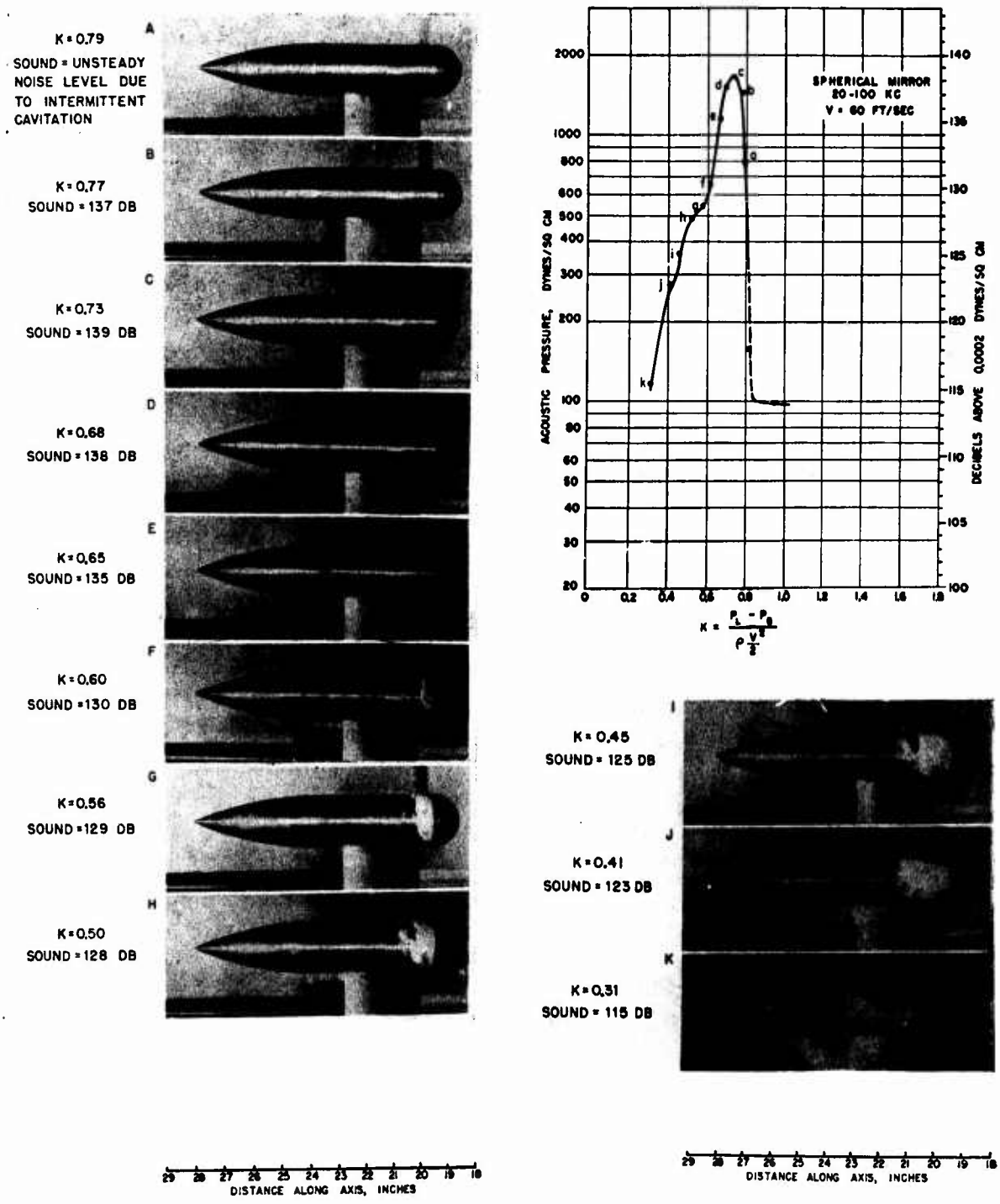


FIGURE 5. Cavitation on hemisphere nose.

on various aspects of the cavitation phenomenon than on any other phase of the laboratory's work. The reason for this is that, basically, cavitation effects constitute some of the most serious limitations to the satisfactory performance of underwater bodies such as projectiles. Furthermore, less is known about cavitation than about most other hydrodynamic phenomena. The first general study in this field made by the laboratory concerned the production of supersonic noise by cavitation and the movement of the sound source and the variations in intensity that accompany the development of cavitation from the incipient stages to a bubble that envelops the entire projectile. Figure 5 illustrates this development. Later, an extensive study was made on the effect of nose shape on resistance to the development of cavitation, with special emphasis on families of ogives, sphereogives, and ellipsoids. Studies were also started to determine the effects of various degrees of cavitation on the drag resistance and the control and stability characteristics of projectile shapes.

Torpedo Control Characteristics

During the life of the project a good many different torpedo shapes were studied. Although they had widely differing dimensions, they had many characteristics in common. Therefore, an attempt was made to integrate these results in a general analysis of the effect of body shape and the size, shape, and location of control surfaces on damping and dynamic stability of torpedoes.

Aspects of the Program

None of these general studies can be considered as complete; in fact, they are only started. It is felt that they can be pursued much further with considerable profit. Although the research program that has been described was wholly directed to the war effort, it has resulted in the development of equipment and techniques of measurement which can be most usefully employed in further research in military and civilian fields. Furthermore, many of the civilian and military needs for knowledge are complementary and can be pursued together to mutual advantage. A good example of this can be seen in the field of cavitation research. Here, practically all of the results are equally applicable to the movement of underwater bodies, such as projectiles and submarines, to the operation of ship and torpedo propellers, and to the behavior of general hydraulic machinery, such as centrifugal pumps and turbines for hydroelectric development.

PART IV

EQUIPMENT DEVELOPMENT

Chapter 11

ANTISUBMARINE DETECTION EQUIPMENT

By *John S. Coleman*

11.1 INTRODUCTION

WHEN THE PROBLEM of devising improved weapons to detect, locate, and sink enemy submarines was imposed on the United States, it was decided to concentrate immediately upon the large-scale production of equipment already designed and proved, rather than undertake major redesigns in an attempt to secure improved performance.

This decision was not unjustified. For although the German submarine of World War II was a far more sophisticated and dangerous weapon than its World War I progenitor, great improvements had also been made in detection equipment, especially in echo-ranging gear which could accurately locate a submerged target by measuring the transit time and direction of a reflected pulse of high-intensity sound energy. Radar, which uses radio pulses in air in the same manner, was rapidly becoming available for use on both surface and aircraft. However, as radar frequencies cannot penetrate more than a few inches of water, no equipment was available to permit aircraft to maintain contact with, or track submarines after submergence.

In the field of antisubmarine ordnance, the picture was darker. With higher submerged speeds and greater submergence depths, the improved German submarines were much more difficult targets to hit with slow-sinking "ash-can" depth charges. Also, the improved hull design of the U-boat greatly reduced the lethal range of depth charges. Improved ordnance, having greater underwater velocity or the ability to direct itself toward a target, was needed.

On the other hand, our own submarines were not provided with entirely satisfactory gear. Like U. S. surface craft, they were equipped with hull-mounted echo-ranging gear. Submarine requirements, however, differ from those of surface craft. Since they must operate undetected by the enemy for maximum effectiveness, they prefer to use listening gear whenever possible, rather than chance being detected by using their echo-ranging gear. Although the function of listening was available, it was possible only in the supersonic range. Further, the location of the gear was not always convenient. One of the most serious deficiencies was the lack of instrumental aids and equipment for use during the depth-bomb attack and evasion periods, which could locate and anticipate attacks or serve as decoys or countermeasures for enemy detection equipment.

With this picture in mind, the NDRC group attempted to plan a balanced and integrated program of equipment development to meet, at least in part, the many urgent problems presented. As trained and experienced personnel were available only in very limited numbers, and time was all-important, it was decided to concentrate upon improvements to existing equipment which could be quickly manufactured and, if necessary, attached in combat areas as accessories, without delaying other parts of the Navy program.

Such improvements were largely designed to close the gap between the performances of experienced and green, newly recruited operators. Later, as experience and knowledge were acquired and the benefits of fundamental research became available, several long-term developments providing improvements of a more fundamental nature were instituted.

Five years is often given as the period necessary for new equipment to evolve from its laboratory experimental form to a production-type equipment. In the case of certain specialized types of Navy equipment, which must satisfy extraordinary performance specifications, the period may be even longer. To assist its own research and development program, the division was forced to call upon many research scientists and their graduate students, most of whom were almost as unfamiliar with commercial engineering practices as they were with the highly specialized background of naval warfare and operational doctrine. Experienced

manufacturers were swamped with new production difficulties and generally were not able to spare trained personnel.

This situation, though it posed problems, worked out to the advantage of the program in several respects. New ideas and methods, borrowed from many specialized fields of research, were assimilated. Fresh concepts of the problems were derived, and analyzed with new tools. Perhaps most important, specific problems were attacked with the aid of a broad scientific background. Production engineering and processing problems were worked out in close cooperation with industry by the loan of individuals or groups between the laboratories and prospective manufacturers. In this way drastic reductions of normal development periods were effected and in at least one case full-scale production was possible within six weeks after the first demonstration of a laboratory working model.

11.2 ASW FROM THE SURFACE

The problems of locating and successfully attacking a submerged submarine are not easy ones. The most successful of the methods now known are, at best, marginal methods that generally operate on the threshold of their sensitivity. Any solution is difficult and may become ineffective overnight with the introduction of countermeasures by the enemy. Therefore, various solutions have to be sought. Underwater radar would provide an answer, except that radio waves can travel only a few wavelengths before their strength is dissipated. Investigation of the entire available radio spectrum has failed to indicate any favorable transmission region. Although, with the use of very long wavelengths it appears possible to reach moderate depths, the instrumental problems involved make the design of such equipment impracticable.

Other schemes involving visible and infrared radiation have been considered and, in some cases, investigated. These, too, have been found to have extremely limited range and were therefore discarded.

Other detection methods have been proposed which rely on the local magnetic anomaly resulting from the submarine's presence in earth's field. Such methods were extensively investigated in World War II, and were incorporated into equipment used by aircraft to search large areas at low altitude. These devices, however, provide an assured range of only several hundred feet and are not suitable for use aboard surface vessels.

The most effective method yet discovered for the underwater transmission of intelligence involves the use of acoustic energy or sound. Thus in both world wars, sound has provided the primary method of obtaining intelligence concerning submerged submarines.

Two methods are widely employed—listening and echo ranging. Listening methods depend upon the detectable sound the submarine target must make in its operation.

Unfortunately, at attacking speeds, the listening vessel generally makes far more noise than the submarine, especially when the submarine is aware of danger and attempts to operate quietly. As a consequence, the use of listening favors the submarine rather than the surface vessel. To overcome the disadvantage of this unfavorable noise ratio, the surface ship normally employs echo ranging.

11.2.1 Modification Program

Recognizing that complete equipment redesign is a comparatively long-term job, the NDRC group concentrated primarily on a program of improvements which could be adapted to the production equipment with which the Navy would have to fight the submarine war. A number of improvements were made which provided a more convenient arrangement of equipment, increased speed and precision of bearing determination, better circuit design, increased ability to resolve small targets, improved transducers, and more convenient test and calibration equipment. Some of the more important of these are described.

Sonar Consoles

As previously mentioned, one of the operational difficulties was caused by inconvenient location of controls and indicators in the current QC stack. For this reason, one of the first

tasks assigned to the section laboratories was that of developing a physical arrangement of equipment components which would permit maximum operator efficiency. After a thorough consideration of the physiological and engineering factors, the Columbia University laboratory at New London [CUDWR] evolved a console arrangement which provided a comfortable seat for the operator with all of the commonly used controls arranged conveniently at hand. In addition to the indicators formerly furnished, the console incorporated *bearing deviation indicator* [BDI] presentation and *maintenance of true bearing* [MTB]. By coupling the ship's gyro-compass system to the projector training gear so that the operator's control called for true instead of relative bearing, MTB provided an automatic compensation for unexpected changes in ship's heading and consequent loss of target contact.

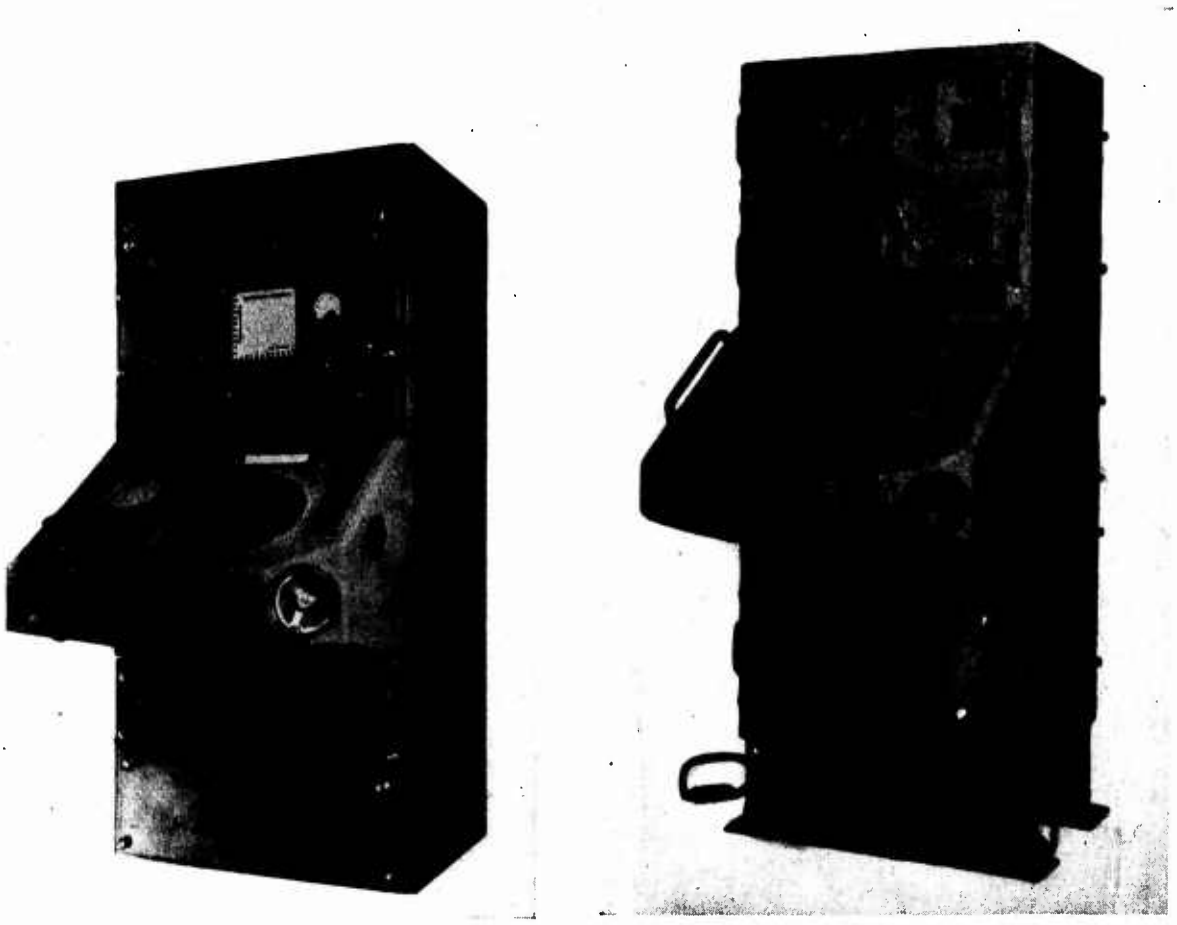


FIGURE 1. (A) The New London [CUDWR] Mark I improved echo ranging receiving rack. (B) RCA Manufacturing Company production unit QGB receiving rack.

BDI SYSTEMS

Perhaps the most important single improvement resulting from this program was the BDI developed by the Harvard Laboratory [HUSL]. This system permitted the operator to determine with a single echo whether his projector was trained to the right, left, or squarely on the target. Since the former procedure of obtaining target bearing depended on the method of cut-ons and cutoffs in which the bearing is formed by defining right and left boundaries of the target through successive pinging and then splitting the difference, the timesaving advantages of BDI are obvious. The Harvard BDI scheme utilizes two directional receiving

patterns which are divergent but overlapping. These patterns are produced by introducing electrical phase lags between the segments of a single, vertically split projector, so that each

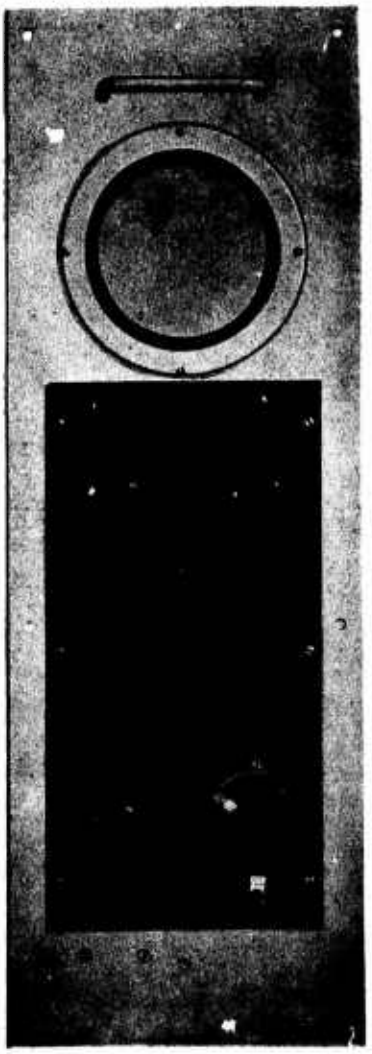


FIGURE 2. Closeup of Model X-3 BDI showing operating controls and cathode-ray indicator face.

pattern is displaced a few degrees to either side of the original acoustic axis.

These two patterns are represented by two electric channels in a comparison amplifier. With the projector axis trained directly on the target, the echo signal is received with equal strength in the two channels. When the projector is not aimed directly at the target, the signal levels in the two channels differ by an amount corresponding to the direction and degree of deviation. This difference in level is measured and used to deflect the beam of a cathode-ray tube indicator thus enabling the operator to make a rapid and accurate correction.

Several models of the BDI were developed of which one, the X-3, was put into pilot production by HUSL. More than 50 of these units were furnished and installed on first-line ASW vessels and saw combat service during the 1943 peak of submarine activity.

Other units, together with the services of laboratory engineers, were furnished to assist the commercial production program, undertaken by the Astatic and Bogen companies.

AUTOMATIC GAIN CONTROL CIRCUITS

Operation of the echo-ranging equipment available at the beginning of World War II was generally characterized by a loud burst of reverberation signal which gradually died away during the remainder of the listening interval. Although no quantitative data are available on the effect of this initial burst of sound in reducing the operator's acuity for a weak echo, its occurrence is at least psychologically disturbing and represents a serious annoyance to other personnel stationed in the vicinity of the sonar equipment. Suggestions had been made in 1941 for the introduction of variable gain amplifiers but no constructive action toward this end had been taken prior to the fall of 1942.

Time-Varied Gain [TVG]. At the suggestion of two naval liaison officers, HUSL undertook the problem of designing a simple circuit modification [TVG] which would eliminate the loud burst of initial reverberation. Within a few hours after laboratory engineers gained access to the circuit diagram of the type 775 sonar receiver, which was in wide use, a scheme was devised for accomplishing this result. A major advantage of TVG was the extreme simplicity of the modification. Almost all receivers used in sonar equipment employed variation of the grid bias for gain control, and it was easy to

arrange to provide the bias voltage from a leaky condenser charged through auxiliary relay contacts during the transmission interval. Variations were made in circuit details to accommodate TVG to various receiver designs.

The basic principle of TVG was adopted for general use by the Navy and was specified as a design feature in all sonar equipment procured between December 1942 and the adoption of the *reverberation-controlled gain* [RCG] system.

Reverberation-Controlled Gain [*RCG*]. Two auxiliary controls are required to enable a TVG circuit to match variable water conditions characterized by differing amounts of initial reverberation and differing rates of reverberation decay. A method of compensating for these two variables automatically is afforded by a circuit arrangement, the functional characteristics of which were suggested to an HUSL staff member by members of a General Electric Company research group working on a related project. The scheme was called reverberation-controlled gain because the rate at which the receiver gain was permitted to return to normal was continuously under the control of the rectified output of the receiver.

This type of operation differs in a significant way from that of a conventional *automatic volume control* [AVC] system. In an AVC circuit the receiver gain is either increased or decreased as may be required to hold the output approximately constant. In the RCG circuit a decrease of receiver output corresponding to reverberation decay allows the receiver gain to increase at a rate determined by a preselected time constant, whereas an increase in receiver output is prevented from producing a corresponding reduction in gain. The important effect of this distinction between AVC and RCG circuits is that RCG preserves the full signal contrast between an echo and accompanying reverberation, whereas AVC tends always to reduce the signal contrast.

The advantages of RCG over TVG, particularly in freeing the sonar operator from having to adjust (or misadjust) the TVG control, were strikingly apparent on demonstration. RCG was promptly adopted. It was not considered desirable to procure modification kits for converting previous installations but inclusion of RCG as a design feature in all new equipment was specified in June 1944.

11.2.2 Transducers

A very large amount of research and development was undertaken in the transducer field.[a] Although the fundamental research, which greatly expanded the available knowledge of the behavior of transducers and transducer materials, is the primary accomplishment, mention should be made of the many new transducers designed and constructed for Service use.

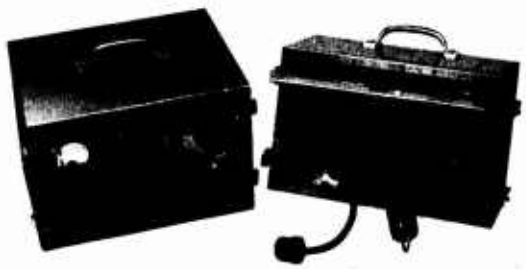


FIGURE 3. X-OCP sound gear monitor (production prototype) with B19H transducer.

It should be emphasized that the fabrication of a transducer having predictable characteristics is an art which requires much background and experience. More important than the actual transducers constructed is the manufacturing "know-how" which has resulted from these programs. The difference between a good transducer and one which must be rejected generally stems from some such cause.

In the course of their programs, each of the three major division laboratories, as well as the Bell Telephone Laboratories [BTL], found it necessary to develop transducers having specialized characteristics for particular applications. Thus the tubular magnetostriction line hydrophone, developed by CUDWR, made possible the JP and JT submarine systems, as well

[a] Refer to Chapter 9 of this volume and Division 6, Volumes 12 and 13.

as the radio sono buoys and the depth-charge indicators. The HUSL B-19 magnetostriction tubular unit saw wide use both in its original application as a monitor hydrophone, and as a reliable reference standard. The same laboratories provided the small rugged laminated stacks that have become production standards for use in aircraft-launched acoustic torpedoes. The University of California [UCDWR] developed many specialized piezoelectric transducers having high performance characteristics.

11.2.3 Sound Gear Monitors

The OAX Monitor. Immediately following the first installations of sonar gear auxiliaries, there was a persistent demand for some simple device to assess the performance of the equipment. The OAX sound gear monitor was constructed to satisfy this need. The apparatus consisted of a rugged transducer having substantially uniform response over the range of 17 to 26 kc and a compact electronic unit which included a tunable oscillator, an untuned amplifier, a calibrated attenuator and meter, and a small speaker. This system permitted tuning of sonar gear to obtain maximum sound output, calibration of output frequency, and maximum sensitivity. Used in pairs, the monitors provide a simple method of making simple response and pattern measurements on projectors.

The OCP Monitor. Following laboratory development of the OAX, the OCP monitor was designed. This extended the frequency coverage to the range of 7 to 70 kc. Both of these units were put into production after a number of prototype models were built by HUSL for use by field engineers and base radio matériel officers.

The Dynamic Monitor. The measurements which can be made on sonar gear with the OAX and OCP monitors are useful in what might be termed a point-by-point operation check. They do not, however, permit a rapid quantitative picture of the overall performance of the sonar gear under normal conditions of operation. The dynamic monitor not only performs this service but also determines the "figure of merit" of the sonar installation.

The figure of merit is defined as the ratio in decibels of the transmitted intensity at 1 meter from the projector to the minimum echo level detectable by the gear under prevailing conditions of water noise. This figure thus allows a valid objective comparison between different types of gear under the same conditions or the same type of gear under different conditions.

Only one experimental model of this device was constructed for local use. However, in view of the convenience of this device and the usefulness of the information it makes available, strong recommendations have been made for further engineering of this instrument in order that it can be furnished to experimental, engineering, and maintenance groups.

11.2.4 QH-QK Systems

Along with the short-term improvement program, two of the division's laboratories undertook to develop integrated sonar systems having new performance features not available in the QC-type sonar equipment. The principal departure from previous designs was the provision of scanning which permits a more rapid examination of a search area than the searchlight type of operation provided by conventional systems.

Two types of scanning systems were constructed. The QH systems, developed by HUSL, scan rapidly in azimuth and normally in range, whereas the QL system developed by UCDWR may be considered to scan rapidly in range and normally in azimuth. Both systems utilize a cathode-ray tube for *plan position indicator* [PPI] presentation of the area surrounding the ship.

Search operations are conducted with standard searchlight-type sonar equipment, by scanning range for a single azimuth bearing and successively repeating this process until the entire desired area has been examined. With radar, the high velocity of propagation makes this search program very rapid. The comparatively low velocity of sound in water, however, renders sonar search by this method very slow. Thus, with a 4,000-yd maximum range and 5-degree azimuth steps, 6 minutes are required to cover the entire 360 degrees.

The method employed by QH-type sonar over-

comes this time handicap by irradiating the whole horizon with a transmitted pulse of sound and then rapidly searching azimuth with a listening beam for echoes from distances which increase slowly in accordance with the low velocity of sound.

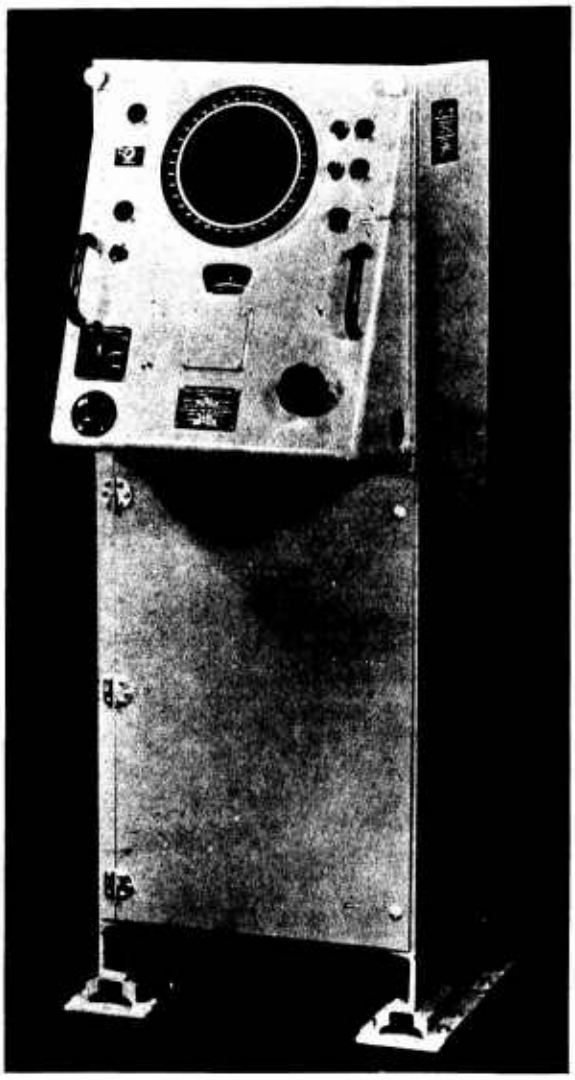


FIGURE 4. Indicator-control unit, Model XQHA scanning sonar.

As a result of this combination of rapid search in bearing and slow search in range, each transmitted pulse enables the sonar system to scan the entire horizon out to the range within which detection is permitted by the water conditions. Thus, searching by sonar is possible within time intervals comparable to those required for coverage of the horizon by radar sets.

The laboratory development of QH scanning sonar involved the study and design of high-powered transmitters for generating the intense sound pulses required to irradiate or insonify the entire horizon. The essential novelty of QH scanning sonar, however, lies in the method by which all azimuth bearings may be examined rapidly. This method requires the production of sharp beams of receiving sensitivity which can be caused to rotate very rapidly. It is, in fact, necessary for the beam of receiving sensitivity to rotate through 360 degrees within a time interval corresponding to the length of the pulse of transmitted sound in order to insure that some portion, at least, of any echo wave train will be received during the scanning cycle.

COMMUTATED ROTATION (CR-SONAR)

Although purely mechanical means of obtaining a rotating beam were investigated, a more attractive method of producing a rotating beam of sensitivity is by control of phase and amplitude of the response from the individual elements of a cylindrical array. A beam can be formed by using the elements in a limited arc of a circular array if time lags are inserted in the circuits leading from the center elements (those closest to the sound source) so that the signals are combined as though received by elements in a plane. By dropping an element from one end of the active sector and adding another element at the other end (an operation carried out by a multiple point switch or commutator) the direction of the beam is shifted through an amount equal to the angular spacing between the individual elements. Experiments proved that if the multiple connections were effected by a commutator utilizing capacitive coupling, the axis of the receiving beam would move smoothly and continuously between the successive positions. The final development of this series, so far as HUSL was concerned, was the commercial commutator design that formed the basis of the XQHA scanning sonar prototype manufactured by the Sangamo Electric Company.

Various details of the scanning equipment

required study and analysis before a suitable degree of reliable operation could be achieved. Studies had to be made of sweep circuits suitable for presentation of target information on the PPI, and lag lines had to be designed that would have constant delays over a wide frequency band. Most important of all was the design of a multielement cylindrical transducer which would have high efficiency and exhibit the necessary uniformity of phase and amplitude from element to element.

Making the large transducers involved great difficulties in theoretical design and required the solving of many shop construction problems. Progress in the development of the scanning system as a whole was regulated by the achievements of the transducer design group.

One of the important steps in the development of scanning sonar was the provision of a listening channel which can be trained by hand to monitor continuously some particular bearing. In this way, in addition to observing the indications on the PPI, the operator can also experience the conventional sounds of echo ranging and can apply his full training in the auditory interpretation of target noise, echo character, target doppler, etc. Normal searching consists of observation of the PPI. Any suspicious indications which might represent echo targets can be investigated promptly by training the listening channel to a corresponding bearing.

Electronic Rotation (ER Sonar)

In the electronic systems devised at HUSL a phase-advancing network was permanently connected to each of the transducer elements. This formed a lead line closed upon itself with a transducer element representing an active source connected to each section of the line. Signals corresponding to a sharp beam did not appear at any single junction terminal of this simple network but combinations of signals appearing at several adjacent terminals would produce such a beam. By connecting a series of vacuum tubes or varistors permanently to each junction of the network, a receiving beam could be made to rotate by activating the varistors cyclically with impulses from a switching line. The shape and duration of the switching pulse controlled the combination of signals to produce the directional beam.

ER for Submarines (XQKA). In general, the receiving beams formed in this way were broader than would be afforded by the same 48-element transducer in combination with the beam-forming networks of a CR system. However, scanning speeds of 350 rps could easily be obtained, permitting the use of transmitted pulse lengths as short as 3 msec and providing excellent range resolution.

The use of short pulses is especially advantageous in the detection of small reflecting objects, such as mine cases. This feature made the ER scanning system especially welcome aboard submarines. Three experimental models of this equipment designed for submarine installations were constructed by HUSL under the designation XQKA. The first of these models, installed in USS *Dolphin* at New London, indicated a normal detection range of 600 to 1,400 yd for standard mine cases, with occasional indications at ranges as great as 2,100 yd. The typical discovery range appeared adequate to permit the submarine commander to conn his vessel safely through a mine field. One of these experimental models was at Pearl Harbor for service trials under Naval Research Laboratory [NRL] auspices when the war with Japan terminated.

Field Tests

Demonstrations of HUSL experimental scanning sonar and, later, of the Sangamo-constructed XQHA equipment evoked uniformly enthusiastic response on the part of naval representatives. A directive issued in the fall of 1944 stated that all "ultimate" sonar equipment should include horizontal scanning as a design feature.

Through cooperation of ASDevLant, a team of officers, which had carried out an extensive series of attack teacher trials for evaluation of attack directors for use with searchlight-type sonar equipment, made a similar series of typical runs with an attack teacher modified for instruction in scanning sonar operation. One of the questions arising in connection with Service acceptance of the QH-type of scanning sonar was whether its simple substitution

for conventional searchlight sonar equipment would involve any sacrifice in attack potential. The ASDevLant report on these preliminary tactical trials set forth the conclusion that information from the PPI display of scanning sonar could be used about as satisfactorily for conning an antisubmarine attack as that from searchlight equipment fitted with BDI. A further conclusion was that addition of BDI to scanning sonar might be of doubtful value in



FIGURE 5. Assembly of elements on experimental HP-3DS depth-scanning transducer proposed for use with the integrated Type B sonar.

view of the relatively satisfactory precision of bearing determination from the PPI scope itself. Since the advantages of scanning sonar in initial search were taken to be obvious, these tests presaged the success of future sea trials of scanning sonar under actual operation conditions.

DEPTH SCANNING

In June 1944, HUSL was asked to consider the adaptation of scanning sonar principles to depth determination and to propose a design for a complete sonar system which would include azimuth scanning for search and depth scanning for attack, and that would give stabilized information required by fire-control equipment. Such a system was proposed, using a two-axis stabilized depth-scanning system to obtain fire-control information, and was designated by the Navy *Integrated Type B*. Another system proposed by the NRL to meet the same requirements, using a three-axis mechanically stabilized searchlight sonar for obtaining fire-control information, was designated *Integrated Type A*. Both systems proposed the use of QH azimuth-scanning system. HUSL set up a program which called for (1) theoretical and experimental investigations of the possibility of depth-scanning itself, and (2) future detailed design and development of the complete system.

The first part of this program called for considerable research and development work. The depth-scanning system, including stabilization, was set up and tested on an experimental basis. The investigation and experience with azimuth-scanning systems led to the general design of the integrated Type B sonar, which was partially constructed, but not completed or tested by HUSL.

FUTURE DEVELOPMENT

Integrated Type B Sonar. HUSL's experiments on depth scanning were successful to the extent that the system operated as expected. Reverberation did not appear to be a disturbing factor, but the echo from the bottom of the ocean was extremely disturbing for both the scanning and listening portions of the depth system. It was found that bottom echo disturbance could be minimized by transmitting on a directional-type beam rather than on the nondirectional beam used originally.

On the basis of HUSL data, it is recommended that, in future experiments, the transmitting beam provide approximately constant echo strength from a target at constant depth as the range from the ship to target changes. Some difficulties also were observed in obtaining proper depth angles for a target at known depth angle. An effort should be made to evaluate the effects on operation of the system caused by the target-image in the surface and by in-

homogeneities in the water path between the target and the experimental ship.

The integrated Type B sonar has a number of distinct advantages over other sonar gear. Original detection of a target by the azimuth-scanning portion of the system is obtained by watching a single indicator without moving any controls. Following detection, placing the cursor of the PPI on the target and keeping it there allows further detection of the target on the *elevation position indicator* [EPI] without moving any other controls. Use of the BDI technique allows continued bearing determination even when the target is no longer detectable on the azimuth-scanning portion of the system. Continuous maintenance of contact with a minimum of effort is thereby accomplished from the original detection throughout the time that the target remains within detectable range, including very short ranges and depth angles to 90 degrees. Because of the ability of this system to retain contact with the target to very short ranges and large depth angles, the conning officer should be able to make a better judgment of the evasive behavior of the target and be able to avoid the uncertainty now existing when contact is lost. With the addition of a suitable attack director (now under development) to include depth angle in its computations, the problem of attacks on the target should be simplified and, on the average, attacks should be more successful. Upon availability of trainable gun-type ordnance, the effect of the first rounds on the target can probably be taken into account.



FIGURE 6. Consoles for proposed integrated Type B sonar.

For navigational purposes, the system could be adapted with ease for detection by the PPI, of surface ships, buoys, reefs, or other obstacles near the surface. The EPI could be used to examine the bottom in the direction of, or at any angle to, the direction of motion of the ship, and could also be used to detect submerged objects on the bottom or between the surface and the bottom for any particular direction.

11.2.5 QL Systems (FM Sonar)

QL-type sonar, the second type of high-speed search system, reversed the roles of range and bearing determination. In QH systems, different bearings are presented simultaneously while range is slowly scanned; in QL systems, ranges are presented simultaneously while bearings are slowly scanned. This method of operation is accomplished by the use of a frequency-modulated transmission signal which irradiates a wide sector. A sawtooth modulation is used, that is, the frequency decreases uniformly with time for a period determined by the maximum range setting after which the frequency returns abruptly to its starting point and another cycle begins. The frequency of the returning echo obviously follows the pattern of the transmitted signal, but is displaced in time by the interval required for sound to travel out to the target and return. The range, therefore, can be determined by measuring the constant frequency difference between the transmission and echo frequencies.

As any particular difference frequency represents a particular range, the receiving system is provided with a range analyzer comprising a series of filters so that echoes from all ranges at a given bearing can be portrayed simultaneously on a cathode-ray screen.

Target information is continuous with the exception of a lost-time interval at the beginning of each sawtooth modulation cycle which is equal to the sound travel time to and from the target.

With FM sonar, a continuous signal is sent out over a wide sector which in present gear is 80 to 90 degrees wide. In practice, the echo is heterodyned against the outgoing signal and it is the difference frequency which is actually used for detection of the echo. Each receiving filter responds only to echoes from a certain level of range. The relatively narrow width of the filters (each 75 cycles wide) results in a high signal-to-noise ratio. Gear of present design employs a directional, trainable, receiving transducer which is rotated mechanically so that any given sector can be scanned in a fraction of a minute. Since the projector is also somewhat directional, it is mounted on the same shaft and is rotated with the receiver.

It was the opinion of UCDWR engineers that FM sound offered a number of advantages over the conventional types of echo-ranging gear utilizing pings or pulses. Principally among these were the ability to obtain continuous range information on multiple targets and a low signal-to-noise ratio by the use of narrow receiving filters. The filter width in an FM system, combined with the frequency of modulation, also determines the equivalent pulse length. Thus, the use of narrow filters results in a very short equivalent pulse length which permits detection of small objects such as mines. In attacking the problem, UCDWR engineers envisioned a device which would automatically delineate the outline of the target on the screen of the *cathode-ray oscilloscope* [CRO]. The realization of this ideal, although possible, was complicated by many factors and many of the early systems were primarily concerned with working out a solution to the problem of using FM sound for underwater detection, without too much emphasis being placed upon the actual portrayal of the target.

COBAR

The FM systems program was undertaken by UCDWR in the fall of 1941. FM systems being studied at this time were designated by the name cobar (continuous bearing and range). A number of these experimental systems were assembled. Although cobar systems afforded a high degree of range resolution, their ability to scan range rapidly was limited by the fact that they searched range in a single annular ring whose radius is adjustable. Cobar's high degree of range resolution led to a fire control modification known as subsight which furnished "time-to-fire" information for forward-thrown weapons. The system included automatic compensation for the range error introduced by doppler shift.

The continuous nature of the information provided by cobar, combined with its high degree of range resolution and good signal-to-noise ratio, led to investigation of its use in small-object (mine) detection. The capabilities of cobar in this application were demonstrated to the Navy at Norfolk, and created considerable interest as early as June 1943.

PRIBAR

Early in the cobar development, February 1942, a modification under the designation pribar was made which introduced the use of a CRO screen for target presentation. The pribar systems employed a fixed-position multielement hydrophone. Phasing networks connecting the various elements of this hydrophone caused its sound beam to scan in bearing as a function of frequency. Increased speed in range scanning was sought by injection into the receiver of a 20-c sine wave modulation which was superimposed on the basic sawtooth frequency and which made it possible simultaneously to scan ranges from zero up to the maximum range for which the system was set.

FAMPAS

Cobar systems and their modifications, subsight and pribar, employed a single narrow band-pass amplifier. It was realized, however, even during work with the early cobar systems, that all range information necessary for the simultaneous portrayal of multiple targets at any range from zero to the maximum range setting was present in the system's first detector, if only some means could be devised for making it available in readily intelligible form.

In January 1943, a multichannel analyzer and electronic switch were developed which made possible this type of target presentation with the FM systems. Systems using the analyzer and multichannel switch were, at first, designated fampas (frequency and mechanically plotted area scan) and gave a PPI plot presenting a plan view of the area surrounding the echo-ranging vessel.

During work on fampas-type sonar, the designation was changed to FM sonar and under the name of FM sonar Model 1, a system was tested at New London in which ranges on a submarine up to 3,200 yd were obtained.

Until late fall of 1943, the FM system had been regarded primarily as an antisubmarine device. However, with the relatively successful progress of antisubmarine warfare, the emphasis was changed to utilization of the FM system as a small-object detection device, and a model was tested for detection of small objects in shallow water.

Subsequent tests led to improvements in design and installation, and the Navy became interested in FM sonar as a prosubmarine device for use in heavily mined enemy waters. Ten FM systems were ordered for installation in submarines operating in Japanese waters, and during the construction of these units, the Navy designation QLA sonar replaced the older FM sonar. In the summer of 1945, nine submarines equipped with QLA gear entered the mined waters of the Japanese Sea, and all but one of these vessels obtained contacts on mines, while all nine submarines were able to avoid the mines safely with the aid of QLA information. Later, comparison of the plots of the mine contacts obtained by these submarines permitted the preparation of a chart showing the character and location of the mine field. After the end of World War II, these charts were found to be in good agreement with those of the Japanese Navy.

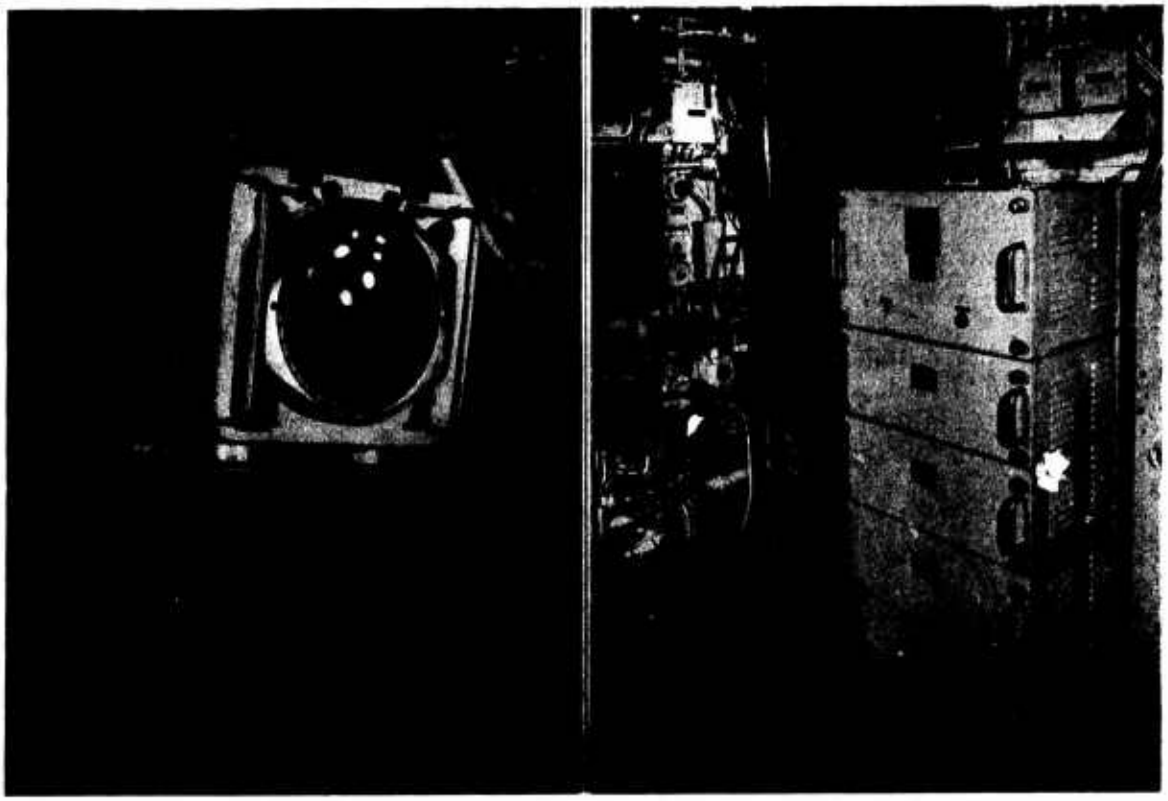


FIGURE 7. FM sonar equipment of type used on USS *Spadefish* installation.

FURTHER DEVELOPMENT

The QLA-1 sonar device does not represent the ultimate in FM techniques or possibilities; but rather, a stage in FM systems development,

tempered by expediency and the need for production of a device which would be of assistance during World War II under particular and peculiar circumstances.

The future development trend of FM sonar is being directed toward the ability to obtain target information faster, more accurately, and in greater quantities. The present system scans range rapidly and provides a simultaneous PPI-type portrayal of multiple targets on any given bearing. Target information, however, is limited by:

1. The indicated range error resulting from doppler shift.
2. The momentary break in target information during the lost-time interval.
3. The limited rate of bearing scan (6 rpm) determined by the width of the transmitted sound beam.

The proposed development program includes means of eliminating these limitations as well as the addition of new functions to the system.

The range error due to doppler may possibly be corrected by combining a pinging system with the FM system in such a way as to give true range as well as continuous range rate information which could be used for fire-control applications.

The problem of eliminating lost time has already been solved. By the use of a nondirectional projector, the bearing scan rate can be increased from 6 to 120 rpm before the build-up time in the analyzer filters becomes a controlling factor. Depth determination has increased importance when one considers the high speeds and great operating depths of future submarines. The addition of a second stabilized sound head rotated 90 degrees and scanning in the vertical plane would provide depth angle and slant range information which can easily be converted to true depth. Such information would also be of considerable value to FM equipped submarines in determining the depth of mine fields.

Bearing accuracy may be increased by the use of a BDI system and range accuracy by increasing the number of filters used to analyze the frequency difference between the transmitted signal and returning echo.

A possible improvement in indicators which should be tried and evaluated for its tactical value involves the use of dark-trace cathode-ray tubes or skiatrons. With such tubes, it is possible to project, greatly enlarged, a PPI trace on a plotting board. With tubes of ordinary dimensions, the trace can be enlarged to a diameter of at least 30 inches. Such a plot combined with depth information fed automatically to the plotting board might make target information available to the conning officer in a form more quickly interpretable.

The use of FM systems as passive listening as well as echo-ranging devices for torpedo detection should also be investigated in face of the extensive use of homing weapons to be expected in the future.

11.3 ASW FROM AIRCRAFT

During the period just before the United States entered World War II, it became increasingly clear that aircraft should possess certain characteristics that would make them effective in antisubmarine warfare. Aircraft are valuable for searching operations because of their long-range and high-speed capabilities, and because, after locating a submarine, they are able to deliver an explosive charge on it. On the other hand, their limitations were equally clear. At that time, aircraft could be used to locate surfaced submarines visually or by radar, but they were not capable of detecting submerged submarines, nor could they follow the course of a submarine after it had submerged. Furthermore, existing ordnance was effective only when direct hits were obtained. Consequently, to be effective in antisubmarine warfare, both the detection systems and ordnance used by aircraft had to be improved.

The introduction of aircraft in antisubmarine warfare did much to change the emphasis from defensive fighting to offensive fighting, by making possible an extension of the search area. Submarines could be attacked before they were close enough to threaten ships. Later, when effective radar detection was added to visual detection, the sweep rate was further increased.

The advent of Schnorchel, however, drasti-

cally reduced the aircraft's search capabilities, because the radar sweep width on Schnorchels is much less than on surfaced submarines. As the use of Schnorchel made it possible for enemy submarines to remain submerged for longer periods, there was an urgent need to develop a satisfactory means for detection and location of Schnorchel and totally submerged submarines.

Section C-4 of the NDRC undertook investigations of existing airborne detection systems and, after some research, found that two different physical methods, magnetic airborne detection and radio sono buoys, promised practical results. Development work was then undertaken to improve the effectiveness of these two systems.

11.3.1 Magnetic Airborne Detector

The *magnetic airborne detector* [MAD] is a device designed to locate a submerged submarine from aircraft by detecting the magnetic anomaly set up by the ferromagnetic mass of the submarine.

In the spring of 1941, the need was urgent for a means of detecting a submerged submarine from aircraft. The British were attempting the development of magnetic airborne gear which, under favorable conditions, proved capable of detection at ranges no greater than 200 ft. This figure was clearly too low to be of operational value. A more promising line of development appeared to lie in improving the systems already in use in the United States for geophysical prospecting, which utilized a saturated-core magnetometer.

If a sine wave a-c voltage is applied to a coil surrounding a strip of permalloy, the metal will saturate magnetically at the peak of every cycle of the alternating current. The self-inductance of the coil will, therefore, vary during the cycle and so the waveform of the resulting current through the coil will be rather complex. Any slight external magnetic field also acting on the permalloy, parallel to its length, will increase or reduce the amount of current in the coil needed to cause saturation, and so will change the point in the a-c cycle at which saturation occurs. This, in turn, results in a slight but characteristic alteration in the waveform of the current in the coil. If the device is connected to an amplifier which is sensitive to changes in the waveform of this current, it becomes an indicator of any external magnetic field having a component parallel to the permalloy strip.

To measure the magnetic field a magnetometer is employed. The Gulf Research and Development Company had produced an instrument known as the Vacquier magnetometer which when completely developed proved to be well adapted to the purpose of submarine detection.

The magnetic field of the earth is defined by magnitude and direction, that is, it is a vector quantity. Because of this, any rotation of the magnetometer due to motion of the plane will cause a change in magnitude of the magnetic flux through its coils which does not correspond to actual change in the magnetic field. These disturbing magnetic effects, or spurious signals, must either be neutralized or the relative motions eliminated. Means had to be devised to maintain the magnetometer in a definite direction in space. Early models used gyroscopes to secure stabilization, but this solution was inadequate, and later models employed magnetic stabilization.

The signals or pulses produced by the magnetometer must be converted into other signals suitable for recording and interpretation. There are various ways to record these signals, the common one being a record secured as a line on a continuously moving tape.

In the installation and operation of MAD, it is necessary to avoid spurious signals produced by magnetic fields associated with the aircraft itself. One means was to locate the equipment away from metal parts or tow it behind the plane. Another means was to provide magnetic compensation for these local fields.

The major problems were solved to the extent that the detection equipment finally developed has a background noise level of about 0.2 gammas under conditions of reasonably straight flight in a magnetically quiet area. If the magnetic fields due to the aircraft itself are properly compensated, the spurious signals re-

sulting from rapid plane maneuvers are not over a few gammas. Thus the equipment is capable even in flight of detecting a submarine where the magnetic anomaly produced by its presence is only a few gammas. Present maximum range of MAD equipment is about 600 ft.

AN/ASQ-1

The first instruments tested, the Mark I and Mark II, used a gyro stabilization and employed a Vacquier saturated-core magnetometer. The subsequent models, Mark IV and Mark IV B-1, and the resulting production models, Mark IV B-2 and AN/ASQ-1, were based on magnetic stabilization of the magnetometer head without the use of a gyroscope. The final, improved model, AN/ASQ-1, was ready for service in December 1942, but later an improved universal magnetometer head was developed to permit operation at any magnetic latitude. This equipment was designated as AN/ASQ-1A.

AN/ASQ-2

In 1943, two automatic units to facilitate the dropping of flares and bombs were perfected. One of these is an automatic flare or bomb release unit, CP-2/ASQ-1, to be used with the detection of targets. The other is a magnetic airborne bombsight designed to determine the lateral position of the target with respect to the aircraft and to release bombs automatically only if the aircraft is within proper range. This unit, CM-1/ASQ-2, is used with dual installations of the detection equipment.

About 50 of these dual automatic installations were made but they came too late in World War II to receive much combat test. Between July 1941 and July 1944 about 400 installations of MAD equipment were made and proved useful in cases where aircraft located a submarine visually or with radar and the submarine submerged before the aircraft could reach it. The MAD was also used in maintaining blockade patrols of small strategic areas. During the last part of World War II, however, the MAD was largely supplanted by the radio sono buoy.

Future Development

The MAD equipment suffers inherently from the handicap of limited range and in certain areas, its effectiveness may be further limited by geological conditions. The present range of not over 600 ft probably cannot be markedly increased. Studies have indicated that present gear accomplished about all that conditions will permit. However, if in the future this method appears to have promise, certain refinements of design should be undertaken. Even if the future submarine is increased in size and has a larger magnetic moment, the most highly developed forms of MAD will probably be restricted to areas where the submarine cannot or does not operate at great depths of submergence. Since conditions of future warfare are so problematical, MAD should not be discarded as a potential tool.

Although MAD AN/ASQ-1 was developed for submarine detection, its usefulness is not limited to this single objective. Investigations were made of the possibility of detecting mechanized field equipment, fixed gun emplace-

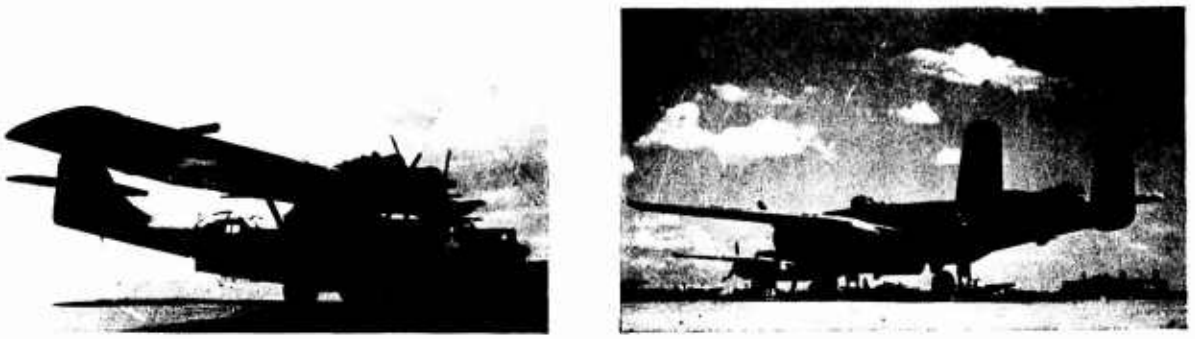


FIGURE 8. (A) MAD installation on wing of PBY-5A. (B) A tailcone installation.

ments, munition factories, and other land targets. Also, the possibility of using AN/ASQ-1 equipment for navigation of bombers to their targets was briefly investigated. The tests were encouraging, but further development work must be done to improve the effectiveness of MAD equipment for these purposes.

11.3.2 Radio Sono Buoys

The radio sono buoy is a device designed to allow remote detection of sounds in water. These sounds are picked up by the buoy hydrophone and broadcast by radio to a receiving station located aboard a ship, airplane, blimp, or on shore.

The Expendable Radio Sono Buoy

The first device to be put in operational use was the expendable radio sono buoy [ERSB]. This device, also designated AN/CRT-1A, consists of a sonic listening hydrophone and amplifier coupled to a frequency-modulated radio transmitter. These elements and a battery power supply are incorporated in a waterproof cardboard tube about 30 in. long and 4 in. in diameter, weighing about 12 lb.

The buoy is dropped from an airplane or blimp by means of a self-contained parachute. Upon striking the water, an impact catch releases the hydrophone which sinks to a water depth of about 20 ft, the length of the supporting cable. The buoy transmitter operates on frequencies between 67 and 72 mc and has a maximum range of about 35 miles when the listening aircraft is at an altitude of 5,000 ft. The operating life is from 2 to 4 hours after planting, after which a plug is dissolved and the device sinks. The aircraft receiver is provided with six frequency channels (later twelve) which allows the simultaneous use of a like number of buoys.

With this device, a submerged submarine can be kept under aural observation, oil slicks can be investigated, and damage to a submarine during attack can be ascertained. It is also possible to track a moving submarine by using several buoys simultaneously. Some evidence of the effectiveness of the ERSB is indicated by the fact that more than 160,000 units were ordered.

Experience showed, however, that the buoy's functions could be more effectively performed if a buoy could be developed which would be capable of broadcasting not only underwater sounds, but also the direction from which these sounds came. Tactical operations could be improved, observation time would be reduced, and space in aircraft would be saved. Because the suggested improvements would increase the weight and bulk of the existing buoy, a general redesign was required.

The Directional Radio Sono Buoy [DRSB]

The DRSB consists of a directional sonic listening hydrophone which rotates continuously to provide 360 degrees scanning in a horizontal plane around the buoy, together with a sonic amplifier, rotating mechanism, and frequency-modulated radio transmitter. The system, including battery power supply, is incorporated in a tubular buoy of bakelite impregnated paper about 52 in. long, 6 in. in diameter and weighs about 30 lb. It also is dropped with a self-contained parachute.

Transmission of directional information is accomplished by means of a compass-capacitor which causes the center carrier-frequency of the radio transmitter to vary with the rotation of the buoy. The aircraft receiver is provided with a circuit to translate these changes in transmitting frequency into directional indications which appear on a meter. The DRSB proved effective in tests and 7,000 units were ordered.

Although ERSB and DRSB were designed for use from aircraft, they were also often launched from surface ships. Both systems played a major part in antisubmarine warfare listening.

Aircraft used sono buoys more frequently toward the end of World War II, and analysis indictated that in over 50 per cent of the cases in which sono buoys were dropped, following visual contact, a sono buoy contact was obtained. Sono buoys were thus responsible for establishing and maintaining underwater contacts that led to the destruction of many enemy submarines.

However, a number of improvements would make the device more effective. Foremost among these is the provision for improved directional indications to enable more accurate location of submerged targets, as well as longer listening ranges and the use of fewer buoys. It is also desirable to double the number of frequency channels for the nondirectional buoys,



FIGURE 9. The directional radio sono buoy in water showing marker dye bog and dye trace.

to provide for connecting receiver output directly into the plane's intercommunication system, and to develop containers for marker dyes which will dispense the dyes on water impact but will not break in normal handling.

11.4 HARBOR PROTECTION

Wartime protective barriers for inner harbor areas are formed by mine fields, submarine nets, magnetic loop cables, and other fixed obstructions. These barriers are generally supplemented by armed patrol craft. However, none of these barriers is capable of indicating the actual location of harbor intruders, although magnetic loop cables can detect the presence of an intruder when it crosses the loop at the seaward end of the harbor. But magnetic loop cables cannot indicate the actual position of an intruder.

There was a need consequently for a harbor protection system which would indicate both the presence and location of approaching intruders of any size. The Navy had done basic development work, and proposed the cable-connected hydrophone system and the anchored radio sono buoy as sonic methods of detecting and locating harbor intruders. Several NDRC laboratories undertook assisting investigations of these two systems to develop them for practical use.

ANCHORED RADIO SONO BUOY

The *anchored radio sono buoy* [ARSB], anchored in a harbor as a part of the harbor protection system, picks up underwater sounds, amplifies, and impresses them by means of frequency modulation upon a radio carrier transmitting them to shore receiving stations. At the listening posts are radio receivers attended by listeners trained to distinguish the sounds of submarines and various types of surface craft. When these buoys are placed in strategic locations, they make possible the continuous monitoring of underwater sounds in the nearby area. They are reserved for use in deep water and for auxiliary or emergency use at advance bases, where the expenditure of time, material, and effort such as needed for a cable-connected hydrophone system would not be justified.

CUDWR collaborated with NRL in a program of tests and development on two experimental models. The first model, JM, provided two buoys, one a transmitter buoy from which the hydrophone was suspended, and a separate anchor buoy to prevent cable fouling. Electrical equipment consisted of a dry cell power supply, a medium gain audio amplifier, FM carrier-wave system and a half-wave antenna. The second model, JM-1, incorporated the desirable

features of JM and included new features such as heater-type tubes, high audio gain, low microphonics, and pre-emphasis on high frequencies. The final JM-1 model operated satisfactorily at an 8-mile radio range and, under favorable weather conditions, equaled the cable-connected system in acoustic performance. The

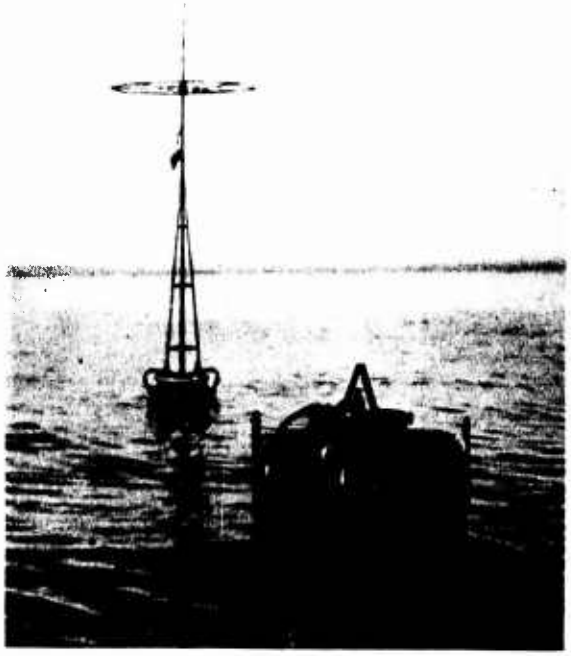


FIGURE 10. The JM-1 anchored radio sono buoy.

buoy itself could not withstand severe storms. Suggestions for further research include improvement of stability, incorporation of all components in one streamlined buoy, improvement of low-frequency response, decreasing background noise, and inclusion of a device to enable alternative directional and nondirectional use of the hydrophone.

CABLE-CONNECTED HYDROPHONES

After investigation of existing and proposed systems, cable-connected listening hydrophones appeared to offer the best possibilities for use as a secondary detection system for harbor protection, since they are capable of detecting and determining the approximate location of an enemy submarine or surface craft.

The cable-connected hydrophone system, as jointly developed, consists of a series of regularly spaced, tripod-mounted, crystal hydrophones, connected by a submarine cable to a shore station, where a switching mechanism and a sonic listening amplifier are provided. The switching mechanism automatically selects the separate hydrophones for listening during an adjustable interval of 2 to 10 seconds. The amplifier has a uniform frequency characteristic over the range of 70 to 12,000 c and provides for monitoring either by headphone or loudspeaker.

To be effective, hydrophones must be spaced to insure overlapping of effective detection areas, and locations must be carefully selected

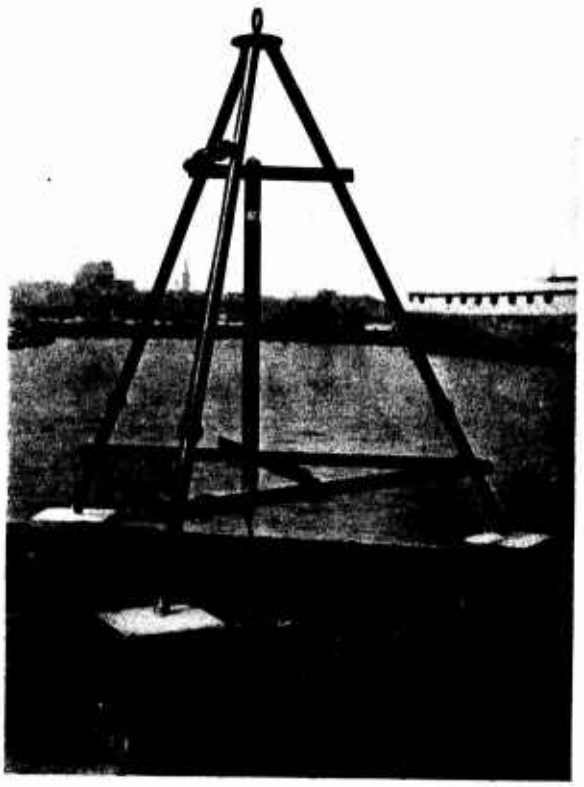


FIGURE 11. Cable-connected hydrophone and tripod assembly.

where favorable listening conditions exist in the seaward direction and along the cable. When a number of spaced hydrophones are available for successive listening, because of the character of underwater sound, they provide information concerning the vessel's loca-

tion and direction of travel. In order to make full use of the potential sources of information, the system provides high-quality reproduction at the listening station, well-balanced sensitivity among the various channels, and freedom from noise interference. Suitable filters are incorporated in the amplifier to discriminate against certain types of ambient noise, such as that made by fish.

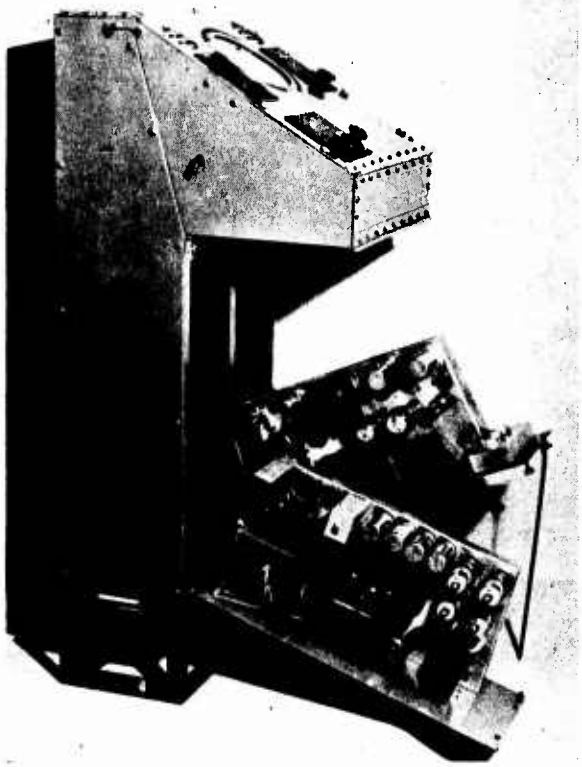


FIGURE 12. Anchored vessel screening console, HUSL model.

The installation at Cape Henry, Virginia, consisted of 14 tripod-mounted hydrophones, spaced 1,000 yd apart along an armored cable beginning at a point about 5 miles offshore and terminating at the shore listening station. Listening ranges of over 7,000 yd were attained for surface ships. Since the construction of the Cape Henry system a number of means of improving or simplifying the performance of the system have been devised. The size and complexity of the system has limited its use to continental harbors of the United States.

11.5 SMALL-OBJECT DETECTORS

Conventional echo-ranging and sonar gear used by the Navy, being primarily designed for detecting large objects, was not well-adapted for the detection of small objects, such as midget submarines. When the course of World War II made it advisable to develop such small-object detectors for harbor protection and other purposes, both British and American laboratories undertook theoretical and experimental investigations to determine design factors characterizing a high-performance small-object system. Experience showed that because of the low level of noise generated by small objects, direct listening was ineffective. Although existing echo-ranging equipment was not suitable, the echo-ranging principle appeared adaptable to small-object detection.

11.5.1 Anchored Vessel Screening

The first problem assigned was that of producing a small echo-ranging device as nearly automatic as possible, and capable of presenting a continuous picture of the location of all underwater objects, down to the size of a 3-ft sphere within a 300-yd range at a maximum depth of 60 ft. The precision in azimuth was originally set at about 10 degrees.

THE BTL SYSTEM

The *anchored vessel screening system* [AVS] Mark III, was proposed by BTL as a means of protecting ships at anchor from miniature submarines and small manned torpedoes. This echo-ranging device comprised (1) a vertical line projector, (2) a receiving hydrophone to give azimuth bearing of target echoes over 360 degrees of azimuth, and (3) electronic circuits. Presence of the target is indicated by a bright spot on the screen of a cathode-ray tube which presents a map of the region around the ship with a bright spot in the relative position of the target. This system operated as expected in tests, although the need for better signal-reverberation ratios was indicated.

THE HUSL SYSTEM

The AVS system developed by HUSL is a

semiautomatic echo-ranging system, operating as acoustic analogue of search radar, with each bearing being searched successively in range. The CRO screen gives a map of surrounding territory but by means more mechanical than the BTL model. This unit also provides an audible indication. Two models were constructed and performed according to expectations. With Navy interest in this problem lagging, both programs were dropped in favor of more urgent work.



FIGURE 13. Recorder traces of typical targets obtained with preliminary model SOD, in San Diego harbor test.

BRITISH 135 ASDIC

The British meanwhile, developed the 135 ASDIC system, to serve as a harbor protection unit capable of detecting midget submarines. This system was based on the principle that for maximum echo to reverberation ratio, the length of the pulse train in water should generally approximate the dimensions of the target. Thus, a 3-ft target would correspond to a pulse length of 0.6 msec. This factor of pulse length appeared to be the most important single operating characteristic, differentiating small-object systems from conventional systems.

11.5.2 Mine Detectors

Faced with the problem of detecting minefields from submarines, interest in the detection of small objects was renewed and the UCDWR was assigned a long-term program devoted to a fundamental determination of physical factors affecting performance of small-object systems. Concurrent with this program of investigation, several short-term equipment developments were instituted.

MINE AND TORPEDO DETECTION SYSTEM [MATD]

CUDWR, convinced that modification of existing submarine sonar installations was practicable, proposed certain modifications in the standard WCA-2 installation. These included the provision of a short transmission pulse which, in turn, required changes in the

keying and transmitter circuits and the recorder. Experiments with this system, designated *mine and torpedo detection system* [MATD], indicated good performance on a 3-ft mine case out to the maximum indicator range of 600 yd. In addition, the feature of torpedo detection was incorporated by providing for continuous rotation of the listening hydrophone with a radial deflection cathode-ray indicator tube.

An experimental installation of MATD saw active service during the war in the Pacific.

San Diego Unit

Several laboratory models of a high-performance small-object system were designed and constructed by UCDWR, San Diego, California. These units generally combined the earlier work of British laboratories together with certain improvements in transducer design and pulse modulation. The SOD 501 using a pulse variable from 0.1 to 3.0 msec, with a special ADP crystal transducer and a chemical recorder modified to have a slow paper speed, achieved maximum ranges of 1,500 yd under good conditions. One experimental installation was in an operational fleet-type submarine operating in the Pacific. Further development work on this program is continuing at the Naval Electronics Laboratory in San Diego.

Chapter 12

PROSUBMARINE EQUIPMENT

By *John S. Coleman*

12.1 INTRODUCTION

BY THE SUMMER of 1943, the successes achieved against U-boats in the Atlantic and a comparative absence of enemy submarine activity in the Pacific made possible a concentration of effort toward aiding U. S. submarines. Conferences were held with NDRC representatives and the Navy, which culminated in the establishment of a program of prosubmarine development by Division 6. The program was assigned to the U. S. Navy Radio and Sound Laboratory at San Diego and the U. S. Navy Underwater Sound Laboratory at New London.

Antisubmarine projects which could not be completed in time to contribute effectively against enemy submarines were therefore set aside or carried at low priority, and a transition phase began which resulted in the laboratories turning the major part of their effort toward the development of prosubmarine apparatus and preparation of training programs for the assistance of submariners.

Because of the urgency for development and improvement of antisubmarine equipment during the first part of the war, development and improvement of prosubmarine equipment had been somewhat neglected. Consequently, it became necessary to develop and improve equipment for (1) aiding evasive tactics, (2) recording and eliminating self noise, (3) detecting and locating mines, torpedoes, and depth charges, and (4) communicating internally and between boats.

The prosubmarine program included the development of new-type submarine listening equipment, developing internal and underwater communications systems, conducting noise-reduction studies, and modifying other equipment to new or expanded functions.

At this time, most fleet-type submarines were equipped with supersonic bottomside listening gear only. In the spring of 1942, exploratory work on sonic listening led to the experimental installation of a sonic magnetostriction hydrophone on an older submarine previously equipped with a topside training gear. The results obtained and the tactical advantages in target detection and approach seemed to justify the development of a simple directional sonic listening gear designed primarily for evasion tactics. A number of experimental units were tested and proved satisfactory, leading to a final design which was made available to the Navy in 1943. This gear designated by the Navy as JP-1 sound receiving equipment is now standard on all U. S. submarines.

A number of other projects stemmed from this beginning. The JP-1 was used on patrol to reveal the existence of noise on the submarine itself, noises which might also be detected by enemy listening gear. Later a simple, permanently installed *noise level monitor* [NLM] was developed to give accurate measurement of ship's own noise while on patrol.

By August another application of sonic listening utilizing JP-1-type components yielded a system capable of giving an underwater range of a target ship by triangulation techniques. This system known as *triangulation-listening-ranging* [TLR], was carried to the stage of prototype construction by a commercial manufacturer. As experience with JP-1 and the TLR experimental models accumulated, plans were formed for a greatly improved JP-1 system affording greatly improved features. This system, designated JT, was accepted and was being installed on all JP-1 equipped submarines.

Requests were also received by the division and its laboratories to assist in the task of improving existing submarine sonar systems and in particular, adapting them to the functions of torpedo and mine detection. A study was made of possible design modification in the WCA-2 system. As a result, a number of recommendations were made which led to the design and construction of 12 experimental conversion units [MATD]. Also, the Bell Telephone Laboratories [BTL] were commissioned to engineer a complete, integrated system having

higher performance characteristics, greater flexibility in operation and capable of listening and echo ranging over a very wide range of frequencies. An experimental model of this system identified as 692 sonar was constructed but had undergone only preliminary sea trials at the end of World War II.

Although the scanning sonar systems, described in Chapter 11, had originally been conceived as antisubmarine equipment, it should be noted that they proved to be very adaptable for submarine service. In particular, the QLA system, developed by the San Diego laboratory and installed on fleet-type submarines is credited with making possible a successful invasion of the Sea of Japan.

High performance reports have also been received by HUSL from an experimental XQHA installation.

12.2 SONAR SYSTEMS

12.2.1 JP and JT Listening Equipment

The JP-1 equipment provides a sonic listening system covering the audible spectrum from 100 to 12,000 c. It employs a 3-ft straight tubular magnetostriction hydrophone mounted in a baffle which reduces response to sounds arriving from the rear. The hydrophone and baffle assembly is rotated by a through-the-hull topside hand-operated training gear which is operated from a station in the after end of the forward torpedo room. An amplifier is provided which receives power from the submarine's main batteries. This insures operation as long as the submarine has battery capacity. The amplifier is equipped with magic-eye visual indicator, filters for selecting various bands in the sonic spectrum, a special detector circuit which aids counting of propeller revolutions, and headphones or a loudspeaker for direct listening to target sounds. Information thus obtained can be relayed to the conning tower via an improved battlephone system. The hydrophone training gear is designed to prevent the possibility of binding at evasion depths. About 110 JP-1 equipments were procured, to which were later added 150 JP-2 and 50 JP-3 installations. The three systems are identical in performance.

The performance of the JP-1 system proved to be very satisfactory. The average initial detection range reported during patrols was about 12,000 yd, although ranges as great as 40,000 yd were reported. Targets were heard with JP-1 gear at ranges greater by an average of 50 per cent than the submarine's supersonic equipment. The equipment has also been used for detecting own-boat noise. It is also possible to maintain reasonably accurate bearing contact with surface vessels running overhead.

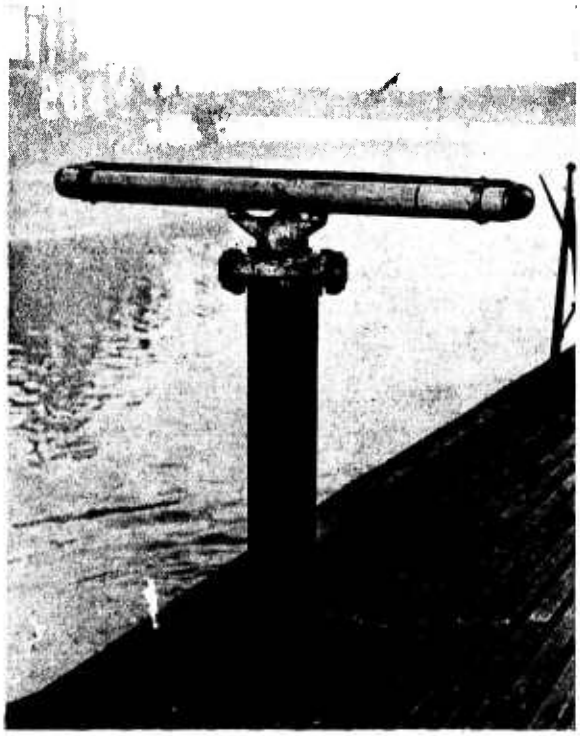


FIGURE 1. JP-1 hydrophone installation.

At the time JP-1 gear was being installed, studies of possible improvements were carried out. A number of improvements were made and included in the JT modification, along with others described in the following section.

Among the improvements made on JP-1 gear were the following.

1. Development of a system providing the approach officer with means for directly observing the hydrophone bearing, for listening to the hydrophone signals, and for communicating directly with the JP-1 operator. This

system, the bearing and sound repeater, in effect makes the JP-1 operator a part of the conning tower attack team, although he remains in the forward torpedo room.

2. Development of a converter for detecting any enemy communication or echo-ranging signals in the supersonic spectrum.

3. Improvement of listening amplifiers which incorporate all the desirable features of

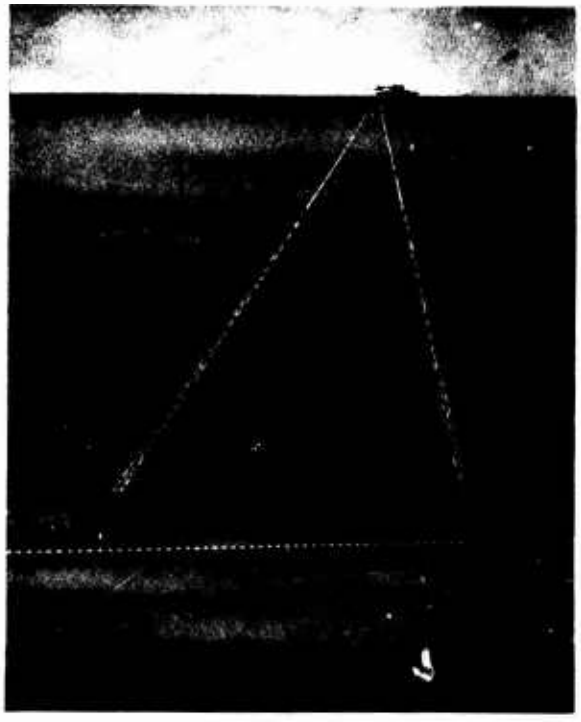


FIGURE 2. Triangulation-listening-ranging system.

JP-1, NL-118A, and NLM, plus certain added features.

4. Provision of a 5-ft hydrophone for better range and bearing accuracy. An improved baffle was also designed and a rubber shock-mounting for the hydrophone and baffle was developed which helped to isolate the hydrophone from the mechanical vibration of the submarine hull and to reduce interference.

In the spring of 1944, it was recognized that the improved features could be engineered into existing submarines as modifications of the JP-1 gear. Active development work was undertaken and the system was designated as Model JT sonar system.

12.2.2 Triangulation-Listening-Ranging

In 1943, the New London Laboratory gave consideration to a possible future time when submarines would be exposed increasingly to improved enemy ASW operations both from aircraft and surface ships, especially with effective radar. Likewise, it was recognized that submarines are hampered by the necessity to refrain from echo ranging because of the danger of betraying their presence to an alert enemy. As a solution to this problem, the laboratory undertook the development of a submarine *triangulation-listening-ranging* [TLR] system to provide means for silent determination of the range of a target when the submarine was below periscope or radar depth.

Essentially, the system consisted of two directional hydrophones, positioned as far apart as possible on the topside, having power training and means for maintaining accurate bearings on the target, together with appropriate mechanisms designed and constructed by the Sperry Company for calculating the range automatically from bearing information fed in by means of synchro repeaters. The accuracies required, particularly in measurement of target bearing, were such as to involve many months of experimental work and the development of (1) a highly accurate training system, (2) new hydrophones possessing improved directional characteristics, and (3) means of automatically tracking the target, using the output of a lobe-comparison system, or right-left-indication [RLI], in order that bearing information might be accurate and continuous. A preliminary system was tested and proved highly successful. As the result of its demonstrated performance, the Navy requested experimental equipment to be installed on a fleet-type submarine for appraisal of operation under patrol conditions. Later, five engineering models were built by the Submarine Signal Company and designated Model XJAA sonar equipment.

12.2.3 WCA-2 Modifications

Developments in the Pacific war in 1944 made it necessary to alter the general prosub-

marine program in order to give attention to means for the detection of torpedoes by submarines. Following various trials, a modification kit known as the *torpedo detection modification* [TDM] was prepared. Test sets were found to be satisfactory and by March 1945 units were being installed in submarines operating in the Pacific.

With the completion of the investigations and sea trials, activity was again applied to the original problem of single ping echo ranging. Although the problem had been limited initially to the improvement of accuracy and reliability of range measurements, as a result of the experience with underwater telephony and TDM it was recognized that the WCA-2 submarine sonar gear was capable potentially of improvement in its established functions, as well as the addition of valuable supplementary functions. Accordingly, the problem of modifying the WCA-2 gear was carefully reviewed and it was found possible to adapt a functional switch through which all system interconnections could be made. By means of appropriate modifications seven different operations of the equipment were available: (1) single-ping echo ranging by modified modulated pulses, (2) torpedo detection by supersonic listening, (3) mine detection by short-pulse echo ranging, (4) underwater telephony, (5) code transmission, (6) supersonic listening, (7) system aligning and testing.

The PPI type of presentation used in this modification permitted immediate reading of both bearing and range of any target giving a distinguishable echo.

Mine Detection

Late in 1944, the New London laboratory concentrated all efforts on the immediate construction of 12 mine detection units. While the preliminary work was in progress it was realized that the mine detection equipment and the torpedo detection modification [TDM] made use of a number of equipment units in common. Accordingly, designs were revised to include provision for torpedo detection as well as for mine detection. Thereafter, the equipment became known as MATD (mine and torpedo detection) gear. A prototype model for trials on a submarine was rushed through on high priority, and simultaneously, further tests of the central fundamental elements were carried out from a surface ship. In the winter of 1945, a prototype model was installed on a ship and an extensive series of trials showed that, in general, the equipment gave the expected operating performance. By adding a simple accessory unit to the MATD equipment it was found possible to provide means whereby all the features to be desired in a single-ping echo-ranging system were at once available. Thus amplified, the MATD modification appeared to permit the WCA-2 equipment to meet adequately all the more important services which may be performed by supersonic apparatus.

12.2.4 The 692 Sonar

At the time work was begun on the 692 sonar system, the standard systems in use on submarines were rather limited in scope. Need was expressed for a system which would supply information comparable to that obtainable with a periscope. A complete sonar system was required which included means for scanning mine fields, self-noise monitoring, torpedo detection, location of depth charges, sonic depth finding, and underwater communication.

The equipment designated 692 submarine sonar, from the OSRD contract number, was designed more to facilitate the investigation of sonar requirements than to supply a working system. The scope of the development, therefore, was quite broad in regard to component features, controls, and adjustments and the parts were not completely integrated as they would be in standard equipment.

The original project called for the development of a listening system only, which was to be supplemented with a standard surface vessel type of echo-ranging equipment operating at 24 and at 50 kc. Subsequently the project was expanded to include the development of a short-pulse, high-peak power, echo-ranging equipment to operate over the range of frequencies from 10 to 50 kc. Finally, it was agreed to include in the echo-ranging system a PPI for mine detection.

The completed system, which was delivered to the Navy, provided continuous search at speeds up to 60 rpm, rapid shifting between continuous search and hand training, automatic or aided target tracking, and maintenance of true bearing. The self noise of the training system was low enough so as not to affect listening. The listening system was capable of differentiating between two targets of the same intensity 5 degrees or more apart. The usable frequency range extends from about 200 c to 60 kc, but the band below 10 kc is used only for detection listening and not for bearing determination because of its poor directivity.

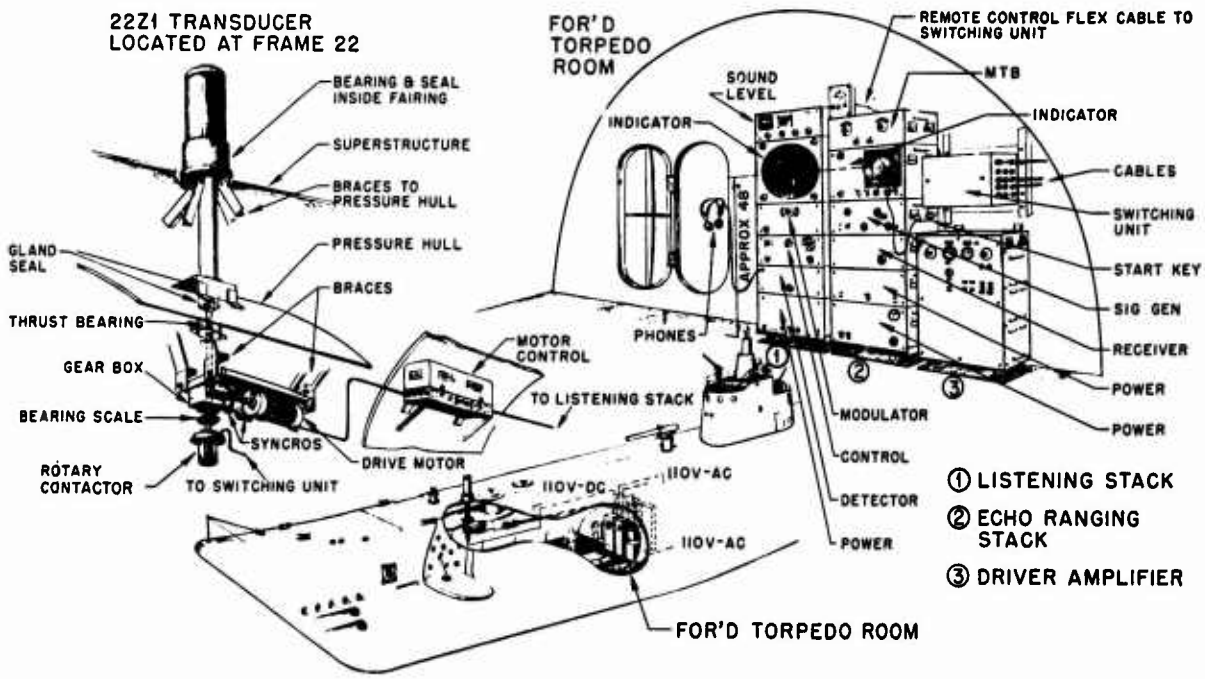


FIGURE 3. 692 sonar.

Although the field trials of the 692 sonar were of a limited nature, sufficient data were obtained to confirm the above statements on performance. No trials were made of the short-pulse echo-ranging equipment except to check its operation. It is expected that further trials will be made by the Navy to obtain additional information on the capabilities of the system.

12.2.5 QLA Sonar for Submarines

The FM (later designation QLA) sonar project was carried out by University of California, Division of War Research [UCDWR] as a part of the general program for development of new antisubmarine sonar equipment as mentioned in Chapter 11. However, by the time the fundamental research and engineering work had culminated in an acceptable scanning sonar system, emphasis had shifted from antisubmarine activities to the prosubmarine aspect, especially in the Pacific theater where our submarines were encountering heavily mined areas close to the Japanese homeland. QLA had earlier demonstrated its ability as a mine detection device in Atlantic and Mediterranean tests, and as a result, the Navy requested several systems for submarine installation.

These systems, although of the same basic design as the evaluation models originally developed for antisubmarine work, were repackaged and slightly modified with an eye to the installation space limitations and the particular mine detection applications contemplated for submarine use. These considerations led to the incorporation of the PPI screen and all system controls in a single compact indicator unit which could be installed in the already crowded conning tower. The bulk of the system could then be installed at some remote point in

the submarine where space was at a lower premium, usually the forward torpedo room. Special attention was given to the choice of range scales best suited for mine detection and plotting. Transducer construction and training gear was improved to provide the strength necessary to withstand the buffeting of heavy seas, especially with deck-mounted installations.

A total of 48 such systems were built, 22 of which had been installed on operating submarines up to the time hostilities with Japan ceased.

12.2.6 XQKA (ER Sonar) System

Harvard Underwater Sound Laboratory [HUSL] developed an electronic scanning system which had scanning speeds of 350 rps. This permitted the use of transmitted pulse lengths as short as 3 msec and provided excellent range resolution. The use of short pulses is especially advantageous in the detection of small reflecting objects, such as mine cases. This feature made the ER scanning system welcome aboard submarines. Three experimental models of this equipment designed for submarine installations were constructed by HUSL under the designation XQKA. The first of these models, installed in USS *Dolphin* at New London, indicated a normal detection range of 600-1,400 yd for standard mine cases, with occasional indications at ranges as great as 2,100 yd. The typical discovery range appeared adequate to permit the submarine commander to conn his vessel safely through a mine field. One of these experimental models was at Pearl Harbor for service trials under NRL auspices when World War II ended.

12.3 SUBMARINE NOISE REDUCTION

In November 1943 a project was initiated to study methods for reducing submarine noises, develop methods for quantitatively measuring submarine under-way or equipment noises, and develop standards for noise measurements. Development work on equipment for making quantitative noise measurements had already been completed in 1943. By means of this equipment, the New London laboratory first undertook a comprehensive survey of the magnitude and spectral-energy distribution of the submarine's auxiliary machinery.

One of the noisiest auxiliaries was the gyro setting regulator which was selected for critical analysis. Extensive measurements made of the component parts of the gyro setting regulator indicated practical ways of obtaining noise reduction by the use of improved mountings as well as redesigning the equipment.

Phonograph recordings, noise and vibration frequency analyses were made of the noises from bow and stern planes, steering, gyro, d-c —a-c motor generators and others, oil, drain and trim pumps, and other auxiliary machinery units in order to determine the most satisfactory methods of reducing noise. Also noise and vibration frequency analyses were made of propulsion motors, reduction gears, shaft and bearing howls. These measurements were made with the submarine at a dock and under way using the hydrophones of the OAY sound measuring equipment at a distance of about 200 ft.

At the time the studies of sound measuring methods were undertaken, such measurements were commonly made on the sound range when the submarine was either under way or on the bottom. Since the measurements on a submarine under construction obviously could not be made on the sound range until it had been nearly completed or placed in operation, the difficulties of making any necessary adjustments or structural changes in the short time available after the measurements were considerably increased.

Therefore an overside technique was developed which permitted measurements of auxiliary machinery noise to be made at dockside during construction of the submarine, prior to sound range tests. This afforded opportunity for any necessary modifications at a stage of construction when changes could be made more readily.

This method was extended to refit areas throughout the United States and advanced bases. However, at certain naval activities where submarine sound measurements were conducted, notably Pearl Harbor, the sound

testing and background noise conditions were unfavorable for dockside measurements and consequently the use of the overside technique was impracticable without supplementary means for reducing background noise. To solve this problem the *auxiliary repair dock* [ARD] was suitably modified by adding an apparatus for creating a sound-insulating bubble screen. The ARD has become an important adjunct of the overside technique because of its mobility and availability in forward areas.

12.3.1 OAY Sound Measuring Equipment

After the New London laboratory initiated its program for studying methods for reducing



FIGURE 4. Model OAY sound measuring equipment.

submarine noise and developing methods for quantitatively measuring the noises, the first step was to develop standardized noise measuring apparatus.

The OAY sound measuring equipment was developed in 1943 and was adopted by the Bureau of Ships. This apparatus thereafter served as the standard measuring device wherever submarine noise measurements were made.

Although field calibrations indicated that the equipment was both reliable and sturdy, certain improvements were made such as the addition of a 1,000-c low-pass (shrimp) filter, and facilities for the use of analyzing equipment. These and other improvements were incorporated in a redesign of the meter and hydrophone. Between 1942 and 1944, the Bureau of Ships' program of submarine noise reduction effected an average 20-db drop in noise level. The New London laboratory, using OAY sound measuring equipment, cooperated in the latter stages of this program.

12.3.2 Noise Level Monitor and Cavitation Indicator

The New London laboratory had developed JP-1 sound receiving equipment in 1943, and had made it available to the Navy for use on patrol. JP-1 equipment revealed merely the existence of own-ship's noises which might be detected by the enemy, and did not measure the noises quantitatively. Observations during initial use of the JP-1 listening system brought out the need for a system which would enable a sound operator to measure accurately the noise produced by his own submarine.

Preliminary monitoring tests were made employing the JP-1 equipment as well as DCDI (depth charge direction indicator) hydrophones connected to the JP-1 amplifier, but these systems were found to be inadequate. A modification of the JP-1 system was finally developed, and named the *noise level monitor* [NLM]. The NLM, which gives accurate quantitative measurement of own-ship's noise, uses four NL-130 hydrophones and either the JP-2 or JP-3 amplifier, together with associated equipment.

A *cavitation indicator* [CI], installed as part of the NLM equipment, gives an indication of cavitation produced by the boat's propellers. The CI employs a fifth hydrophone mounted on the submarine pressure hull close to the propellers, the red light indicator channel of the auxiliary 755 receiver-amplifier, and suitable neon glow lamps. The neon lamps, which give the cavitation indication, can be located either in the conning tower, the forward torpedo room, the maneuvering room, or in more than one of these places if desired, in order to permit quick control of propeller speed and thus avoid cavitation.

The first models were installed on three submarines and later five more were manufactured. Construction of 359 units was authorized by the Navy and installation was begun in the spring of 1945.

12.4 EVASION AIDS

12.4.1 Depth Charge Position Indicators

In March 1943, the New London laboratory began development of a device intended to provide a submarine with reliable indications of the approximate bearing of exploding depth charges. The *depth charge direction indicator* [DCDI] was finally developed which was capable of indicating in which quadrant a depth

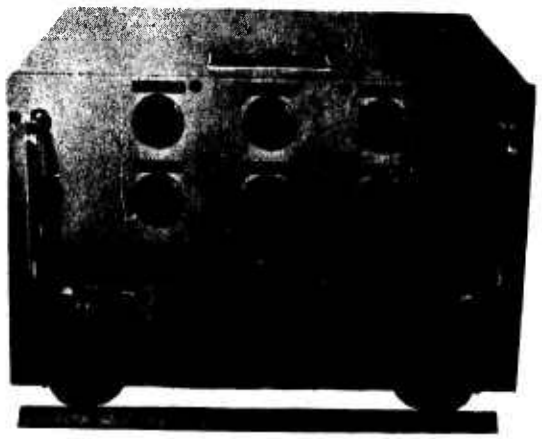


FIGURE 5. Amplifier-indicator panel view of depth charge direction indicator.

charge exploded with respect to the submarine and whether or not it was above or below the boat's centerline. Initial tests of the first model were encouraging and additional, improved models were built. These proved satisfactory in the quadrant indications, although the above-below indications were not always reliable because of the water temperature gradients. The laboratory oceanographic group subsequently devised simple rules for interpretation of above-below indications in terms of bathythermograph traces.

As now designed, the DCDI employs six magnetostriction hydrophones mounted and connected so that when subjected to the shock-wave from a depth charge explosion, an amplifier-indicator in the conning tower indicates whether the exploding depth charge is forward or aft, port or starboard, above or below.

In the process of developing the DCDI, and as submariners visited the laboratory, it became evident that only half the problem had been solved. It was desirable to know not only the general direction of the exploding depth charge, but also the approximate range. It was determined that a rough correlation existed between the range of the exploding depth charge and the amplitude of the initial pressure impulse received. Since the initial pressure impulse is subject to the vagaries of sound transmission in the ocean, the limits within which the range could be determined became the important consideration. A practical *depth charge range estimator* [DCRE] was finally designed which is capable of indicating the range of the depth charge explosion in the following increments: 0-250, 250-500, 500-1,000, and 1,000 yd or greater.

Six development models of the DCRE were built, and after tests proved satisfactory operation, it was recommended for production.

12.4.2 Noisemakers and Decoys

A basic part of the program was the development of sonar countermeasures. Evasion devices of many types were produced for use by submarines and were designed to jam echo ranging, to provide false target indications, to mask or to confuse sonic and supersonic listening, and, in the decoy devices, to simulate submarine target characteristics. Although no single one of these devices was believed to provide absolute protection, tactics were developed using several different devices in combination which significantly enhanced the submarine's chances of escape.

In the spring of 1943, as the emphasis in naval warfare shifted to the Pacific, requests were received from submarine commanders for devices to neutralize or misdirect enemy detection methods. In cooperation with a number of the Navy laboratories, Division 6 laboratories undertook a countermeasures program. The UCDWR laboratory at San Diego had acquired a great deal of directly applicable experience in developing training devices for antisubmarine personnel. The Massachusetts Institute of Technology [MIT] laboratory had participated

in the development of mechanical noisemakers for sweeping acoustic mines. Both groups were experienced in the measurement and analysis of the ship sounds which were to be masked or simulated.

NAC Sound Beacon

The first evasion device to be used in combat was the NAC sound beacon, designed to jam echo ranging. This device, 3 in. in diameter and 31 in. long, after release from the signal ejector



FIGURE 6. The NAC sound beacon.

of a submarine, radiates from a crystal transducer a supersonic signal that sweeps the range of frequencies used in echo ranging several times a second, thus causing a periodic jamming signal. The NAC is equipped with a depth control which supports it at a depth of 50 ft so that it cannot be seen from the surface or recovered by the enemy. This device was used during the spring and summer of 1945 in combination with the Navy's FTS (false target shell) and NAE noisemaker in submarine evasion maneuvers.

XNAG Sound Beacon and Pepper Signal

Both the XNAG sound beacon and the pepper signal were developed by the NDRC laboratories as noisemakers to mask or disguise submarine noises from sonic listening detection. The characteristic noises produced by a submerged fleet-type submarine include a constant-frequency reduction-gear whine which varies in pitch with speed, and an amplitude-modulated wide-band noise caused by propeller cavitation when running above certain vertical speeds. To blanket these noises from detection in any region of the spectrum in which the enemy may be supposed to be listening, a noisemaker must have a high output level throughout the same range of frequencies. The XNAG utilizes two soundheads; an electromagnetic soundhead is driven electronically to sweep through the range of low frequencies where gear whines occur, while a rotary impactor head produces the wide-band output. The high ratio of stored energy to volume, which is characteristic of



FIGURE 7. Mark 20 pepper signal supported on depth control.

explosive materials, led to the development of the explosive noisemaker, pepper signal, which has a firing rate of two shots a second. Effective performance is obtained in shallow water where reverberations maintain a masking level of noise between explosions. In deep water, however, tests have shown that contact with a submarine can be maintained by listening be-

tween explosions. The pepper signal development was completed in time for one unit to be used in the course of a successful evasion.

NAD Sound Beacon

Realistic simulation of actual submarine noise and behavior is approximated by the NAD sound beacons. These decoys are self-propelled, proceeding upon a preset course at preset depth and emitting noise similar in character to submarine self noise while returning echoes with doppler to echo ranging. The NAD-6 and the NAD-10 are released from torpedo tubes rather than from the signal ejector, and have operating lives of 30 to 60 minutes. The self noise simulation of the NAD-6 is provided mechanically by a gear and roller system which vibrates the cylindrical housing of the beacon, simulating both gear whine and cavitation noise. In the NAD-10, a cylindrical magnetostriction loudspeaker is driven by an electronic signal which is made up of an amplitude-modulated wide-band noise and a constant-frequency whine. The echo repeaters in these two decoys are adjusted so that any ping striking the receiver hydrophone is retransmitted at a level equivalent in strength to the echo from a full-size submarine. The smaller NAD-3, which can be ejected from the signal tube, provides simulation of self noise only. NAD maintenance shops and training schools were set up at San Diego and Pearl Harbor during the spring of 1945, and one NAD-6 was used in a successful evasion maneuver.

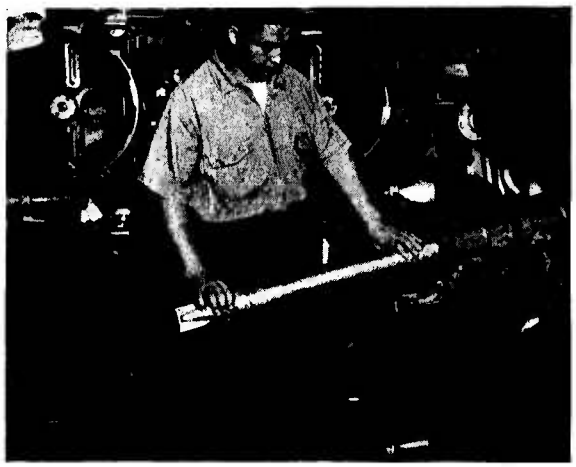


FIGURE 8. Loading NAD-3 sound beacon in signal ejector.

12.4.3 Other Aids

Many other schemes were investigated for jamming, masking, and decoying. Although those devices accepted by the Navy proved useful, their many limitations show that the art is still in its infancy. In the continuing Navy programs, attention is being directed to the re-

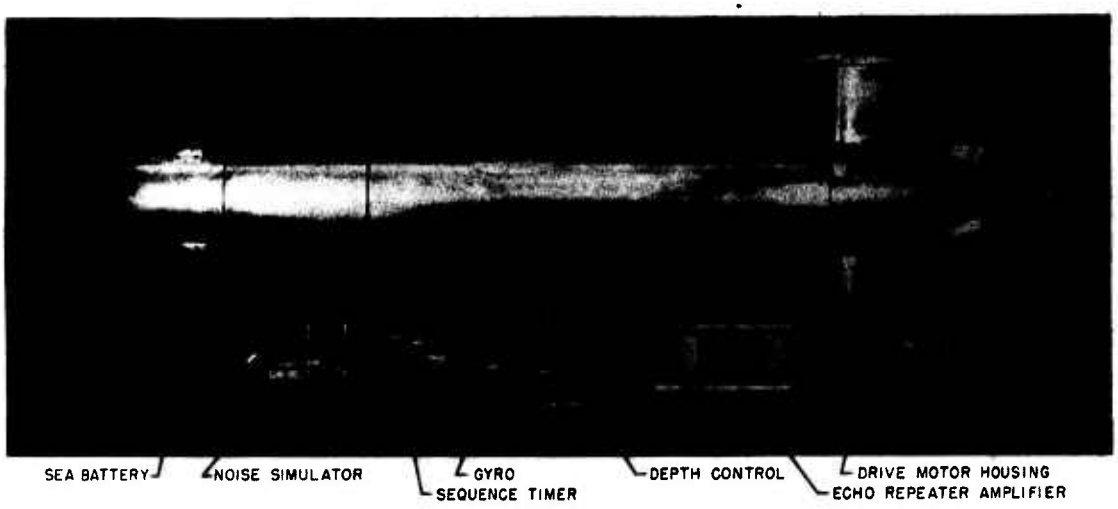


FIGURE 9. NAD-6 sound beacon assembly and subassemblies.

finement of many of these devices. The NAH, using a self-tuning mechanism to keep the radiated jamming signal automatically at the exact echo-ranging frequency in use by the enemy search vessels, is expected to replace the NAC. New, compact fuel sources give promise of increasing the efficiency of sonic noisemakers.



FIGURE 10. The NAD-10 sound beacon.

The development of depth controls, which was an important part of the development of these expendable devices, is also continuing.

A somewhat different approach to the problem of neutralizing enemy detection methods was in the development of an acoustic absorbing coating, to be applied like paint to the exterior of the submarine. Calculations indicate that such a material, if it produced an absorption of 10 db throughout the echo-ranging frequencies would so reduce the effectiveness of echo-ranging detection, that in many oceanographic conditions it would become altogether useless. Both German and Japanese laboratories were carrying on similar developments at the close of World War II. In the coating under development in the NDRC laboratory at MIT, the active part consists of a number of layers of synthetic rubber in which small air bubbles are trapped. This coating appears to be practical. It provides absorption of 10 db at its optimum temperature and pressure and its absorption is independent of frequency between 10 and 30 kc. The work continuing on this program is directed towards increasing control of the pressure and temperature dependence of the coatings, and making fundamental studies of the absorption mechanism to permit better evaluation of its operational performance.

The future development of submarine evasion devices will depend upon the development of new subsurface detection techniques both in the field of listening and echo-ranging gear, and on the development of guided ordnance. A new NAD might be designed to represent a submarine for wake detection, magnetic detection, optical detection, and so forth, as well as for listening and echo-ranging methods. It might also be equipped to execute maneuvers, diving,



FIGURE 11. NAD-10A sound beacon partially loaded in a torpedo tube.

and changing course during a protracted life to increase its resemblance to a submarine. On the other hand, the general concept of false targets might be extended, to provide false wakes, false optical targets, or false propeller sounds. The emphasis on homing ordnance for use against submarines calls for immediate attention to this type of problem.

Chapter 13

ACOUSTIC TORPEDOES

By *Eric Walker*

13.1 INTRODUCTION

BY THE TIME of the first World War the torpedo had reached such a stage of development that it was used both by surface vessels and by submarines. Ever since the proposal by Whitehead in 1866, study had been made of methods for controlling and directing a torpedo toward a target. Many methods for remote control were suggested and some were tried. One of these schemes, which achieved functional if not operational success before 1925, used long-wave radio signals which could be received by the torpedo when it was running at shallow depth. None of the control methods tried before World War II, however, seemed to meet military requirements.

The idea of acoustical tropistics, that is, the use of sound waves to influence a missile to home on its target, was frequently reinvented after 1918. In spite of the attractiveness of applying such homing control to a torpedo, the scheme had always been judged to be impractical because the torpedo was so noisy. It is in fact difficult to imagine a less promising location for a sensitive hydrophone than a position close to a compact, high-speed steam turbine delivering more than 100 horsepower through brass gears to two small propellers threshing the water in opposite directions.

Despite this discouraging prospect, British scientists, prior to the entry of the United States into World War II, undertook experiments to determine just how noisy a torpedo was. On the basis of these noise studies the British developed a satisfactory echo-ranging acoustic torpedo. The Germans also experimented with various types of control and developed several models of acoustic torpedoes. The Italians, too, developed a listening acoustic torpedo, but of questionable effectiveness.

In the United States all consideration of acoustic homing control had been pointed toward its application to full-scale, high-speed torpedoes of the type used in surface warfare. However, the self noise of high-speed torpedoes prevented the application of practical acoustical control. In the fall of 1941, the Navy proposed the application of acoustical control to a small, slow-speed torpedo, and requested the NDRC to set up a research and development program. This program, identified as Project 61, was distributed among several groups and resulted in the development and production of a successful aircraft-launched acoustic listening torpedo which played an important part in underwater warfare against enemy submarines.

Success in application of acoustical homing control in Project 61 naturally revived interest in extension of such control to full-scale, high-speed torpedoes. For this purpose three new development programs were undertaken, beginning in the spring of 1943. One of these, Project NO-149, was intended to provide acoustical homing control for air-launched torpedoes to be used against surface craft. Another, Project NO-157, was intended to lead to application of similar acoustical homing control to an electric torpedo for use by submarines against surface craft. Development of echo-ranging control for torpedoes to be launched from surface craft against submarines was conducted under Project NO-181.

In order to start Project NO-157 as quickly as possible, the Mark 18, an electric torpedo with a speed of 29 knots, was selected as an experimental vehicle and it served in this way throughout the remainder of the program. From the Mark 18 were developed three acoustically controlled torpedoes, designated Mark 28 (20 knots), Mark 29 (25 knots), and Mark 31 (28 knots). Also, the Mark 20, a high-speed (39 knots) electrically powered antisurface ship torpedo was provided with acoustical control.

In a similar way, the steam-driven 33-knot Mark 13 aircraft torpedo served as the experimental vehicle for development of an air-launched acoustic torpedo for use against surface ships, under Project NO-149. The acoustic version was designated as the Mark 21.

The small antisubmarine mine (which in its acoustic version was the Mark 24), served as

an experimental vehicle in Project NO-181 for development of a ship-launched antisubmarine torpedo with echo-ranging homing control. The final model was designated Mark 32. Later, echo-ranging control was also applied to the 29-knot Mark 18 ship-launched antisubmarine torpedo.

Many of the basic development problems encountered were common to all three projects and the various aspects of the problems were pursued with whichever torpedo body seemed best adapted for the purpose. The major part of the effort was directed toward studies of torpedo self noise, improved hydrophones, and electronic control systems. Studies and tests were made to eliminate self noise by developing vibration- and noise-isolating techniques and developing quieter power systems. The program also included tests and studies of stability and control, buoyancy, batteries, motors, and propellers.

The self noise of the torpedoes was reduced by improving the directivity of the hydrophones, by reducing noise and vibration by isolating various components of the torpedo, and by elimination of sources of waterborne noise at the torpedo tail by improving propeller design and by isolating reversing gear supports from the shell of the torpedo tail.

An electronic control system was designed to furnish improved stability and ease of maintenance. This system was called the pilot panel because it used an auxiliary pilot signal to stabilize the amplification of the different hydrophone channels. The electronic control system, improved hydrophones, and isolating techniques, made it possible to furnish manufacturing designs meeting the specifications set up under the three projects.

Although the prototypes of the Mark 21 and Mark 31 performed in accordance with their specifications, neither was manufactured in quantity for operational use before the end of World War II. In July 1945, limited production of these two models was begun at Forest Park and the Newport Torpedo Station in order to continue field tests.

While the Mark 21 and Mark 31 were being developed, BTL and HUSL designed and developed the Mark 28. Some of these torpedoes, manufactured by Western Electric Company, reached the Pacific in time for service trials before the end of World War II.

The Mark 29, successor to the Mark 28, incorporated all the improvements as they became available from the basic research program. The Mark 29 used counterrotating propellers driven by a newly developed counterrotating motor. It included most of the vibration-isolating features developed previously. Preliminary models were completed and tested but the models were lost during the trials and the program had to be terminated before it was possible to determine the relative merits of the Mark 31 and Mark 29 designs.

The echo-ranging model of the antisubmarine mine, Mark 32, was completed by Leeds and Northrup, and tests conducted in 1944 yielded reasonably satisfactory results. No field trials were conducted with the echo-ranging model of the Mark 18. The final experiments under the NDRC program were with the Mark 20 which, in tests, produced self-noise levels at 37 knots comparable to the Mark 31 at 28 knots. The Mark 20 had excellent acoustical steering in both azimuth and depth.

13.2 PROJECT 61

In 1941, the Navy proposed that NDRC set up a research and development program to design a slow-speed torpedo which could be launched from aircraft for use against submarines and which would be quiet enough to permit application of acoustical homing control. The development program (NO-94, later Project 61) was assigned to Harvard University Underwater Sound Laboratory [HUSL], the Bell Telephone Laboratories [BTL], the General Electric Company [GE], and the Columbia University Special Studies Group [CUSSG].

A speed of 12 knots was suggested since this would be sufficient to overtake the fastest submerged submarine then operating and acoustical control could be more easily applied to a weapon of this slow speed than to a standard (noisy) high-speed torpedo. As the acoustical control would lead the antisubmarine torpedo into direct contact with its target, a relatively

small explosive charge would be sufficient to inflict lethal damage. Therefore, development of a device was undertaken to meet the following tentative specifications.

1. Propulsion: electric, single-rotating motor.
2. Power source: lead storage battery.
3. Speed: 12 knots.
4. Duration of run: 5 to 15 minutes.
5. Explosive charge: 100 lb.
6. Dimensions: 84 in. long and 21 in. diameter.
7. Type of directional control: acoustical.

Basin designed a propeller to meet estimated thrust requirements.

BTL AND HUSL SYSTEMS

Several parallel lines of attack on the hydrophone problem were followed. BTL proposed the use of crystal hydrophones mounted in the cylindrical body section of the torpedo, while HUSL explored the use of magnetostriction hydrophones mounted on the nose. The only important differences between the BTL and HUSL systems were the location of the hydrophones and the material of which they were made. The method of operation was the same.

TABLE 1. NDRC torpedo development program (acoustically controlled torpedoes).

Original model designation	Description	Project number	Acoustic control specifications	Final acoustic model designation
Antisubmarine mine	Small-sized, stubby, electrically powered; 12 knots	(NO-94) (Fido) project 61	Air-launched, antisubmarine; acoustic homing control	Mark 24* Mark 27* (revamped Mark 24)
Mark 18	Antisurface ship, electrically powered; 29 knots	NO-157	Submarine-launched, antisurface ship; acoustic homing control	Mark 28 (20 knots)† Mark 29 (25 knots) Mark 31 (28 knots)
Mark 20	Antisurface ship, electrically powered; 39 knots	NO-157	Submarine-launched, antisurface ship; acoustic homing control	Mark 20 (37 knots)
Mark 13	Antisurface ship, steam driven; 33 knots	NO-149	Air-launched, antisurface ship; acoustic homing control	Mark 21 (33 knots)
Antisubmarine mine	Small-sized, stubby, electrically powered; 12 knots	NO-181	Ship-launched, antisubmarine; echo-ranging homing control	Mark 32 (12 knots) (also air-launched)
Mark 18	Antisurface ship, electrically powered; 29 knots	NO-181	Submarine-launched, antisurface ship; echo-ranging homing control	Mark 18, echo-ranging model. (Untested)

* Used successfully in World War II combat.
† Combat performance record classified.

In the BTL system, steering was accomplished by mounting four hydrophones symmetrically around the axis of the body, two for vertical control and two for horizontal control. Arranging the hydrophones in pairs for up-and-down and right-and-left directional control made it possible for the mine to steer always toward the location of the noise source regardless of how the highly maneuverable body might roll or twist in attacking and reattacking.

A depth control was designed so that in the absence of any signal from the target the mine would cruise at a depth of 45 ft. Rudder areas were sufficient to produce a turning circle of small radius (35 ft). In the absence of target signal, the combination of proportional rudder response and small unavoidable unbalance in the hydrophones, amplifier channels, and received self noise usually produced rudder positions which caused the body to execute a satisfactory searching circle about 50 yd in diameter.

Early systems utilized a comparison amplifier which employed a mechanical commutator allowing a single amplifier channel to be used alternately for right-and-left or up-and-down steering. This mechanical commutator was eventually replaced by an electronic switching arrangement.

Effort was devoted during 1942 to problems arising from air launching of the device. A strengthened body was constructed to permit drop tests of the electronic components and control equipment. Information was thus obtained concerning the methods of constructing and mounting the equipment to withstand the shock occurring at water impact.

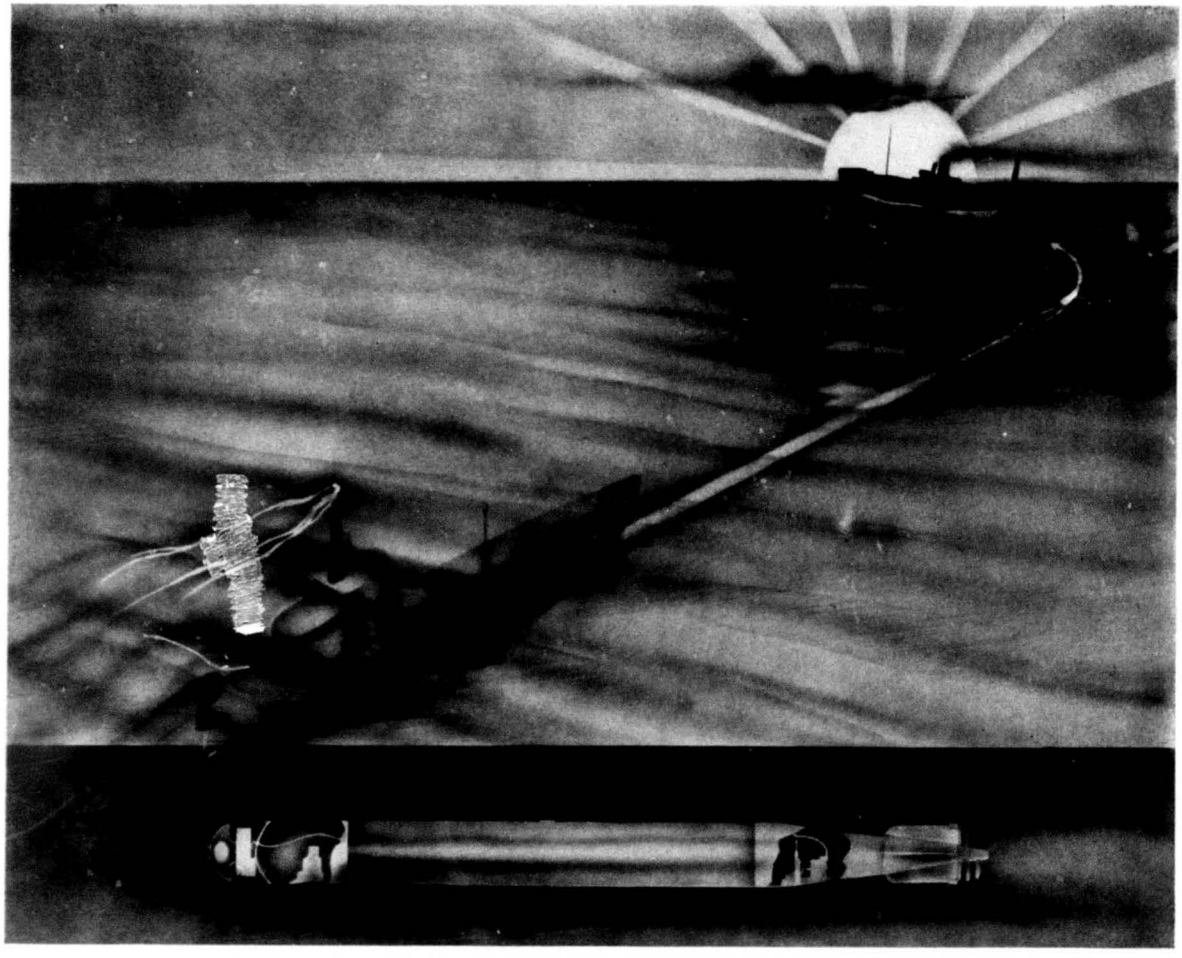


FIGURE 1. Project NO-157, submarine-launched listening torpedo.

THE MARK 24

The final production model selected was based on many of the features developed by BTL including the provision of crystal hydrophones mounted symmetrically on the body. Further tests were carried out during 1943 and 1944

to investigate the behavior of the production model of the Mark 24 under special operating conditions. Particular attention was given to adjustments permitting the mine to attack deep submarines. Successful attacks were carried out on artificial targets at depths of 435 ft and preliminary tests have indicated that the limiting depth of the body is about 600 ft. In order to facilitate deep attacks, a standard running depth of 150 ft was recommended and corresponding changes were made in the mines already in the operating theaters.

THE MARK 27

Later, a longer torpedo body was used and this revamped Mark 24 developed by BTL was designated Mark 27. The Mark 27 was intended to be a protective device to be used defensively against attacking enemy submarines. However, skippers found that it was also an effective offensive weapon. The Mark 24 and Mark 27 were the only acoustic torpedoes used extensively during World War II and a record of their results shows that they were an important factor in controlling and eliminating the U-boat menace.

13.3 PROJECT NO-157

This project, concerned with the application of acoustical homing control to an electric torpedo for use by submarines against surface craft, resulted in the designing of four models, the Mark 28, Mark 29, Mark 31, and the Mark 20 (37-knot acoustic version). Each of these four models met the specifications of the project. However, the Mark 31 and the Mark 20 were the most successful in field tests, and further development work on these models is continuing.

During the successful field trials of production units of the low-speed acoustic antisubmarine mine, the Mark 24, engineers became eager to experiment with the application of similar acoustical control methods to a full-size high-speed torpedo. In April 1943, two units of the electric torpedo Mark 18 were made available to HUSL for experimentation. The first problems tackled were those of installing hydrophones in the nose of the empty warhead and providing amplifiers and recording equipment for measuring the self noise of the torpedo under operating conditions. The first trials revealed that at the high speed of 29 knots this torpedo was indeed very noisy. Consequently, adjustments were made to provide for lower operating speed.

The sound fields produced at various distances by various warcraft were studied and target specifications were established. For a 20- or 25-knot torpedo to be effective it should be susceptible to the sound levels produced at a range of at least 200 yd by a destroyer or cruiser operating at 15 knots, or by a merchant vessel operating at 8 to 12 knots. Studies indicated that acoustical control on a sound field of the order of −39 db spectrum level (db vs 1 dyne per sq cm for 1-c bandwidth) would be required to provide a useful tactical range for the acoustic torpedo. Early trials indicated that the Mark 18 electric torpedo would not meet this specification at its full operating speed.

The development program was accordingly subdivided so that the three overlapping aspects of the problem might be attacked simultaneously. They were:

1. Continuation of the program of torpedo self-noise measurements and analysis.
2. Development of hydrophones to have improved discrimination against self noise originating near the stern of the torpedo.
3. Experimentation with methods of quieting the reversing gears.

The program of noise measurements led to improved understanding of the role played by cavitation at the torpedo propellers and also revealed that even in the absence of cavitation there were enough other sources of self noise to justify the long-held skepticism of the feasibility of acoustical control for high-speed torpedoes.

However, it has been found that good noise-reducing results could be obtained by a simple modification of the standard Mark 18 torpedo tail, namely, the vibrational isolation of the three-pronged spider which carries the reversing idler gears. Also the nose section, carrying the hydrophones, was isolated by a gasket arranged to avoid any metal-to-metal contact and

the directivity of the hydrophones was improved.

Another opportunity to introduce vibrational isolation in the noise transmission path was afforded by the mounting of the hydrophone itself. The hydrophone mounting problem received intensive study aided by a long series of measurements. Continued hydrophone research had led to design of a unit having such improved directivity that under favorable conditions there was as much as 35 to 50 db discrimination between sounds arriving along the axis of the hydrophone and sounds arriving from the rear along the axis of the torpedo body.

Combining the results of these various studies, it appeared possible in late 1944 to assemble a modified Mark 18 torpedo containing isolated idler gears, vibration-isolating gaskets between the body and the nose, and a group of four isolated hydrophones mounted in the nose section.

The combination of these modifications together with a new four-channel comparison amplifier (utilizing pilot signal method) yielded an acoustic torpedo that operated on specified sound levels at a speed of 28 knots.

The Mark 28

During the development program, the HUSL and BTL groups obtained sufficiently optimistic indications to suggest that it would be feasible to undertake commercial production of an acoustic torpedo that would operate at 20 knots with a single propeller, thus eliminating gear noise. The device was frozen for production purposes at the prevailing stage of developments, and Westinghouse Electric Corporation [WE] was assigned to design and manufacture the torpedo designated Mark 28. Acoustical control equipment was produced by the Western Electric Company.

The Mark 29

As the research program continued, designs by BTL and WE began to take shape for a 25-knot successor to the Mark 28, designated Mark 29. Among the new features introduced in the research program for the Mark 29 was the use of a counterrotating electric motor which could be coupled with two propellers without the use of noisy reversing gears. Though an improvement from the standpoint of noise reduction, this arrangement failed to achieve either the weight reduction expected, or the advantage of automatically balanced torque.

Several hundred Mark 28's were manufactured and delivered to the Navy. Three experimental Mark 29's were constructed, but were lost during initial trials before their acoustical behavior could be tested.

The Mark 31

As mentioned previously, when the Mark 18 was equipped with modifications for self-noise reduction and increased directivity, it displayed satisfactory acoustical control at 28 knots. Such modification of the Mark 18 was given the designation Mark 31 and an experimental lot was manufactured. Performance of the Mark 31 in reasonable accordance with the design objectives was obtained in trials at Solomons, Maryland. However, the ordnance development program was transferred from HUSL to the Ordnance Research laboratory at the Pennsylvania State College and took place before tests had been made to establish the relative merits of the Mark 29 and the Mark 31. Future development work might be directed to combining the inherent advantages of the counterrotating motor of the Mark 29 with other desirable features of the Mark 31.

The Mark 20

Early in World War II, GE had developed a high-speed motor with reducing gears for torpedo propulsion. This relatively lightweight motor was incorporated in the Navy's Mark 20 torpedo which was expected to operate at 39 knots with a primary battery. A new spherogive head was designed for the Mark 20 and four of the latest 12-tube magnetostriction hydrophones, shown in Figure 2, were fitted in forward-looking, downward-tilted internal mounts. With this new head, the recorded self-noise level of the Mark 20 at 37 knots appeared to be even lower than that of the Mark 31 at 28 knots. The acceptability of this noise level was confirmed by reconnecting, as a steering

amplifier, the pilot channel amplifier used for noise measurements and conducting steering trials. Acoustic steering with this torpedo at 37 knots was obtained in two runs (one in azimuth and one in azimuth and depth) in October 1945.

13.4 PROJECT NO-149

Project NO-149, to provide acoustical homing control for air-launched torpedoes to be used against surface craft, resulted in development



FIGURE 2. An exploded view of the 12-tube magnetostriction hydrophone and an internal view of four similar hydrophones mounted in a torpedo nose.

of the Mark 21 steam-driven torpedo which met the original specifications. Experiments are in progress, however, to improve further the acoustic performance.

While HUSL was working on the acoustical development of the Mark 18 torpedo, two 33-knot Mark 13 steam-propelled aircraft torpedoes were received to serve as interim vehicles for experiments leading to design of an acoustic aircraft torpedo. It was soon apparent that very drastic steps would be required if acoustical control of the noisy device was to be achieved.

Hydrophones and noise-recording equipment were built into the empty warheads and noise tests were conducted. It was concluded that in order to permit satisfactory acoustical control, all noise from the turbine would have to be suppressed until it was at least as low as that generated by the propellers and the passage of the body through the water.

Methods were worked out for operating the Mark 13 at speeds as low as 18 to 20 knots, but although the self noise became more nearly acceptable at these speeds, this low speed was not tactically useful against fast surface craft. Still other modifications were needed. Because the device was to be air-launched, the domes had to be built up in order to protect the electronic gear.

THE MARK 21

Continuous noise-reduction tests proved discouraging, and just as the project was about to be abandoned in the spring of 1944, the engineer in charge of the noise-reduction program was given permission to make six additional runs. Disregarding the scientific principle of changing only one variable at a time, he undertook to do everything possible to quiet the device.

These changes included isolating mounts for the hydrophones, vibration-isolating gaskets to support the bulkhead which carried the turbine and the propeller-reversing gears, and wrappings of acoustic insulating material for all interior conduits and piping. (See Figure 3.) During the next run, the observed self noise was very much lower than had been observed previously, and repeated trials demonstrated that a profound change had been introduced.

Further studies indicated that vibrational isolation of the engine bulkhead was the principal quieting feature. Careful study was then devoted to methods by which this isolation could be carried out without interfering with the droppability of the torpedo. Fairprene, a laminated canvas impregnated and faced with neoprene, was found to be by far the best gasket material of those tested. In addition to isolating the engine bulkhead and the hydrophones, vibration-isolating joint rings were installed between the nose and the center section. Thus, three breaks were introduced in the path

leading from the turbine to the hydrophones. These relatively simple changes, in conjunction with the improved directivity provided by 12-tube magnetostriction hydrophones, produced a 33-knot torpedo with self noise of approximately —41 db spectrum level. This performance was sufficient to provide a tactically useful range on a 15-knot destroyer. During development it was not possible to conduct theoretical studies on vibrational isolating materials. Since bilization of the gain of individual chan..els of the amplifier; the other, identified as the quadrature system, was based on an amplifier development made in Project NO-181. The quadrature amplifier required fewer tubes and selective circuits than the pilot channel amplifier, but the latter appeared likely to require less field maintenance and to impose less stringent requirements on the precise adjustment of band-pass filters. Although both amplifiers per-

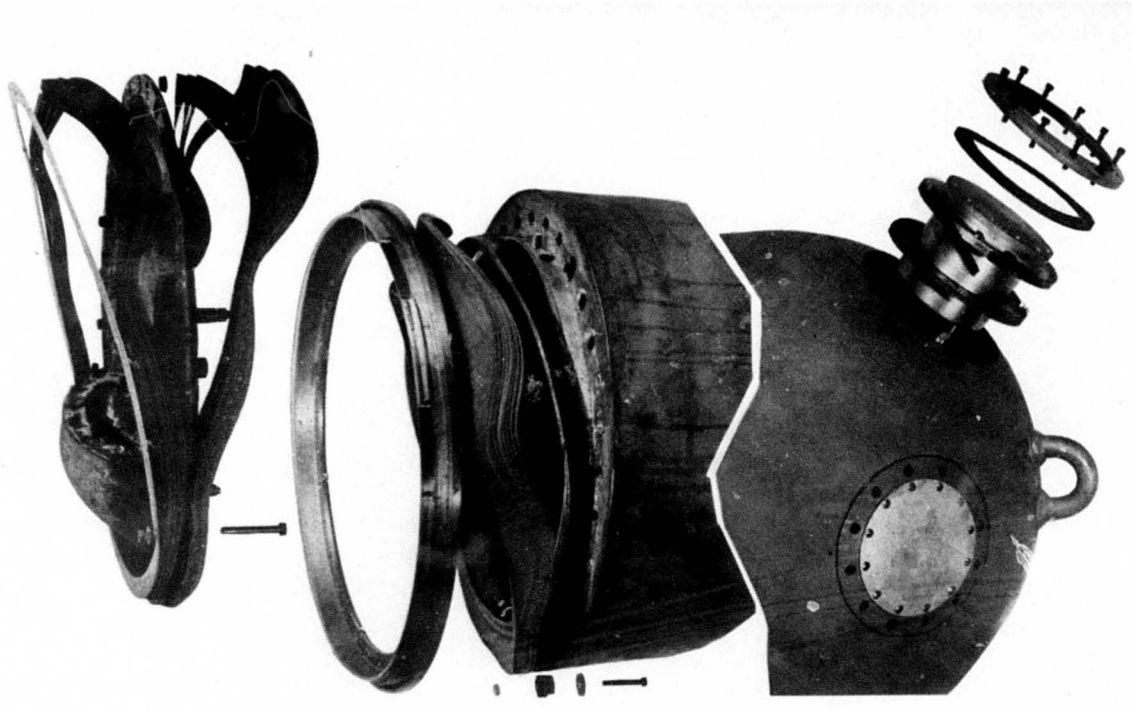


FIGURE 3. Exploded vibrational isolation for self-noise control showing *(left)* the vibrational isolation of the high-speed steam turbine, *(center)* the vibration-isolating forward joint ring with a bayonet lock joint for easy access to the control equipment in the nose, and *(right)* the vibration-isolated hydrophone mounting.

the minimum amount of Fairprene to give maximum isolation efficiency is still unknown, additional studies should be made of this problem.

Before the experimental units of the Mark 21 were recommended for manufacture, it seemed advisable to design a new four-channel comparison amplifier which might incorporate advances in technique made since the rather hurried design of the control panel for the Mark 24 antisubmarine mine. Two plans were advanced. One utilized the pilot signal technique for staformed satisfactorily, the pilot signal unit was selected for manufacture.

In working out the control features of the Mark 21 torpedo it was necessary to provide for transmission of electrical control signals from acoustical equipment in the nose to the air-operated steering engine in the tail. Modifications were necessary in order to adapt the diving mechanism to electrical control. Arrangements had to be made to superimpose the electrical control upon the action of the

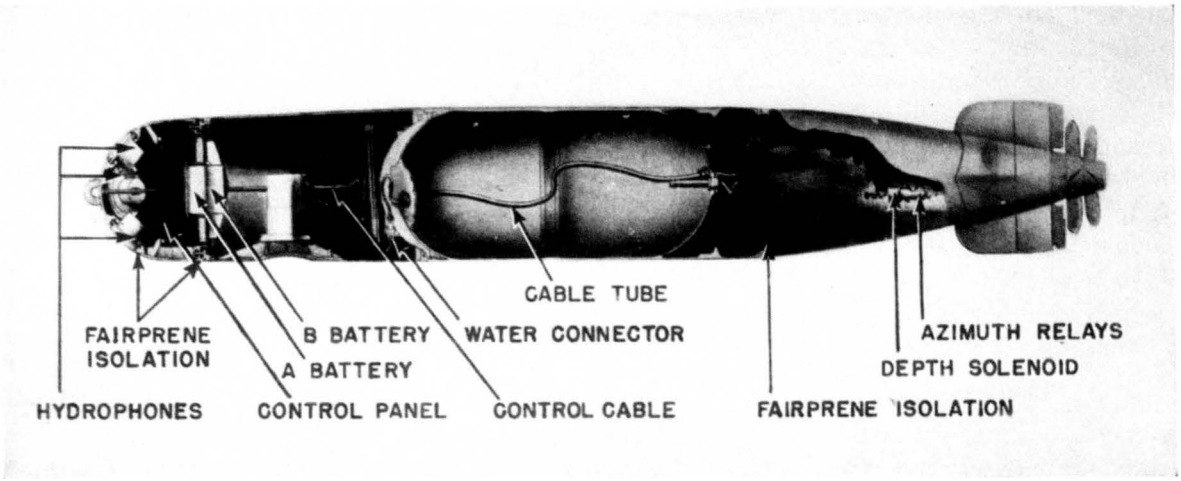


FIGURE 4. Phantom cross section of a prototype of the steam-propelled air-launched acoustic torpedo, Mark 21.

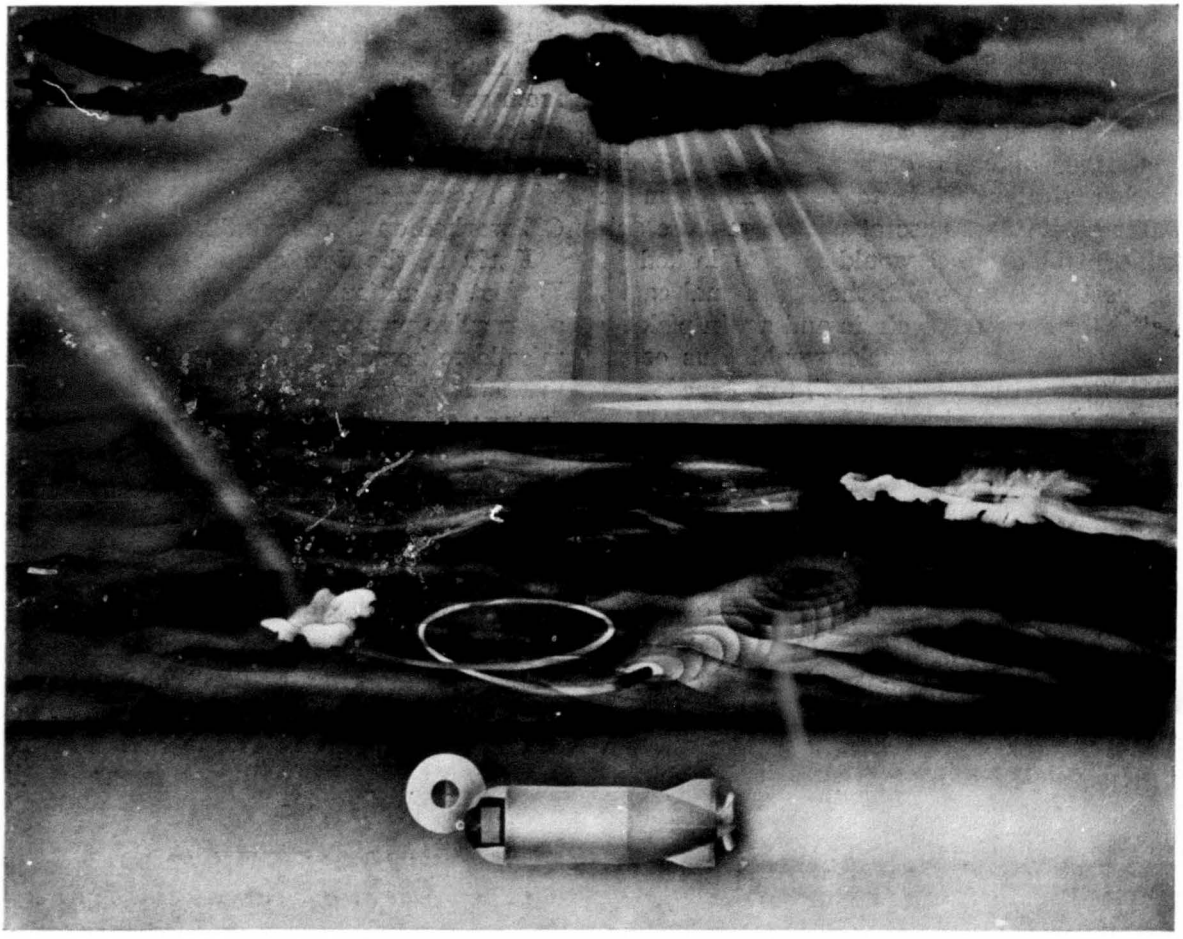


FIGURE 5. Project NO-181, echo-ranging antisubmarine mine.

depth-control mechanism as well as upon the mechanism by which steering information is normally derived from the gyroscope. It was found possible to introduce an elastic link in the latter mechanism in such a way that a small electric solenoid could override the gyroscope information without imposing additional load on the gyroscope. This made it possible for the torpedo to be launched under normal gyroscopic control, with the electrical circuits taking over control after a certain time interval or whenever a suitable control signal became available.

The plan of acoustical depth control selected for the Mark 21 (and Mark 31) called for normal operation at a depth of 50 ft. The azimuth-steering channel was made more sensitive than the depth-control channel so that the first target signals would be received on the azimuth channel alone and would override the gyroscopic control and steer the torpedo in the direction of the noise source. As the torpedo approached the target, the increased signal strength would affect the depth-control channel and cause up-steering which, in turn, would cause a lockout relay to operate, eliminating any further influence of the gyroscope on the torpedo trajectory. If the torpedo failed to make contact on its first pass at the target, the azimuth-control channel would remain locked in the direction from which the last signal came, causing the torpedo to circle and again pick up the target noise. Re-attacks would thus occur until the target was hit or until the torpedo ran out of fuel.

Some difficulty was encountered with broaching when the torpedo was drawn to the surface at too steep an angle. Broaching is undesirable not only because it may reveal the presence of the torpedo but also because the shock at reentry into the water may cause premature operation of the exploder mechanism, and because the torpedo may lose speed by porpoising in the target's wake on a stern chase. To avoid these difficulties a climb-angle limiter was introduced which prevented the torpedo from climbing at so sharp an angle that it could not turn downward again without breaking the water surface.

Previous experience in air-launching the Mark 24 proved valuable in dealing with the aircraft launching problems of the Mark 21. In almost all details, the designs for the Mark 21 components proposed for the production model proved to be droppable without alteration.

In June 1945, full-scale tests were conducted at Fort Lauderdale. These tests involved air launching against both stationary and towed artificial targets and launchings from a PT boat against a destroyer. Several hits were scored during the tests. Although the homing behavior was moderately good, the trials revealed that the increased turning radius resulting from the addition of a shroud ring at the tail had reduced the torpedo's maneuverability for last-moment course corrections. Experiments on methods to decrease the turning radius were in progress when the war terminated. Further development is being continued by the Ordnance Research Laboratory.

13.5 PROJECT NO-181

Project NO-181 called for the development of an echo-ranging control for torpedoes launched from surface craft against submarines and resulted in the development of the 12-knot Mark 32 and an echo-ranging version of the Mark 18 which operated at 29 knots. Both HUSL and GE worked on the Mark 32 development.

Early in the development program for the Project 61 antisubmarine mine (Mark 24), an alternative proposal was made to equip such a missile to home on its target by echo-ranging methods. It was suggested that the most satisfactory solution of the surface vessel conning problem might lie in the use of a self-propelled depth charge which would home on the target submarine by echo ranging. Such a mine could be launched from a surface vessel and, using the attacking vessel's sonar information, could then take up the attack where the surface vessel left off, thereby simplifying the conning problem. In the spring of 1942 a group of GE engineers was assigned to develop such an echo-ranging antisubmarine mine and late in the same year HUSL engineers began studying echo-ranging methods.

The Mark 32 Mine (GE System)

In developing the GE echo-ranging control system, computations were made which indi-

cated that a simple tactic would protect the launching vessel and lead to an almost certain attack on the target. According to this plan the self-propelled body would be arranged to glide downward at a small fixed angle while steering tight circles and pinging as it went. With a reasonable assumed range of echo detection, the speed of the mine body was such that the target could be intercepted before it had escaped from the vicinity of the launching point even if it were operating initially at a depth as great as 400 ft. Submarine operating depths greater than 400 ft and higher submarine speeds reduce the certainty of such interception but a favorable balance can be restored by increasing the speed and rate of descent of the homing depth charge or by increasing the missile's echo-detection range.

Besides offering these attractive tactical possibilities for use by surface vessels, the proposed weapon seemed equally likely to be useful as an air-launched antisubmarine device. Since it would retain its effectiveness in the face of noisemakers which would decoy a listening torpedo such as the Mark 24, its development was undertaken on high-priority basis.

The Modified Mark 18 (HUSL System)

A systematic study was made of echo-ranging methods which might be employed. Development work was begun at HUSL on a high-frequency (60 kc) magnetostriction transducer capable of handling considerable electrical power and which would withstand air launching (see Figure 5) when mounted in the nose of a torpedo body. Then, an echo-ranging transmitter and receiver as shown in Figure 6 had to be designed to fit into a space not much greater than that previously occupied by the comparison amplifier of the listening Mark 24.

In one HUSL version, gating arrangements were incorporated in the rudder-control circuits which blocked all signals except those which met predetermined specifications of pulse duration, amplitude, and frequency shift. The requirement that an echo have target doppler in order to qualify for control insured that the torpedo would home only on moving targets and would ignore artificial bubble targets or other echo-producing decoys.

The transducer program produced a unit designated SPEP which seemed entirely satisfactory at the dropping speeds specified for the project.

An extensive series of field tests were conducted with the Mark 32 in 1944. The most notable shortcoming in the behavior of the HUSL Mark 32 was its operation at ranges less than 50 ft, where the loss of signals occasionally led to glancing impact with the target or to a turn-away just before impact. Although it was believed that this behavior could be remedied by circuit modifications, the anticipated military need for an echo-ranging successor to the Mark 24 was so great that manufacture was initiated on the basis of the simpler GE form of echo-ranging control.

Construction of the improved electronic equipment for the HUSL device was completed in 1945 and plans were made to install it in a full-size Mark 18 torpedo which would provide enough space and buoyancy for the equipment to record all the principal performance factors. No field trials had been conducted when the program was transferred to the Ordnance Research Laboratory.

13.6 FUTURE INVESTIGATIONS

In retrospect, there appears to be a wide gap between the skepticism with which acoustical control for a slow torpedo was undertaken in 1941 and the acceptance of a successful high-speed torpedo in 1945. However, there has been very little advance in the design of the targets throughout this period, and indeed throughout the period between the two wars. Although, the Germans made considerable advances in submarine design, the submarines that saw service in World War II were not much faster than those of the first World War; neither were they much heavier, nor much more highly armored, nor did they carry more potent weapons.

The advent of the atomic bomb may radically change this situation, and much of the scientific talent which has been occupied with weapons and detection equipment for air warfare may be devoted to instruments for underwater warfare. Perhaps it is too early to forecast the effect of atomic power on underwater warfare,

at least in so far as such sources of power will be used for propulsion or destruction. But the fact that torpedoes can be constructed with atomic explosive warheads has already been demonstrated almost beyond reasonable doubt.

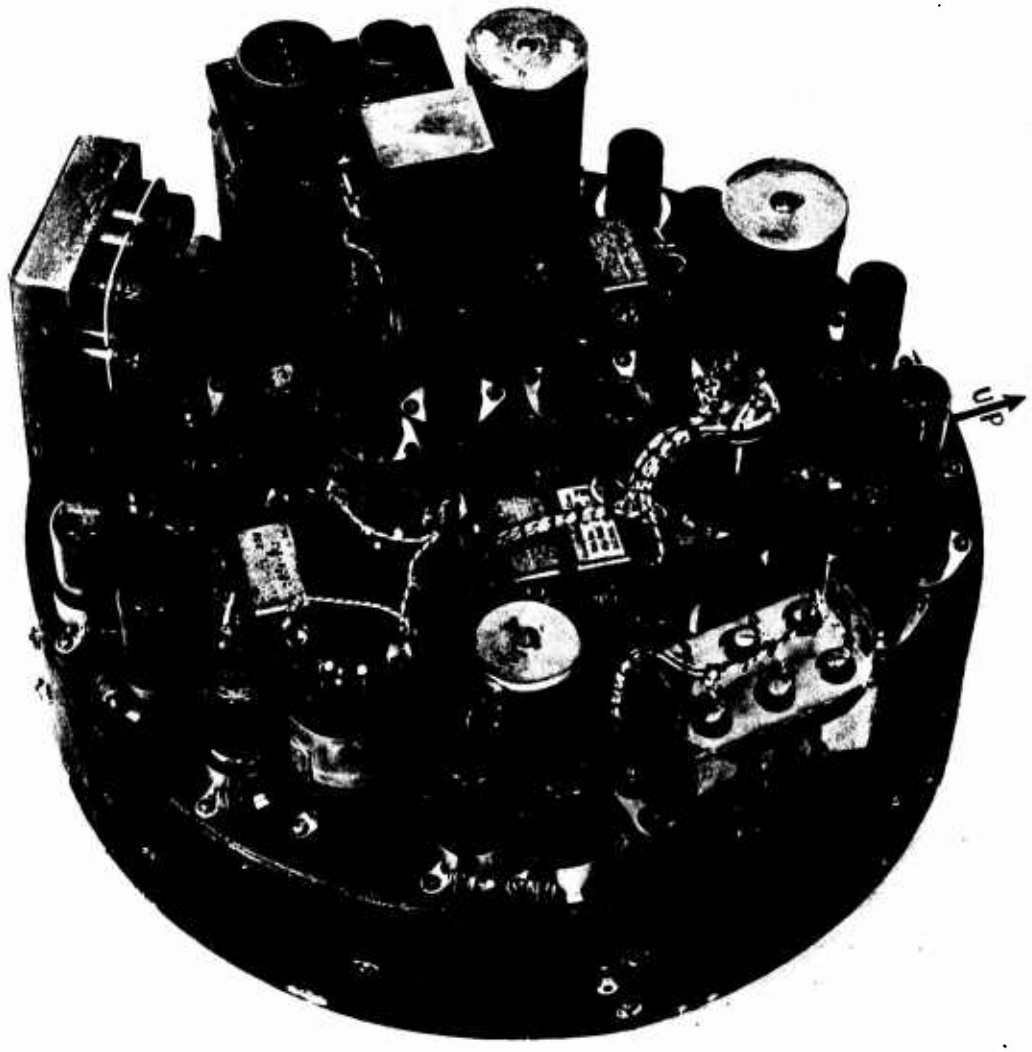


FIGURE 6. Control chassis, for the echo-ranging mine, containing a complete echo-ranging transmitter and receiver.

Also it seems perfectly possible that before too long atomic energy may be used to propel submarines and might even be used to propel guided missiles such as torpedoes. However, the possibilities of other forms of propulsion, such as rockets or jets, should not be neglected. Meanwhile, hydrogen peroxide as part of the combustion mixture is already in use.

No matter what happens, it seems that weapons of stealth, such as the submarine and torpedo, will become more important as time goes on and consequently more time and energy should be directed toward the improvement of such weapons and their countermeasures.

Most of the research and development in

subsurface ordnance during World War II was directed toward modifying and improving existing torpedoes, since the problem of setting up a new line for production of these complex and expensive bodies was very great. But the limiting of research to modifications of existing weapons imposes very severe scientific limitations, which in peacetime can be discarded or neglected. It is quite evident, therefore, that the peacetime research should be directed toward more fundamental research and development to produce entirely new target-seeking torpedoes. The most appropriate method by which this can be accomplished is to direct various scientific groups to obtain all necessary fundamental information for the design of underwater ordnance. Few limitations should be placed on the scope of this research, since it is so difficult to assess the value of any problem before it develops. If possible, the specifications for new weapons should be flexible until the problem has been formulated. Perhaps a proper statement of any such problem would be, for example, "To produce the best aircraft-launched antisubmarine weapon by 1950." Such a specification would allow scientists unhampered exploitation of all their knowledge and encourage them to replace old systems by newer and better ones.

The possibilities of achieving a more universal design should not be neglected, and it may be quite possible to produce a torpedo which can use any one of several homing methods, the proper one to be selected just prior to firing.

Although studies and development of homing torpedoes to date have been almost entirely concerned with those employing acoustical homing means, other methods, including optical, thermal, mechanical, and chemical, should be more thoroughly investigated. In particular, the properties of wakes, which are characteristic of all ships, both surface and subsurface, should be analyzed and evaluated to determine if they can produce a reliable signal on which a weapon can home.

Obviously, any future investigation should also include a consideration of countermeasures to possible enemy weapons, as part of the value of any new system is the time required for an effective defense to be organized.

PART V

TRAINING AND MAINTENANCE

Chapter 14

ASSISTANCE TO THE NAVY IN TECHNICAL TRAINING

By *Gaylord P. Harnwell*

14.1 INTRODUCTION

THE OVERALL PERFORMANCE of an aggregate of technical components such as a ship, its detecting gear, and ordnance, is dependent on the efficiency of the human links between them. More frequently than not, the human elements are the weakest in this complex association, and the successful attainment of the objective is dependent entirely on the abilities and training of the human participants. It was early recognized that a high standard of ability and training was essential for the effective operation and maintenance of sonar gear and for its tactical utilization. The operator's auditory and motor skills are vital factors in the performance of the equipment, and the conditioning through training of his automatic reflexes is essential for his adherence to doctrine and the performance of his duties under the stress of attack conditions.

The efficacy of the gear itself is dependent upon adequate maintenance and adjustment. The matériel problem is a complex one, necessitating on the part of technicians a familiarity with the mechanical and electronic components, the projector, and the tests necessary to insure correct adjustment and optimum performance. The operation and maintenance of the equipment are tasks assigned to enlisted personnel, and large numbers of comparatively new recruits had to be trained in these responsibilities.

In addition to the operation and maintenance of the equipment, both officers and men are involved in the conduct of the attack on the basis of the information supplied by sonar gear. The problems of the officers directing the attack are difficult ones, for the information supplied by sonar is not continuous nor of the highest quality and requires critical assessment at every stage. As the target is not visible, its position must be inferred, and the blind conning of an attack requires a highly developed visualization of a complex relative-motion problem having a wide variety of tactical possibilities. Innate aptitudes for such tasks are undoubtedly of greatest value, but training and experience can greatly increase proficiency in their performance.

It was clearly recognized that adequate training of all personnel participating in the antisubmarine attack was vital to success. However, personnel training was a field somewhat removed from the research and development undertaken by scientists assisting the Navy at the outbreak of World War II. During peace, the field of training occupies a major portion of the time and attention of naval personnel and extremely high competence is developed in broad and diversified skills. But the vast expansion of the Navy in time of war presented a situation which differed fundamentally from that of routine peacetime operation. Large groups of inexperienced civilians were being inducted and had to be given specialized training courses. Broad competence had to be sacrificed to narrow specialization.

The types of services rendered by NDRC appointees and contractors' personnel fall in a number of categories. Industrial psychologists and specialists in training at various levels furnished technical advisory services in selection and training techniques for the guidance of bureaus and operating units. Psychologists and physical scientists having academic backgrounds worked in close and intimate cooperation with naval training activities in the study of methods and techniques in use, in order to improve the efficient use of the brief training period permitted by the urgent demands of the Navy. Physical scientists and engineers, with the guidance of psychologists and other training specialists, developed new training devices. This work was of maximum value when performed in close association with the training activities which were later to use the devices. Finally, civilian training personnel who were experienced in the problems of naval training activities were able to assist the research and development laboratories in the design of combat devices.

On many occasions, specialists assisted in the

introduction of new devices and the establishment of an understanding of the basic principles of their operation in order that Navy units could intelligently establish or maintain local training activities. Temporary training assistants were often assigned to remote commands for the conduct of pilot training programs until this work could be taken over under official Navy auspices. In particularly urgent situations, civilian technicians were furnished to naval training activities for the conduct of technical courses, and in individual instances special advanced courses of lectures on technical subjects were given at the sound schools and other sonar training establishments throughout World War II. In addition to the personal services rendered by such men, the laboratories and other technical groups with which they were associated prepared movies, slide films, slides, charts, manuals, and other training aids to expedite and improve training programs under way or being established.

11.2 THE SONAR ART BEFORE WORLD WAR II

Underwater echo ranging dates in principle from World War I, but the subsequent years of peace did not see a sufficiently well supported and integrated program of research and development to insure adequate preparation for antisubmarine warfare on the scale required by the situation faced in 1941. There were between 150 and 200 destroyers and a somewhat larger number of smaller craft equipped with the old types of QC gear obtained from 1937 to 1940. The equipment was well designed and much of it served throughout World War II. It was also the basic prototype upon which later improvements were made. The gear could be used for supersonic listening as well, and in fact constituted the only equipment for this purpose available to most of the small group of antisubmarine vessels. Submarines had JK equipment which was better adapted for their purposes. The antisubmarine ordnance techniques had remained even more static than those for detection and location. The standard depth charges and throwing and dispensing systems had undergone little change between wars.

Prior to the fall of 1941, a start had been made on the development of tactics and the training of crews in antisubmarine warfare [ASW] attacks. However, knowledge of the potentialities and limitations of underwater sound was limited, very few officers or men were familiar with ASW methods, and the problems of large-scale selection and training were not yet formulated. The effects of temperature gradients, sea state, marine life, bottom character, and water depth were largely unrecognized. The effects of surface-ship speed, target speed and target depth, and aspect on echo strength and character were imperfectly appreciated. Experience had been insufficient to determine the effect of range and bearing precision and of submarine evasive maneuvers on attack success. The value of listening tactics had been given some thought but the subject was a controversial one, and the limitations imposed by self noise, ambient noise, and bearing precision were not well understood. Thus, attack doctrine was in its infancy.

The first information regarding the employment of supersonic equipment for echo ranging purposes was brought to the United States by a commission of French naval officers in about May 1918. Early experiments were later conducted on the USS *Fish Hawk* in the New London area in October of that year, and a report of the Naval Consulting Board dated November 7, 1918, states that, "Equipment located submarines at from 500 to 1,000 yards." Shortly after the *Fish Hawk* tests, the New London Experiment Station was decommissioned. For several years thereafter progress was desultory, but beginning in 1924, experimentation by the Naval Research Laboratory [NRL] resulted in the building of two service models during the winter of 1926-27 which subsequently were installed on the S-49 and S-50. A naval board observed and reported on tests of these equipments which were conducted during January and February 1927. The board's report credits the apparatus with echo ranges of from 1,500 to 1,800 yd for vessels with 18- to 20-ft draft and 1,000 to 1,200 yd on ships having 10- to 12-ft draft. Various echo-ranging equipments were built by NRL and by commercial laboratories under Navy contract in the years immediately

following. By 1933-34 this developmental work produced reasonably rugged and reliable gear that was credited with submarine detection at 4,000 yd at 15 knots (QC-1, Sub Sig).

Training in the operation of echo-ranging and listening equipment during the early developmental period was limited to Navy personnel immediately concerned, who probably were largely self-taught. Initiation of the development of sound tactics was carried on as the primary assigned mission by Destroyer Division Sixty operating in waters off San Diego, California, during the last quarter of 1935. Training of sound operators and officers was a secondary purpose of this mission, but nevertheless, in the period from September to December 1935, a total of 80 enlisted men and 8 officers were given varying amounts of training. In reporting on progress of underwater sound training and development in February 1936, ComDesDiv 60 makes a number of observations and recommendations which give an excellent picture for that time of the status of the echo-ranging art, its tactics, training, beliefs, and aspirations. The report is of especial interest because it covers initial work in an essentially virgin field, the viewpoints are fresh, the shortcomings of the equipment and methods are clearly stated, and desirable improvements in gear and method are envisioned. Condensations and excerpts from the report of ComDesDiv 60 for the period September to December 1935 are given below.

Sound Training

A total of 88 officers and men have been given varying amounts of training (average 22.2 hours operation). A page has been printed, filled out, and forwarded to ships concerned for insertion in the service record of each enlisted student. The average student is far enough advanced to complete his training by himself if given the opportunity. The six best operators of Division Sixty each has about 70 hours of individual experience. They averaged about 76 per cent effective in attack and about 54 per cent reliable in search.

Training Methods

Selection of student operators is worthy of special care. Intelligence, interest, education, hearing, patience, and mechanical aptitude are of importance, and perhaps also a natural musical bent. Basically, the training must develop the faculty of discriminatory hearing, the translation of sounds into a complete mental picture. Expediency requires that students should be chosen from the ratings which are familiar with ship control and associated with it throughout their naval careers, such as quartermasters, signalmen, etc. A general classification (Navy GCT) of 85 and completion of tenth grade is a desirable minimum.

Elementary training consisting of 20 to 25 hours of individual operating ordinarily brings the student up to the point where he can complete his education for himself. However, no limit can be set for advanced training. After 150 hours the student is still learning, and perhaps 500 hours will be needed. Enduring results will come only through a continuing program of sound training for students, and an established routine of practice for operators. Officers must be trained, especially those who may have to conn the ship during attack.

Sound Tactics

Protection of the Fleet at Sea. At present no dependence whatever can be placed upon defense sound screening as a guarantee of reasonable protection of the Fleet. A cleverly handled submarine has two chances out of three to get through. On the other hand, once the submarine's presence and location are known, time permitting, her ultimate destruction can be made fairly certain. In training problems, aircraft made a high percentage of sight contacts with submarines well ahead of the Fleet. The "Offensive Sound Screen" tests show that sound-equipped destroyers could have exploited these contacts with 87½ per cent chance of destroying in 1½ hours all submarines spotted within six miles of them.

Sound Search Attack. Head toward the submarine and try to get on collision course. Increase speed to 15 knots by the time you are 600 yards from the target. Watch the range and bearing dials attentively and pay close attention to radio information from other ships. They are usually in a better position than you are to track the submarine. Be prepared for the submarine's last-minute maneuvers, as they will cause you to miss if you do not counter them instantly. Keep the sound operator training across the target to catch her turn, and listen for the change in echo pitch (Doppler effect) to catch variations in the rate of change of range. You must listen and watch the instrument yourself, forming your own opinion of the submarine's position and movements. There is no time for "passing the word" or risking any interruptions. Run the last 120 yards (12 to 14 seconds) "blind" by stop watch. Passing the word from the sound room causes lags of 50 yards or so, and you must be within 25 yards to get a destructive hit. Listen for the sound of the submarine's propellers. Watch the depth indicator. "Mushy" flashes will be showing if you are coming up close along the submarine's wake. The sudden change to a "hard" flash shows contact. At this moment, or at the stopwatch time that it is estimated this should occur, commence laying your depth charge pattern. A diamond of three from the racks and two from the Y gun should be sufficient, with 50-yd spacing.

Look for oil or other visible evidence of the location of the submarine.

Training. In training, drop two potato crates, with smoke pots attached, and sound sonic oscillator to inform submarine of the exact moment of the attack. Submarine then fires water slug from after tube and recognition bomb from projector amidships. With these data, i.e., the log of sound bearings from both submarine and destroyer and the courses and speeds of both vessels, it is possible to reconstruct the attack and study the effect of every maneuver of attack and defense.

PROBLEMS OUTSTANDING

Sound Training. (1) Establishment afloat of a permanent sound operating and tactical school for officers and men, with a permanent staff of instructors.

(2) Requirement that all graduates of the Radio Matériel school at Bellevue complete the sound matériel course as well as the radio course.

Sound Tests. (1) Repetition of all tests held by Destroyer Division Sixty to check the results and determine the relation of results against hours of operating experience and variations of water conditions.

(2) Extension of tests to include many other uses to which sound seems applicable, such as detection of mine fields, detection of buoys, shoals, and channels, etc.

Sound Tactics. (1) Service trials to test practicability of the formations and procedures.

(2) Continuous revisions to accord with new prospects brought out in subsequent tests, service trials and suggestions.

(3) Development, above all else, of improved methods of sound search, and of coordination with aircraft.

Sound Matériel. (1) Correction of the few mechanical and electrical weaknesses in the echo-detection and depth-finding gear.

(2) Redesign of 24 kc transceivers to eliminate reception through the rear.

(3) Provision of supersonic listening gear.

(4) Installation of bridge sound-control stations.

(5) Provision of radio telephones on bridge.

(6) Installation of depth-charge racks, Y guns, and bomb-throwers and controls.

(7) Development of "attack tracers," "mechanical ears," and any other devices that can expedite, simplify, or insure the placing of a depth charge on top of the submarine, under service conditions.

Miscellaneous. (1) Study and, so far as practicable, actual tests of water conditions in all important areas of the world, to determine the probable performance of our apparatus under all conditions.

(2) Continued observation of the effect of wakes, speed of sound vessel, marine growth and life, etc., to check and amplify data so far collected.

Conclusion. The foregoing comments . . . and opinions and recommendations voiced are based entirely upon the observations and data collected in four months, of which fully half had to be spent in training selected operators before any development work could be attempted. The aim has been to bring up all points of any apparent consequence so that all conflicts may the sooner be brought to light and proved or disproved by actual test before the new construction program has advanced too far to profit by the decisions.

Commander Destroyer Division Sixty.

The foregoing report shows that at the beginning of 1936 the main features of the antisubmarine attack doctrine based on the use of underwater sound were outlined substantially in the form they were employed in World War II. The job of sound training done by DesDiv 60 in 1935 was outstanding both in the number of personnel concerned and in the number of hours of training in operating the sound equipment. This was a record not to be equaled again for some years. The men who received their initial training at that time formed a nucleus for subsequent tactical and training development. However, only a very limited number of men in the Navy were afforded any experience with sound gear during this program, and apparently there was no regular adequate provision for the earmarking and retention of men thus trained. The early work was that of a handful of enthusiastic and aggressive exponents of sound which struck a spark that did not encounter particularly inflammable tinder.

Sound training had first place in the foregoing list of "Problems Outstanding" and the establishment of a permanent sound operating and tactical school for officers and men was recommended. But presumably the time was not thought to be ripe for this, and in the next few years the primary objective of the Navy in underwater sound was the development of sound tactics. For this purpose, Destroyer Division Nineteen was ordered to operate with fleet-type submarines in waters of the Pacific Ocean, based alternately at San Diego, California, and at Pearl Harbor, Hawaii, throughout the years 1936, 1937, 1938, and the first quarter of 1939. The successive quarterly reports of the Commanding Officer of DesDiv 19 to the Commander-in-Chief, U. S. Fleet, covering this period, tell the story of the steady development of supersonic screening, searching, and attack doctrine and of submarine evasive and attack tactics. Various proposals, such as that for a fixed projector with a wide angle (cowcatcher type), were tested and rejected,

performance data of echo-ranging equipment under various conditions were obtained, the disturbing effects of an own-ship's noise at various speeds and of temperature gradients on maximum range were noted, and sound exercises were formulated and practiced in the development of a satisfactory moving-beam search plan up to 15 knots. It was a period of testing and trying the underwater sound equipment under service conditions. At the close of the period, although the gear retained the essential form of the 1933 equipment, more rugged components had replaced those which had given trouble in service and a 1,000- to 5,000-yd dual-range scale had been substituted (1939) for the original 800-yd single-range scale. Although the desirability of a bridge-control station for the echo-ranging gear had been suggested in the DesDiv 60 tests of 1935 and renewed in other reports in the following years, progress along these lines was limited to placing the sound stack in the chart room with access to the bridge through a porthole and installing a loudspeaker and bearing repeater on the bridge so that the conning officer could both hear and observe. Range was transmitted verbally by the sound operator to the conning officer.

Sound operator training during this period was confined with trifling exceptions to men needed by DesDiv 19 in its development program. A fundamental trouble in securing suitable men, however, had already become apparent as noted by ComDesDiv 19 (December 20, 1937) as follows.

> . . . It has been found that superior mental types of non-rated men, i.e., those best qualified for training as sound listeners, are soon rated, leaving only the inferior type of non-rated men available for training. It is recommended that recruits at Training Centers be selected for mental and mechanical ability and sent to destroyers for training as sound operators. It is also recommended that a rate be established, or that a present rate be extended to include sound listener's qualifications.

But in spite of some deficiencies, the general situation was regarded as reasonably satisfactory. Underwater sound had come a long way. Tight defensive screening and effective attack doctrine had been developed and tested and a considerable number of destroyers and some cruisers were equipped with simple, sturdy echo-ranging gear. It was recognized that in order to obtain the very excellent results in submarine destruction reported in some of the training and development work by DesDiv 19, a very high efficiency would be required of sound operators and conning officers. The Navy was now ready for the next step, of undertaking to develop this high efficiency of personnel through training.

Steps were taken to overhaul the sonar training of the experienced personnel of Destroyers, Battle Force, by requiring attendance of the best soundman from each destroyer at a summer sound school held in San Diego from June to August 1939. The primary purpose of this school was to train experienced enlisted men thoroughly in the fundamentals of the newest sound-search and depth-charge attack procedures. A secondary mission of the school was to test the current sound-training exercises with a view to improvement or rejection. The school continued for 7 weeks, 2 weeks on shore at the Destroyer Base, San Diego, and 5 weeks at sea on the four school-ship destroyers of DesDiv 19. The school also accommodated submarine sound operators who were assigned on board the two school submarines. Approximately 70 men satisfactorily completed the course.

On August 7, 1939, the first class of the permanent school, Elementary Sound Operators Class 1-A, was convened with 30 men and six officers attending. The training schedule called for the completion of a 6 weeks' course, of which 2 weeks were shore instruction and 4 weeks were operations at sea. Class 2-A convened on September 18, 1939, and thus was started a succession of elementary sound-operator classes which continued throughout World War II.

In January 1940, the matériel course of the Fleet Sound School at San Diego was begun. The course was announced as a short course in Radio and Sound Matériel. Radiomen, second-class or third-class only, were eligible. A 6½-week curriculum was laid out and classes were limited to 9 men because of restricted shop facilities and because the teaching work had to be carried on as additional duty by the staff.

The quarterly report of the school for the last quarter of 1939 states that the preparation of two instructional pamphlets had begun: (1) *Sound Operator's Handbook* and (2) *Notes on the Care, Operation, and Maintenance of Underwater Sound Equipment.* The first was later to run through several editions and both proved of primary importance for sonar instruction during the next few years.

One of the junior officers of the school had for some time in 1939 been giving attention to the requirements and design of a shore-based attack teacher suitable for use in training sound operators in echo-ranging techniques and for training conning officers in the delivery of antisubmarine attacks. These efforts were encouraged and resulted ultimately in the construction of an attack teacher. This equipment was installed in the Fleet School Building, Destroyer Base, San Diego, and was ready for use in December 1940. Thus, by the early part of 1941, the West Coast Sound School [WCSS] was firmly established as a permanent sound school, with curricula in all phases of antisubmarine instruction.

In the meantime, World War II had broken out in Europe and was being carried across the Atlantic almost within the territorial waters of the United States. The deadly effectiveness of the submarine as an offensive weapon, and especially against merchant vessels, was being demonstrated anew and almost daily. The expansion of the U. S. Navy antisubmarine force, and with it the expansion of training activity to include the Atlantic coast, was an urgent preparatory measure. In the spring of 1941, the Fleet Sound School [FSS] was begun at Key West, Florida, with Destroyer Division Sixty-Six, consisting of four destroyers which in 1935 had operated with DesDiv 60 in the pioneer Navy antisubmarine development program in the Pacific, with Submarine Chaser Thirty-One (three ships), with Submarine Division Twelve (seven boats of the R type), and with a Coast Guard detachment of four ships.

At the outset, the Fleet Sound School at Key West had the example of the more recent training experiences of the school at San Diego, as well as the use of textual material, training exercises, and training aids which had been developed by the older school. The submarine war, moreover, was closer and seemed more imminent on the Atlantic coast and lent point and urgency to the training work. In the fall of 1941, sound operator classes were being graduated at intervals of 5 weeks. The average size of these classes was approximately 50 enlisted men and 15 officers. This was roughly double the output of WCSS. This relative difference in numbers of graduates was maintained throughout the following 4 years.

Small classes in Advanced Sound Matériel (6 men) and in Radio and Sound Matériel (10 men) were being conducted for enlisted men already rated for radio work, but no training in elementary matériel maintenance was given at this time at Key West nor was one established until much later (June 1942). An 8 weeks' course for officers which undertook to qualify an officer to supervise or effect any repairs to sound gear, subject to the supply of necessary spare parts, was started in December 1941.

In the light of present knowledge, it is clear that the early sound-training program proceeded under a number of very severe handicaps. There was a general lack of knowledge both of the capabilities of the gear under various conditions and also the performance that could be expected of the men. The criteria for evaluating individual and team competence were poor and the estimates of success based on them were unduly optimistic, as can be seen from the quotation earlier in this section. Most of the training was given at sea, and although this phase was essential, only one operator at a time could be trained. A shore phase was necessary for a large or thorough training program, and little information was available as to the proper content of such a training course. Standard methods had not been developed for selecting persons with appropriate aptitudes for the various sound functions, nor was it known whether any particular qualification rendered a man most likely to succeed in the operation of sound gear. The ASW attack-team concept was imperfectly formulated and methods of training the several individuals composing it had not been carefully considered.

It is also evident that there were further

very grave difficulties to be overcome even after a ship's company had become proficient in submarine attacks. The maintenance of a high standard of performance requires constant practice, and opportunities for shipboard drill and maneuvers with submarines were rare in a destroyer's schedule. This remained an important problem throughout World War II. Possibly the most serious situation was the lack of professional recognition for the job of soundman. The fact that no rating existed had two serious consequences. The first was the absence of incentive to learn sound operation and the consequent acceptance of such an assignment as additional duty carrying little or no prestige. The second effect produced by the lack of a road for advancement for sound operators was the attrition produced in their ranks. As soon as a man had been aboard ship for a few months, he would strike for a rating in some other branch and be diverted from the very small pool of operators. Estimates of the loss of operators vary from 50 to 80 per cent in the days before the rating was established. In one extreme instance at the outbreak of war, a destroyer which actually had six men aboard who had received sound training had untrained electricians, boatswains, and cooks assigned to operation of its sound gear.

14.3 IMPACT OF THE WAR ON SONAR TRAINING

In anticipation of hostilities, an enormous program of antisubmarine construction was undertaken by the Navy and its extent can be seen by reference to Figure 1. During the initial period, these ships were equipped with standard QC gear up to model QCJ and QCL. For the operation of these vessels prior to the commensurate expansion of the training program, reliance had to be placed on individual shipboard training without the benefit of competent instructors. The program of expansion was greatly complicated by the inadequate development of tactics and doctrine. In consequence, both the combat units and those assigned to instructional activities had to devote much time to the improvement of antisubmarine tactics and the establishment of adequate doctrine. This necessarily impaired the initiation of suitable training programs and retarded the furnishing of a sufficient number of well-trained operators during the early years of World War II. It was necessary to accept compromises in the quality of training that could be given in order to meet the demand for operators by vessels equipped with sound gear. The diversion of soundmen to other assignments upon joining their ship further aggravated the situation. It has been estimated unofficially that from 50 to 80 per cent of the graduates of the sound schools in early days were assigned by the commanding officer of the ship to some duty which was considered more essential than that of sound operator. In consequence, for every two steps taken forward by the schools, one step backward was taken by the Navy.

The problem of instructors was one of the most serious ones for the schools because of the great pressure for the release of all competent operators to combat units. The instructional methods in use were inefficient in the utilization of the instructor's time. A chief petty officer on one side of a sound stack and a student on the other represents a small and unprogressive school. However, time was needed both to assemble competent instructional staffs and also to design equipment and devise curricula which would permit more efficient instruction.

The pool of sound operators provided by the ships was quite inadequate and inferior for providing candidates for the expanded training programs in all technical specialties. It was necessary to draw men directly from training centers and although they lacked the valuable background of a sea experience, it was easier to select entrants for the schools with suitable intelligence and aptitude ratings.

The expansion of the shipboard phase of the training program was also handicapped by the demands of the operating units of the Navy for all ASW vessels and submarines. The surface ships available were few in number and frequently had the oldest types of gear. The number of submarines available for targets was so small that sound school graduates in the early days frequently had but a few minutes of actual individual operation at sea. Sound conditions in the areas adjacent to the sound

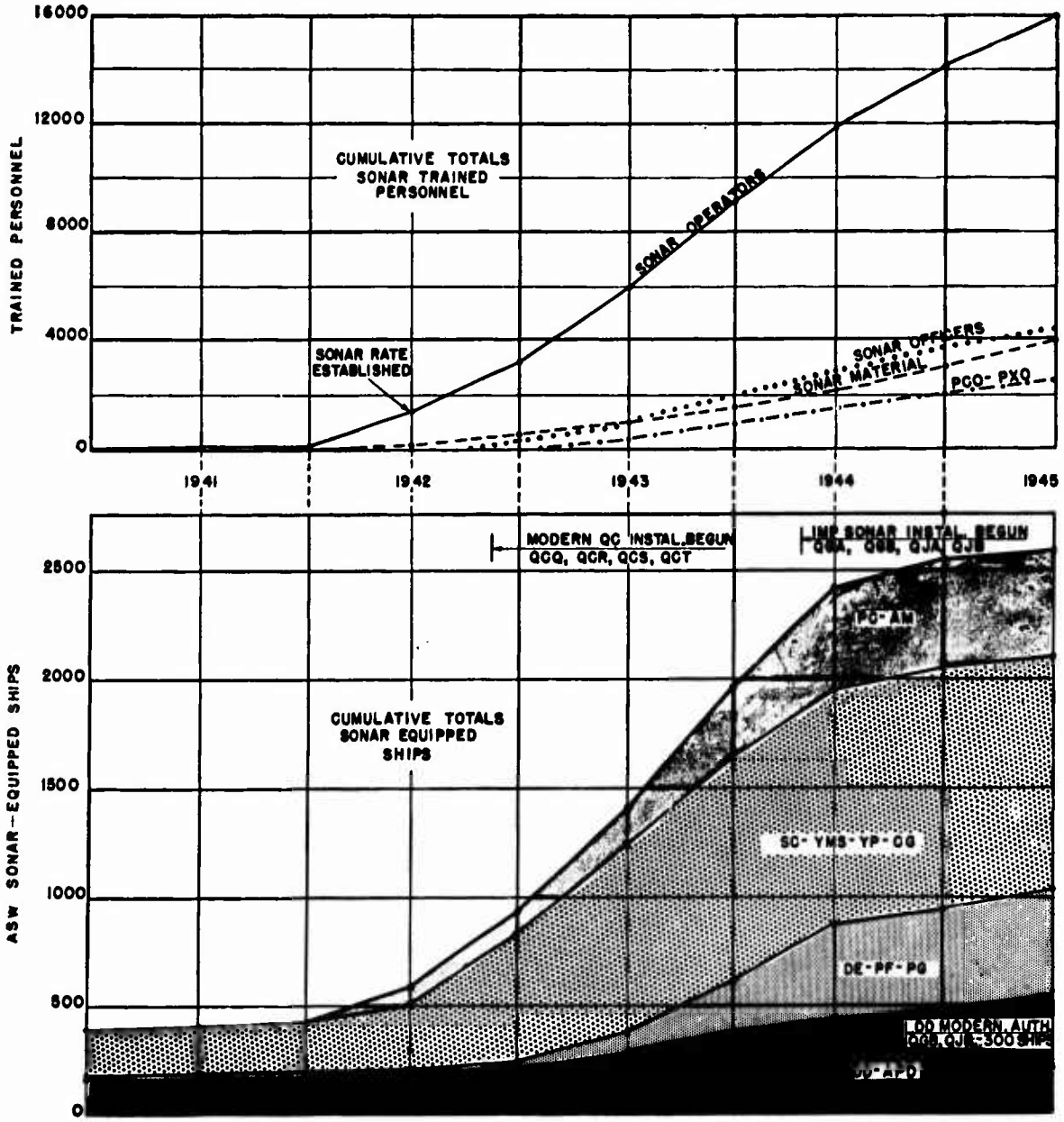


FIGURE 1. Cumulative totals—ASW ships and personnel. The charts indicate the tremendous increase in the number of sonar (echo-ranging) installations made and sonar personnel trained during World War II. The data presented have been obtained in large part from the Navy sound schools and from two Navy publications, the *Sonar Installation Record*, NavShips 900,073, and the *Ordnance Vessel Register* (BuOrd), although considerable interpretation has been necessary. No attempt has been made to show the number of vessels equipped with any particular type of gear; but the advents of the modern QC types, beginning with QCQ, and the QG-QJ (BDI) series have been indicated. Very few adequately trained sonar personnel existed at the outbreak of World War II; and those trained during its early months received only the barest essentials. Thus, the relative effectiveness of the total sonar pool was even greater after the establishment of the sonar rates than is indicated by a simple numerical comparison of the figures.

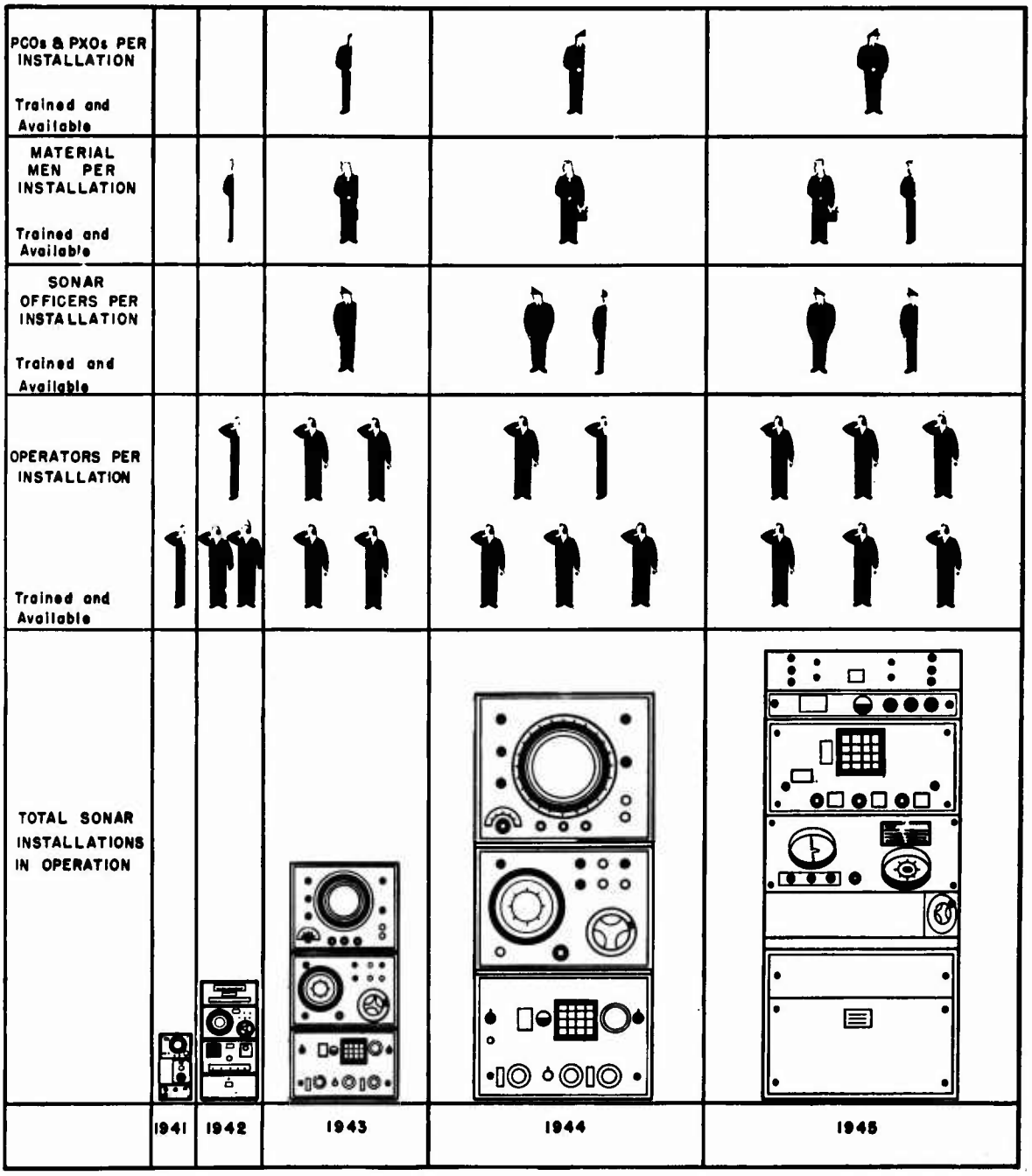


FIGURE 2. Sonar pictograph chart. As the total number of sonar installations grew, the gear was continually redesigned and improved, and the complement of trained personnel for each equipment experienced a large relative increase. The figures, indicating the totals as of July 1 of each year, show personnel trained and available for assignment to sonar duties. In the period 1943-1945 the numbers are also substantially correct for the number of men so assigned, but in 1941 and 1942, prior to the establishment of the sonar ratings, the rate of attrition determined by the assignment of sonar-trained enlisted personnel to other and unrelated duties may have been as high as 80 per cent. The figures given for that period are consequently subject to correction by such a factor. The complete absence of officer training in the first two years should also be noted.

schools were very poor during much of the year, further reducing the effectiveness of training through lost contacts. The evaluation criteria at sea were questionable, and it is dubious whether the scores attained had other than incentive value. It was recognized that the realism of sea training was essential for an adequate program, but the exigencies of the situation demanded that greater emphasis be put on the development of the shore phase of training as it was possible only in this way to attempt to handle the large number of students assigned to each class. Ameliorative efforts were directed to the development of simple instructional devices suitable for shore use and to the provision of training aids and the establishment of methods that could handle large classroom groups.

Since the proper functioning of the gear depended not only upon the competence of the operator but on the provision of adequate maintenance, the schools' program in matériel training also had to be greatly expanded. There was little general knowledge of the intricacies of sonar gear among Navy radio men nor was there any pool of electronic specialists from which to draw for the training of men in installation, repair, and maintenance. The best practical solution which was adopted by the schools was to retain the most promising men from successive operator classes for a future program of matériel training. There was little basis for the selection of such men other than the intelligence and interest evinced during the operator course, though some consideration was frequently given to previous civilian technical experience. The paucity of instructors in matériel was an even greater handicap than in operator training, and little basis for the establishment of an adequate curriculum existed. The shortage of equipment led perforce to an undesirably theoretical trend in this training. The initial matériel manuals that were available were sadly inadequate, and the nonuniformity of the gear aboard different ships led to great confusion.

The major emphasis in the expanded training program was upon the enlisted men, as these had to be furnished in large quantities and they entered the schools with a minimum of background knowledge. However, it was recognized early that the skill of officer personnel played a crucial role in the success of antisubmarine attacks and as soon as possible, careful attention was given to the officer's functions and the selection and training of officer personnel. Few officers, however, had the benefit of school training early in World War II and had to rely on self-instruction aboard their own ships. The higher basic educational level and the greater learning aptitude enabled officers who reached the schools to obtain the maximum of benefit during the short courses that were initially provided. The role of the captain and other officers during submarine attacks was not well established for many months, and it was not until the advent of the range recorder and the introduction of other conning aids that the concept of a sonar officer emerged distinctly. The commanding officer of the ship frequently exercised his prerogative of taking over the personal conduct of antisubmarine operations. Still later, many prospective commanding and executive officers attended the schools, thereby gaining a familiarity with the difficult ASW techniques and greatly contributing to the success of their ships' operations. The officer's role in conning and the operation of attack aids not only is a complex and essential one, but his thorough knowledge of all phases of sonar operation is important for the maintenance of the highest standards of performance by enlisted personnel. Failure to appreciate properly the effect of gear adjustment and sound conditions or inability to evaluate doppler or other echo character is not only prejudicial to attack success but has an adverse effect on the standard of performance of the sound crew.

The major initial problem faced in training was that of meeting the enormously increased demand for trained personnel to operate standard equipment. However, standard equipment was not entirely satisfactory, and a keen need was felt for the improvement of ASW gear, tactics, and techniques. The percentage of attack success was very small, usually reckoned at less than 5 per cent and the seriousness of the submarine menace forced the greatest urgency upon the improvement of methods to

combat it. The proper choice of methods to improve the effectiveness of operations against submarines was not immediately evident and the many suggestions that were made had to be carefully studied and the promising ones thoroughly evaluated. This phase of the effort, though not directly a matter of training, had important implications because the introduction of new devices or techniques, or the modification or improvement of old ones, involved the establishment of new training programs and methods. A decision on the adoption of one or another expedient frequently depended on the ability to secure an adequate number of competent personnel to render it effective.

The advent of air participation, which eventually assumed a role of comparable importance, soon presented a number of training problems in which the Subsurface Warfare Division of NDRC was of assistance. One of the division's contractors developed a magnetic device for the detection of submarines from aircraft, known as the *magnetic airborne detector* [MAD] and played a major role in the training program thus presented. The *expendable radio sono buoys* [ERSB] were also developed for this purpose, and their use by aircraft presented a training problem in which one of the division's contractors was of great assistance. Successful attacks on submerged submarines by aircraft alone present great difficulties, and another successful innovation was the combined air-surface attack. No particular device emerged in response to this development, but as the doctrine developed it became a part of ASW school curricula and assistance was rendered in this type of instruction.

The surface ship continued to be an effective arm against a submerged submarine throughout World War II. The magnitude and urgency of the program for equipping these ships impeded the introduction of any major improvements in sonar gear and World War II was fought essentially with the gear in existence in 1941, with but relatively minor improvements as could be introduced from time to time into the production schedule. The greatest effort was applied to the most effective employment of essentially standard gear and the improvement of the doctrine for its use. However, many innovations were made in a sufficient quantity to be operationally significant, and in connection with these, civilian training personnel were of assistance both in suggesting modifications and introducing appropriate training changes to take proper advantage of the improved operation thus permitted. The installation of domes increased the permissible attack speed, with consequent changes in doctrine and instructional methods. The introduction of the *bearing deviation indicator* [BDI] improved the precision with which the angular location of the target could be determined, and the training in attacks was modified when center bearings were available in addition to the older bow and stern cut-ons. A number of improvements in the electronic circuits of the gear affecting the variation of gain with time and the doppler effect had a pronounced bearing on the type of training given operators in echo recognition and discrimination. The range recorder, when it was introduced in quantity, was a major step in the improvement of attack success. Better ranges were available, more appropriate keying intervals could be used, and the memory feature provided was invaluable in extrapolating to the firing point. Training in this device was a very important phase of work in the schools for both operators and officers, and training devices built around the recorder gave the first precise quantitative criteria in the school curricula. Depth-determining gear was not installed in sufficient quantity to present an important training problem during the period of NDRC participation, but some assistance was rendered in planning for the future incorporation of such equipment in the school training program.

Training personnel also assisted the laboratories and procuring bureaus in the design of those features of new gear bearing on both basic operation and superficial features. The efficiency of the operator is influenced by the convenience of the controls, the ease with which dials and indicators can be read, and the fatigue incident to prolonged watches. It was frequently possible to consider these matters in the design of equipment, and much of the newer sonar gear was markedly superior to the older installations in ease of operation. In conse-

quence, better results could be achieved with it by its human operator.

The influence of the training program was not restricted to innovations in the sound gear itself. The strategic and tactical information and aids produced by the laboratories had a marked bearing on the training programs. As basic knowledge of the ocean as a medium for the propagation of sound increased during the war years, officer courses in particular changed markedly in character, reflecting the improved understanding of the possibilities inherent in underwater sound attacks. A knowledge of refraction, reverberation, and noise provided a firmer basis for determining sonar ranges, the selection of keying intervals, the placement of ships on sound screens, and the conduct of attacks to avoid wake interference.

As an understanding of the problem of the conning officer became more general, effort was seriously devoted to the provision of simple attack aids. Among these the *antisubmarine attack predictor* [ASAP] was installed in significant numbers, and training in this device occupied an important part in the school curriculum for officers.

Although ordnance continued to be one of the weakest links in the submarine attack, certain improvements were made in the standard depth charge, such as increased rate of descent and improved fusing. These modifications likewise had their reaction on attack doctrine and training programs. Assistance was given at the schools in the evaluation of depth-charge attacks as well as practice in laying effective depth-charge patterns. The introduction of projected charges, such as the *mousetrap* and *hedgehog*, also affected training programs. A great deal of work was done in collaboration with Division 3 in the assessment of the success of such attacks during school operations and in the training for making effective use of such projectiles.

14.4 INCEPTION OF NDRC TRAINING ASSISTANCE

14.4.1 Selection and Training Committee

Shortly after the establishment of a section within the National Defense Research Committee concerned with antisubmarine warfare, it became apparent that possibly the most important factors in the successful prosecution of the war against submarines were first, the skill and training of the sonar operators and, second, the training and experience of the officers responsible for conducting the search for enemy submarines and attacks upon them. As the personnel constituting the NDRC and its associates had been largely drawn from educational and engineering fields, it appeared that this group could be very useful to the Navy in solving the problems that it faced. The experience of industrial and educational psychologists in the selection of personnel for technical jobs, including special auditory and intelligence qualifications, together with their experience in instructional methods and techniques, suggested that this group could contribute materially in the planning and inauguration of an improved and expanded training program. Also, the laboratory facilities which were being provided by the section for the development of ASW devices could be drawn upon for the design and construction of suitable training devices for pilot use in the schools and as prototypes for subsequent large-scale procurement by the Navy. Finally, the central liaison with the Navy provided by the NDRC organization and the flexibility of fiscal policy and procedure enjoyed by the NDRC placed this group in a particularly favorable position to study the problem as a whole and initiate experimental projects in collaboration with the Navy.

After consideration of the various aspects of the situation by the Coordinator of Research and Development for the Navy and by NDRC, the latter formally undertook a project for the study and formulation of aptitude tests for personnel to be trained by the Navy in the operation of sonic and supersonic apparatus and for the formulation of improved training programs for such persons. The undertaking was assigned to Section C-4 of the NDRC, and the chief of that section instructed his assistants to interpret the problem in a broad sense as one dealing with the training of all personnel in the ultimate objective, namely, submarine detection and destruction. Interpreted in this way, the first step was the assembly of a group of

persons qualified by psychological, engineering, and mathematical skills to contribute advice and recommendations. The group should then, in consultation with the Navy, take such immediate steps as appeared feasible to familiarize itself with the problems of the ASW training program and to acquaint itself as thoroughly as possible with pertinent Navy records and current selection and training procedures. Early in December 1941, a committee on the selection and training of sound operators of Section C-4 was appointed by the chief of the section to constitute the advisory group indicated above.

Arrangements were made for the first formal conference of the committee on December 5, 1941, in Washington, with representatives of the Division of Fleet Training, the Naval Research Laboratory, the Bureau of Ships, and the Coordinator of Research and Development. At that meeting, a representative of the Division of Fleet Training presided and outlined briefly the projected Navy requirements for the next six months. The committee was informed of the number of sound operators that would be required by July 1, 1942, and was told that on the basis of the training program then in force and the anticipated attrition, this figure appeared difficult to achieve. It was suggested that the committee visit the sound schools and prepare a report for subsequent consideration. Arrangements were made for supplying the committee with representative reports of the Division of Fleet Training for study to provide background for the projected visits to the training activities. A representative of the Bureau of Ships emphasized that the committee could be of most immediate service by placing the emphasis of its work at that time on the preselection of sound operators.

During December 1941, the committee visited the New London Submarine Base and acquainted itself briefly with the basic program of selection and auditory testing of submarine personnel. A more extended visit was also paid to the Fleet Sound School at Key West, and the committee administered exploratory tests to determine as expeditiously as possible whether certain contemplated procedures would be feasible and profitable. The results of the tests were encouraging, and the committee recommended that additional work in cooperation with both of the sound schools be authorized for the purpose of developing these tests further and following the validation of the various items involved. The committee also suggested that it be authorized to draw up specifications for instruments and devices likely to be of value in a selection and training program and recommend their development through the section's facilities for subsequent naval evaluation. These recommendations were approved, and the committee was also authorized to visit the West Coast Sound School in San Diego, as it was anticipated that the interruption of the program at that activity caused by the opening of hostilities in the Pacific would be over in the near future and normal operations would be resumed.

During the week of January 6, 1942, the committee visited WCSS. On the administration of tests similar to those employed at Key West, the committee verified that the situations at the two schools were quite comparable, and on February 20 presented the results of its findings to its naval liaison. The urgency of the requirement for some system of selecting operators was such that the committee was authorized to draw up its interim recommendations and confer with the Division of Fleet Training on the immediate installation of a selection procedure at training stations.

It was recognized early by the committee that the chief difficulty in evaluating the success of any selection procedure would be the adequacy of the final criteria employed for assessing the competence of sound school graduates. The establishment of such criteria, however, presented a problem that could be solved only by continuing close cooperation between training specialists and the school staffs. The necessity for basic and varied technical training assistance by the schools prompted the committee to recommend the establishment, through NDRC contractors, of groups of competent and experienced personnel to work intimately with the laboratories and the schools in the interest of providing the most effective assistance possible to the major sound training activities. The committee expressed its opinion that an im-

provement in liaison between the east coast and west coast schools would be very advantageous. An interchange of officers at that time, however, did not appear to be advisable. The hope was expressed by the committee's naval liaison that a unified program of civilian participation as proposed by the committee would tend to bring about a closer relationship and promote uniformity in instructional techniques. At the same meeting, the question of increasing the emphasis on listening instruction was raised, and although it was recognized that this feature was not of so great importance as echo ranging in antisubmarine attacks, it was considered a valuable auxiliary technique in which training was a proper activity of the Navy schools. Information in regard to listening and the training of listeners obtained from work at the Navy schools would be of considerable value to other naval groups, in particular those concerned with the operation of submarines or engaged in coastal patrol or harbor defense.

During the spring, the committee visited New London on several occasions for the purpose of studying questions posed by the design of new gear under construction in the New London laboratory and familiarizing itself with the work of training activities in that area. The designers of sound gear conferred with the committee on such matters as operator fatigue and the incorporation of features tending to provide convenience and comfort in operation, in order to improve operator efficiency during the relatively long watches which were necessary during the early part of World War II. A very active program of sound training was under way at New London, centering around the USS *Sylph* and involving the patrol activities of the Third Naval District and the Coast Guard.

It had previously been observed that many of the sound operators reaching the sound schools came from the Navy rather than from training stations and that these men were frequently not as well qualified for the training program as those selected by the tests which were then in operation. It had therefore been proposed that some Navy selection procedure be instituted, and the committee had been instructed to study this question and propose a feasible program. In order to inform itself more fully about the considerations involved, and incidentally contribute to the improvement of training in the sound schools, a questionnaire on sound operator performance had been formulated by the committee and circulated to the Navy by the Readiness Division in April 1942. The Navy selection tests, which were subsequently prepared, sustained preliminary validation during the summer and were turned over to the Bureau of Personnel. Questions that subsequently arose as to the proper method for their distribution delayed their use for such a long period that they were never employed on the scale originally contemplated.

At the July 1942 meeting of the committee, the preliminary results of the reports on Navy sound operators were presented and a number of interesting items were noted. The commanding officers making the reports emphasized the fact that the operators were, in general, deficient in maintenance ability; in fact, nearly 90 per cent indicated the lowest possible scores for their sound operators in this phase. In an appreciable number of cases, sound operators were considered deficient in tonal discrimination and also in target recognition. This information, together with other more minor specific points, assisted in the proper assignment of emphasis both in the selection of men for sound training and in the program of the schools. It had been realized for some time that additional matériel instruction was urgently needed, and this program was shortly accelerated. The prominent position of auditory requirements in the selection tests was retained, and a program for improving these tests was instituted.

On the occasion of this meeting, the committee also added its observation that the lack of opportunity for promotion in the field of sound operation undoubtedly contributed to the large attrition characterizing sound operators as a group. The initiation of sound ratings would provide greater motivation for men to enter this specialty and remain in it, thus building up a skilled technical corps analogous to radio electricians, signalmen, etc. Later, the committee strongly advocated the adoption of the special designation "sonar" in place of the longer and more cumbersome "underwater sound" as an

important step, tending toward the formation of an esoteric bond among the operators and the establishment of *esprit de corps.*

During this period, requests were made for assistance at the Submarine Base, New London, in a training program for expendable radio sono buoy listeners. It was proposed that the assistance of the National Research Council Committee on Service Personnel be enlisted in connection with the undertaking and that, in collaboration with the Bureau of Personnel, a training program be instituted and the necessary instructional material prepared. In December, formal liaison with the National Research Council Committee on Service Personnel was established, and a technical aide to the chairman of that committee participated in much of the work in hand by contractors' training groups.

The emphasis in the work of the committee had been largely on selection procedures and elementary training programs during 1942, but it had long been realized that an important aspect of the work which related to the advanced phase of the ASW team training and provision of refresher and in-service experience should receive more attention. As a part of the advanced training program in the sound schools, a study was made of attack-team practice as a factor in the effectiveness of ahead-thrown attacks on submarines. It was later concluded that although the period that could be devoted to this work in the school program was important in familiarizing personnel with the attack procedure, it was inadequate to instill a high degree of skill in the ASW personnel. Errors even at the conclusion of training remained large, and it was found that only those vessels which had had an opportunity to devote extensive periods to practice in this type of attack achieved a sufficient degree of skill to make their effectiveness outstanding.

It was also observed that the usual assignments of the ASW vessels permitted few opportunities for the maintenance of training in ASW work. The need for some device which could be carried aboard an ASW vessel and used to provide opportunities for realistic training without interference with the operation of the ship led to the recommendation that the development of such a device be undertaken by the section. As a result of the work at a contractor's laboratory, two types of *shipboard antisubmarine attack teacher* [SASAT] were developed. The simpler but less realistic of the two was procured in some quantity and its effectiveness demonstrated. The later provision of additional submarines for operation with the sound schools also contributed materially to the improvement of the sea phase of training and greatly enhanced the value of the over-all training that could be given at these activities.

Early in 1943, it became evident that as the selection and training procedures for operators had improved during the preceding year, much more efficient and competent sound operator graduates had been furnished the Navy. No selection procedures, however, had been followed in the assignment of sound officers to the schools, and the period of their training at the schools was very brief. In consequence, it appeared that a considerable increase in the efficiency of this member of the sound team could be effected by making a somewhat similar type of study of their qualifications and their training curriculum as had been made for sound operators. As a first step, the Bureau of Naval Personnel directed that the selection tests for operators should also be used in the selection of sound officers from the small craft training centers, midshipmen schools, etc. At the same time, the committee was requested to visit the Submarine Chaser Training Center at Miami and attempt to formulate a selection procedure which would be more definitely directed to the selection of those skills particularly required by the sound officer for the performance of his specialized assignments. In previous conferences with the sound schools, it had been determined that it would be desirable for such officers to be volunteers for this service, have a high intelligence rating, and, if possible, an analytical turn of mind and a gift for visual imagination. Mechanical aptitude would also be of great importance in the operation of special attack aids, and superior auditory discrimination would be particularly beneficial in enabling them to assist in training and in monitoring the performance of sound operators during search and attack.

A survey in September 1943 of the results achieved in the work indicated that they were not sufficiently convincing to warrant recommending the use of an improved test battery by the Bureau of Personnel at that time. It was proposed that such improvements as appeared most promising should be made in the battery of tests and greater emphasis laid on the uniformity of the conditions of administration. It was also recommended that, in collaboration with the commanding officers of the schools, an effort be made to secure more adequate criteria of success wherever possible through the use of standardized written examinations, doppler discrimination and echo-recognition phonograph recordings, the range recorder trainer, and standard scoring sheets for job performance.

By the early summer of 1944, records of a sufficient number of student officers under the new program were available for a resurvey by the committee, and it was agreed that the steps which had been taken during the first half of 1944 had greatly improved the experimental results. It was felt that the test battery appeared very promising and that a complete report should be submitted to the Bureau of Personnel to enable it to institute whatever modified selection procedures seemed desirable. Further validation was thought to be advisable, but the number of officers being selected for school attendance was rapidly dropping and it was not evident that significantly improved results could be achieved in time to be of use to the Navy during World War II. One of the tests in the experimental battery dealing with relative-movement problems had proved quite discriminating, and it was recommended that a separate report be prepared on this test for submission via the office of the Commander-in-Chief in case it might be thought applicable to other special groups of Navy personnel.

During the autumn of 1943, the success of the ASW operations in the Atlantic and the emphasis on submarine work in the Pacific suggested that greater attention be given by Division 6 to prosubmarine problems, and the chairman of the committee visited the training activities of both the destroyer and submarine forces at Pearl Harbor. However, the work of the committee on ASW selection had been made available earlier to the Submarine School, and the program that had already been followed at that activity had reached such a stage that further study by the committee in this field did not seem justified.

The role of the committee throughout its existence was that of an advisory group of specialists who were available for consultation within a special field to the NDRC and the Navy. The committee enjoyed the additional privilege of submitting recommendations as these appeared appropriate in the course of its observations and experience. As indicated in the foregoing section, the committee periodically reviewed the progress of the various programs which it had initiated or with which it had been associated. It also provided special liaison for the training groups of the section's laboratories with the office of the Commander-in-Chief and the various naval bureaus involved in different aspects of training in the sonar field.

The experience of the members of the committee in both industrial and academic selection and training work was found to be very largely applicable to the situations faced by the Navy in its sonar training program. It was appreciated early that wartime conditions imposed severe limitations upon systematic procedures and that expeditious approximations had to be adopted, particularly in the early work. Adequate assessment of the value of many of the proposals that were made was frequently precluded by the operating duties assigned to the naval training activities with which the committee was working. The committee's lack of previous experience in the special problems confronting the Navy in wartime was a handicap which was gradually overcome by its frequent visits to the sound schools and similar organizations. As this intimate collaboration developed, the Navy also acquired a better appreciation of the way in which such specialized civilian advisory personnel could be most effectively utilized. The committee enjoyed most wholehearted cooperation from the training activities with which it was associated, and upon the establishment of a mutual understanding of the many obligations and limitations to which

both the Navy and the civilian personnel were subject, effective cooperative programs were carried out.

The difference in the instructional situation between a civilian organization and the Navy presented many problems to the naval training activities in accepting the recommendations that from time to time resulted from the committee's studies and observations. The training courses were in most cases much shorter than would have been desirable because of the urgent need by the Navy for trained sound men. The conflicting requirements of the Navy and training activities for training vessels, new types of gear, and other special facilities often imposed limitations on the equipment available to the sound schools which materially reduced the effectiveness of the training that could be given. Naval personnel in charge of classroom and laboratory instruction had frequently had little experience in imparting their knowledge and skills to students, and the many other urgent considerations affecting naval assignments, particularly during the earlier stages of the war, permitted little consideration of this point. As facilities became available and the manpower situation less critical, the schools and other training activities rapidly improved in effectiveness under the able guidance of the officers successively assigned to their command.

Frequent meetings with the committee's naval liaison served to focus its attention on the most important and pressing problems as they arose in the development of the Navy's training program. Its meetings also provided an opportunity to profit by the advice and experience of representatives from the National Research Council's Committee on Service Personnel and later NDRC's Applied Psychology Panel. The channel for the interchange of opinion and information thus afforded was mutually helpful to the specialized civilian groups engaged in assisting the Navy in the field of technical selection and training during World War II.

The early work of the committee was almost exclusively directed toward the training of operators for antisubmarine warfare, as this was the problem of paramount importance during the war with Germany. The emphasis in the training program was on search and attack and the maintenance of the gear employed for these purposes. In the later stages of World War II, the prosubmarine aspect of the Navy's work in subsurface warfare became the field in which the committee could be of more assistance. Here, however, the extent to which previous work with the committee could be applied reduced somewhat the number of remaining fundamental problems in the committee's field. The difference in naval cognizance for elementary and advanced training in this work also reduced somewhat the committee's effectiveness. The Submarine School at New London, at which elementary sonar training was conducted until the autumn of 1944, was under the operation of the Bureau of Personnel. New construction training and the advanced and refresher phases were under the direction of the submarine commanders of the two Fleets, and this division of responsibility and the wide geographic separation between training units made it somewhat more difficult to obtain an adequate overall picture of the program. With the concentration of submarine sonar training at WCSS in the autumn of 1944, the contractors' training groups were in a better position to lend their specialized assistance, and from time to time the advice and suggestions of the committee were drawn upon.

14.4.2 Contractors' Training Groups

In addition to the centralized exploratory and advisory functions performed by the Selection and Training Committee, effective assistance was rendered to training activities through projects assigned to contractors. Although this phase of NDRC assistance was largely in the hands of the training groups associated with the major laboratories, invaluable contributions to training were made by the NDRC—BuShips Field Engineers and the Antisubmarine Warfare Operations Research Group [ASWORG]. The central organization of the Field Engineers and their many local representatives played an important part in facilitating the activities of training personnel and they themselves contributed greatly to matériel training problems. ASWORG was helpful

in directing attention to training opportunities and in furnishing information upon which instructional material could be based. One of their representatives also devoted several months to the organization and conduct of an air training problem at Norfolk to provide needed assistance not otherwise available.

The major laboratories of the section furnished the scientific and engineering talent needed for training-device development and also served as essential bases of operation for psychologists and industrial training specialists. Much of their work lay outside the laboratories. In the cases of the larger schools they had offices and other facilities in the school buildings. They also roamed far afield in response to various requests for assistance, but the backing, prestige, and procurement facilities of the laboratories were invaluable to them on any assignment.

The training activities of contractors may be considered as being of two types: introductory training and general training. Introductory training is assistance rendered in the assimilation by the Navy of combat equipment devised and introduced by the several laboratories. This is an essential final phase of any program of technical development and all the laboratories undertook work of this nature. The Harvard laboratory was concerned largely with BDI training, the Mineola laboratory with introductory training in MAD, and the Woods Hole laboratory with the initial *bathythermograph* [BT] program. However, introductory training on a particular device was seldom conducted exclusively by the developing laboratory because of geographical factors.

The general training program of furnishing assistance to Navy training schools and commands was one of the principal projects assigned the San Diego laboratory. From the spring of 1942 until the assignment of the contract to the Navy in the spring of 1945, a large and active group of training assistants worked with the West Coast Sound School. From the autumn of 1942 until the summer of 1944, a somewhat smaller group was stationed with the Fleet Sound School in Key West. From the autumn of 1943 until the spring of 1944, a training group was conducted in association with the Submarine School at New London. This group was then transferred to the New London laboratory which had previously been engaged in some training-device development and had served as host to the training group in that area. The San Diego and New London laboratories maintained numerous small groups of training assistants and individual specialists for varying periods of time at a number of coastal and island stations. Their activities will be mentioned further in connection with special projects. Occasions arose for sending training assistants on special missions before adequate formal provision for such civilian assignments with the Navy was established. The training activity antedated that of the Field Engineers or ASWORG, and, unlike those groups, training assistants seldom proceeded under Navy orders. This was in general disadvantageous, though many individuals who worked informally during the early days were highly effective.

The training groups in the laboratories and on detached assignments were kept apprised of one another's activities through periodic reports issued chiefly by the San Diego laboratory. These reports were of great value in maintaining unity of effort and general cognizance of the common problems by all participants in the training program.

14.5 SELECTION PROGRAMS

14.5.1 Selection of Operators

First Operator Selection Plan

As a result of the preliminary observations by members of the Selection and Training Committee it was thought by the research men that the following standardized tests would have some degree of usefulness in determining aptitude for the rapid learning of sound operation.

1. Otis Mental Ability Test (intelligence).
2. Bennett Mechanical Comprehension Test, Form AA.
3. Seashore Sense of Pitch Test, First Edition.
4. Seashore Sense of Intensity Test, First Edition.

5. Seashore Tonal Memory Test, First Edition.
6. The NDRC Personal History Inventory (a listing of items of the social, educational, and occupational factors in each candidate's background).

These tests were administered to 109 sonar student operators at WCSS in January 1942, and were later administered to 92 additional students at FSS during the same month. Both the test scores and the performance data were given to statistical advisers for computation and report. The results of the computations were available by the middle of March 1942. The pressure to secure men was so great that the resident psychologist at WCSS made tentative use of the tests during February and early March for the selection of recruits from the San Diego Naval Training Station. This was done rather hesitantly because the validity of the tests was as yet unknown. Later validation reports showed that this preliminary use of the tests had been justified and had saved the Navy from the inclusion of a large number of sonar students who would have come in without the intelligence, mechanical, and tonal aptitudes necessary for adequate job performance.

Scores from the various individual tests and combinations of the test were correlated with every available job criterion (measure of performance on sonar), such as written examinations, attack-teacher grades, and overall ratings made by the sound schools on each man. This was the only feasible procedure, although it was adopted with much trepidation since the criteria were known to be unreliable because of the nature of the curriculum, the lack of objective grading technique, and the poor control of both shore and ship phases of training. The correlations gave some encouragement and the first selection plan was designed on the basis of a two-screen process. The intelligence test was used as the first screen on all available candidates. Only men who could secure a better-than-average score were accepted. The second screen was applied only to the men who had passed the first screen; it consisted of the mechanical comprehension test and the tonal tests averaged together. Approximately the lower one-third of men taking the second screen tests were rejected.

The selection psychologists met in conference with the U. S. Navy Bureau of Navigation on March 24, 1942. At this meeting it was agreed to use the plan substantially as devised, except that the Navy General Classification Test [GCT] would be substituted for the Otis mental ability test, to avoid a multiplicity of test devices in the hands of the selection officers who would soon be under an avalanche of screening jobs for all branches of the Service. The Navy GCT was also a general intelligence test, and later data showed that it correlated highly with the Otis scores (correlation coefficient of 0.82 to 0.91).

At the same meeting, arrangements were made for the resident NDRC psychologist to travel the circuit of the naval training stations, meeting the selection officers, demonstrating the selection procedure, inspecting the equipment and test locations, and following through with continuous assistance to see that the difficulties in administration were overcome and that the screening procedure was carried out as accurately as possible. During 1942 and 1943, this contact with the training stations was continued. The old hand-scored test answer-sheets were replaced by a method of machine scoring and tabulating which allowed selection officers to use mass-screening procedures and keep up with the growth of war mobilization.

In the meantime, the resident psychologist at San Diego established an office with subordinate personnel, permitting extensions of the first statistical studies. Many sonar students were coming from other sources than the naval training stations. There were transfers from ships' crews. The U. S. Coast Guard was now engaged in antisubmarine warfare, and no provision had been made to screen Coast Guard students. At first these students from miscellaneous sources constituted as much as half of the classes. Many were completely pitch-deaf, and some did not have either the general or mechanical intelligence to learn the job adequately in the time allowed. The commanding officer of the school authorized the NDRC psychologist to apply the new selection method to all students entering from other than recruit

centers, and a large proportion of the failing men were dropped before they could consume the badly needed space in the training program.

During the first year of World War II, several verifying statistical studies were made on much larger samples of men, to see if the original study, based on a relatively small sample of operators, was a valid one. These further researches showed that there was no need to change the original opinion of the research men that the selection devices were essentially good. There was obvious room for improvement, however, and a statistical program of test and experiment, with modifications of the original tests and new ones suggested in the course of the work, was in continuous operation. It was difficult to obtain time in the schedules of the conduct of experimental work as the schools operated under great pressure to furnish operators at the maximum rate. Training operations came first and improvement second. Such experimental work as was accomplished resulted from constant vigilance by psychologists to make use of every minute and the wholehearted cooperation of instructional officers who appreciated that the schools' product was dependent on receiving the best possible candidates for training.

Revised Operator Selection Plan

The original operator selection methods were used with only minor changes until the spring of 1944. Several important defects were discovered as time went on. The original plan allowed some men to enter sonar training who were pitch-deaf, because the tests were scored by averaging mechanical comprehension with tonal discrimination, and a man could compensate for a bad tonal score by an unusually high mechanical comprehension score. The refinement of doppler grading by means of doppler drills and tests revealed the weakness of this method. The Bureau of Personnel also wished to investigate the possibility that one of the tests in the standard naval battery given at selection centers might be substituted for the Bennett test, thus saving needless overlap on testing time. There was also the difficulty that the originally authorized GCT had been changed, and the new basic battery of naval tests had unknown validity for sonar operation. Furthermore, the Seashore sense of intensity and sense of pitch tests showed a low level of statistical reliability.

As a result of these conditions, it was decided to plan a two-screen selection procedure wherein the first screen would combine the general and special comprehensional requirements, and the second screen would be restricted to tonal aptitude, thus making it impossible for pitch-deaf cases to get sonar training.

The following tests were chosen for experimental administration to some sonar classes then in WCSS, although they were already a selected group under the old plan.

1. Navy General Classification Test (general intelligence).
2. Navy Reading Test (comprehension of technical reading).
3. Navy Arithmetic Test (arithmetical reasoning).
4. Navy Mechanical Aptitude Test (mechanical comprehension and visualization).
5. Bennett Mechanical Comprehension Test, Form AA.
6. A new NDRC Sonar Pitch-Memory Test. The sonar pitch-memory test took the place of the Seashore tests.

The results of experimental administration were satisfactory except that the Bennett test proved to be less reliable than the Navy mechanical aptitude test, and the latter was therefore substituted for it. The new plan was approved by the Bureau of Personnel in May 1944 and was instituted by directive to the various naval training centers having selection offices. To pass the first screen, a candidate had to secure at least an average score on any three of the four basic naval tests.

14.5.2 Selection of Sonar Maintenance Men

It was evident very early that inefficient use of sonar was often the result of maladjustment of the equipment, if indeed it were not an actual casualty, and though the operator might be well trained in the routine execution of attack doctrine, he frequently did not know when his

equipment was out of order. It was not possible in 5 weeks of training to give the average student operator sufficient knowledge of such a complicated electronic device to enable him to maintain maximum serviceability. The Navy, therefore, decided to train about one-third of the operators to make repairs and adjustments, assuming that a ship with four or more sonarmen would then have at least one man who could service the gear. The course was given at each sound school, following the training course for operators, and graduation with a satisfactory mark carried with it later an increase in both rating and pay. About one-third of the top graduates from each operator class were selected to take the 10 weeks' maintenance course.

It was gradually realized that the top third of the operators was not necessarily the best source of candidates for maintenance instruction. Therefore a composite selection plan was designed, using each of the following factors on an experimental basis.

1. Navy General Classification Test (intelligence).
2. Navy Arithmetic Test.
3. Bennett Mechanical Comprehension Test.
4. Educational background (units of education in mathematics and sciences from high school and college).
5. Average grade made on three operator written examinations.

This new selection plan for maintenance candidates was installed in December 1942 at WCSS, and was administered by NDRC psychologists for the duration of World War II. Later a similar plan was established at the FSS. This method of administration was necessary because there was no trained classification officer located at either sound school until the fall of 1944, and there were no other places where sonar maintenance selection was needed.

14.5.3 Selection of Sonar Officers

At each sound school sonar officers were taught sonar operation, interpretation of sonar information, and the tactical use of sonar and antisubmarine attacks. In the sea phase, the officers were given practice in conning ships during practice attacks on tame submarines.

Some of the officers were poorer operators than the enlisted sonarmen who were in the same classes, and some found it impossible to make adequate auditory discriminations, to visualize the tactical situation, or to execute the required navigational maneuvers. At first these men were allowed to go through to their permanent assignments without being dropped. Later the Bureau of Personnel provided a means whereby the schools could report the unsatisfactory performance of particular men and they were accordingly reassigned to other duties.

The work in the officer program was handicapped because it is not possible to secure a validation coefficient for a selection plan unless the final job grade is a reliable one and it is very difficult to compute a prediction coefficient if the job is constantly changing. Both of these handicaps, however, had to be faced because there was continuous development in attack doctrine throughout the first two years of World War II and corresponding frequent alteration in the duties of sonar officers. No job analysis was ever stable, and it was seldom that the men were graded on the same basis for more than a few successive classes. Officers were generally graded even less consistently and objectively than were enlisted men. The grades were generally contaminated, from the psychologists' standpoint, by factors not concerned with the technology of sonar, such as ability to command men, aggressiveness, and appearance. It was for these reasons that it was not possible to achieve a selection plan for officers which had the objective selectivity attained for enlisted men.

During most of World War II the sonar officers had been routed through the Submarine Chaser Training Center at Miami, before being sent to the sound schools. This activity gave some sonar training and was in a position to effect some selection of officer candidates for the more advanced sound schools at Key West and San Diego. In March 1943, WCSS recommended that the NDRC sonar selection plan for operators be applied to sonar officers. The recommendation was adopted and issued as a Navy directive, but it was not presumed that

the selection procedure covered all of the officer requirements. The intelligence requirement was considered to be adequately covered by the more stringent educational standards for all naval officers. The commanding officer at Miami requested and was furnished with the NDRC sonar testing materials. In practice, the scores from the tonal tests and the mechanical comprehension test were tempered by further knowledge concerning a man's performance on the sonar attack exercises.

In 1943, an advisory NDRC psychologist designed a selection research program involving some 13 tests from Navy batteries and other sources. These included such devices as officer general qualification tests, mechanical comprehension tests, tonal tests, mathematical comprehension tests, and visualization tests. A statistical study of the predictiveness of each test was to be undertaken and the battery was to be shortened to include only those with the highest values. The research study consumed most of the summer of 1943, with NDRC psychologists working at both San Diego and Key West. The period was one of rapid change in attack doctrine and the job grades on officer performance were at the time largely influenced by the previously mentioned nontechnical qualifications.

Five tests which survived the elimination process were administered to 88 men at San Diego and 60 at Key West and a report of the results submitted to a meeting of the Selection and Training Committee with the Navy in Washington. It was decided that the results were not sufficiently assured to warrant a positive recommendation. It was, however, strongly recommended that the research be continued, and that additional work be done to strengthen the reliability of the grading of officer performance in the schools.

Shortly after this decision, the range recorder trainer [QFL] was completed and gave more objective scores on interpretation of recorder traces and firing errors on the tactical range recorder. At San Diego, the NDRC psychologists, with the approval of the commanding officer, designed a complete set of written examinations for officers on the technical aspects of sonar attack navigation, in objective form. A similar set of examinations was already in existence at Key West. It was hoped that these might improve the predictions for a further selection study. The general form of these examinations was used for the duration of World War II. In addition, the officers were now using the new NDRC doppler drills and tests, which gave a very reliable grade for the most important of the tonal requirements in the job performance. A new selection test was created by the NDRC psychologist, namely, the relative movement test for measuring aptitude in continuously visualizing the relative positions of two vessels proceeding at various speeds and on various courses. It was also found that the Seashore tests were subject to several acoustic and administrative errors which limited the reliability of tonal scores when used as an aptitude test. The NDRC sonar pitch-memory test was standardized and experimentally applied to over 600 recruits, with the result that the statistical reliability was almost doubled as compared with that of the Seashore tests.

The second research selection program used the residue of tests from the first program, except that the relative movement test was added and the NDRC sonar pitch-memory test was substituted for the Seashore tests. This time it was decided to make tonal discrimination a separate and independent requirement. It was planned, therefore, to devise a first screen for the comprehensional aptitudes and a second screen for the tonal aptitude.

The tests in the first screen, after elimination of the poorer selective devices, were:

1. Bennett Mechanical Comprehension Test.
2. Relative Movement Test.
3. Army Air Force Visualization Test.

The second screen consisted of the NDRC sonar pitch-memory test.

After experimental analysis of this plan, recommendation was made to the Bureau of Personnel for its use, with a passing score for Screen I such that by rejecting one-half of the candidates with the lowest selection scores, the worst 10 to 12 per cent of sonar officers would be surely eliminated, and the remaining students would be all of passable aptitudes. The tonal score on Screen II required that every officer be average or better on pitch-memory

discrimination, and this was exactly the same as the requirement later installed for enlisted sonarmen. The selection method was accepted and installed in part, with the understanding, however, that still further work would be done. By the end of 1944, the induction program at Miami was considerably curtailed, most of the sonar officers were already in service, and the need for any further work had largely passed.

14.6 ANTISUBMARINE WARFARE TRAINING

14.6.1 Work with the Sonar Schools

The major contribution to the sonar training program was made in association with the sound schools. A resident psychologist was provided at WCSS in the spring of 1942, and thereafter the group grew by the accretion of additional industrial psychologists, engineers, and training specialists, until it reached eight or ten members early in 1943. By the summer of 1942 a similar but smaller group was established at FSS at Key West. Both of these groups were concerned with the selection programs described in the preceding sections, and this was their principal assignment during the earlier days of their establishment.

By the autumn of 1942, however, a considerable portion of their time was given to assisting the school officers in training activities. The importance of this function rapidly increased and could be considered their major assignment by the spring of 1943. While living at the schools and working intimately with the officers and men in charge of instruction, they obtained a very thorough familiarity with the training problems and with the Navy's methods of conducting training activities. The civilian groups concerned themselves with the analysis of the school programs into separate learning problems, the study and solution of these problems, and the improvement of general training methods and techniques. Their assistance was welcomed in the preparation of lecture material and in the development of presentation of techniques for both laboratory and classroom exercises. Many suggestions were also made for the introduction of films, charts, and other training aids and devices.

At both schools it was evident that the maximum use was not being made of detailed objective grading methods, and continued emphasis was placed upon this point. The basic handicap was the lack of firm criteria of accomplishment in the different shore and sea phases, and marked progress resulted from the introduction of synthetic training devices in the shore phase. These devices, which will be described in Section 14.7, incorporated certain features suggested by resident training groups which were designed to facilitate precise evaluation of student performance. They were largely successful in this objective, particularly in the preliminary weeks of sound training. The existence of such devices did not in itself insure the scoring of students in individual accomplishments. The tendency of Navy instructors was to form an overall subjective impression of a man's success, and this impression was not only frequently biased by irrelevant factors but it did not serve to insure the necessary detailed competence in the various skills required of an operator.

The sea phase of operation was subject to this criticism in a much greater degree and there the problem of evaluating success was even more difficult and the precision of evaluation was insufficient to judge properly an attack's success or failure.

However, experienced observers could assess the individual performances of operators and officers, and significant grades could be given. Through a study of these observations, a check list for evaluating sea performance was introduced at FSS in 1943 and led to noticeable improvement in the efficiency of the sea phase of instruction. This was clearly indicated by comparative tests of operator proficiency made over an extended period by ASDevLant on selected operators from the two schools. Although these operators were presumably chosen from groups of comparable standing at each school, the performance of operators from FSS was found to be consistently superior to that from the school in San Diego. This was largely attributable to the fact that detailed attention was given at Key West to each of the many functions in which an operator must be proficient and to the assurance through the checkoff system that

such proficiency was gained. A similar program of close scrutiny of operating details by an examining board was instituted a year later at WCSS, and thereafter their graduates achieved equally good ratings by ASDevLant.

In addition to assistance in instructional techniques, the formulation of periodic and final examinations was given careful study, and suggestions were made for improving their discrimination between good and poor operators and for increasing the ease with which they could be scored. Standardized examinations permitted more adequate comparison of attainments between succeeding classes and provided a firmer basis on which to evaluate improvements in training techniques.

The training groups at the schools worked as closely as possible with those divisions of the laboratories which were concerned with the design of training devices. Frequently these groups would present to the laboratory their observation of the need for a device to facilitate training in a particular skill. They would then work with the laboratory in the design of a pilot model of this equipment and, upon its delivery to the school, study with small classes its efficacy in training and devise efficiency tests in its operation. This work would almost invariably uncover certain inadequacies in either the design or functioning of the equipment and modifications or redesign would be suggested. Several units of the improved equipment would then be constructed and a larger program of incorporating it in the school curriculum undertaken. The training group would assist in the training of instructors for this equipment and work out exercises and drills. A more complete study would be made of learning, manuals would be written for the instructors and students, and examinations formulated. The laboratory would, in general, furnish the installation, maintenance and operating manuals for the school, and other installations as these might be requested by the Bureau of Personnel. In those cases where the device was of interest to the Bureau of Personnel, through its general concern with sonar training, or had possible applications to other training fields, manuals and recordings were furnished the bureau and assistance rendered when necessary in its introduction at other training establishments. Assistance in the writing of manuals for both operators and matériel students was the principal assignment of several individuals at the schools. Instructional manuals in general emanated from the schools themselves and after submission to the Commander-in-Chief, were issued as official Navy publications. Civilian assistants participated extensively in the compilation, editing, and revision of the material.

With the advent of newer types of sonar gear, the problem of adequate maintenance texts at the schools became particularly critical. A considerable group of men and officers was assisted by an engineering member of the training group in the capacity of editor in the preparation of a sonar maintenance manual. This undertaking occupied 8 months, and when issued in January 1945, consisted of more than 800 pages. A distribution of 5,000 copies was made to other maintenance and training activities.

From time to time, various specialists were attached to the training groups at the schools and elsewhere for the purpose of giving lectures at an advanced level to sonar and prospective commanding officers. These lectures were intended chiefly to provide scientific background for ASW doctrine.

The establishment of maintenance courses in the two schools early in World War II was greatly handicapped by the lack of suitable naval instructors, and as the situation was a critical one, civilian specialists in electronic engineering were located and retained to form a nucleus of matériel instructors at the two schools. These staffs numbered six to eight at each school for a period of a year or more, and rendered invaluable assistance during the early period of matériel instruction. Later, the training program for electronic specialists and radio technicians furnished naval personnel to take over these assignments, and civilian instructors either joined the staffs of the development laboratories or received other assignments within the Navy.

14.6.2 Subsidiary ASW Training Projects

The major effort in general training was made through the training groups associated

with the sound schools but training assistance was furnished by a number of smaller groups and individuals on special assignment from time to time as opportunities were presented.

For several periods of a few months' duration, training assistants worked with harbor defense activities at both Fisher's Island and San Pedro. Experience gained in work with the sound schools contributed to the establishment of curricula and the preparation of lectures and examinations at these harbor defense activities. Training assistants were likewise assigned for intervals of several months to the Antisubmarine Warfare Instructor's School [ASWIS] at Boston on the utilization of new training devices and techniques, and to the Tenth Fleet for liaison with civilian training groups and laboratory device-development programs. Similar assistance was rendered on a somewhat longer term basis to shakedown and refresher training activities with COTCLant at Norfolk and Bermuda, and with COTCPac at Seattle, San Francisco, and San Pedro. These men contributed in a number of technical ways through their assistance in the introduction of training devices, maintenance assistance on attack teachers, and the provision of liaison with civilians in schools and laboratories.

A training assistant on special assignment to the Bureau of Ships, beginning in the autumn of 1943, assisted in the inauguration of the *Sonar Equipment Log* which was a periodic matériel publication circulated to RMO's for the purpose of keeping them abreast of current matériel developments. A training assistant was assigned to ComDesPac in the autumn of 1943 primarily for the introduction of shipboard attack teachers, but in the hope that he would also be generally useful both in the local training program and in bringing the facilities of the laboratories more effectively to bear on particular problems encountered in the Pacific. This assignment was a very successful one and resulted in a number of suggestions which improved the operation of this equipment in the Southwest Pacific.

At a somewhat later date, the assistant with ComDesPac gave his principal attention to sea-air rescue work and was largely instrumental in the adapting of the expendable radio sono buoys to this use. The application of ERSB to this service grew out of ASW operations with CVE-DE hunter-killer groups. The method there in use was known as raser (radio sonar echo ranging) because of the way in which the buoys were used to receive sonar signals and transmit these back to the echo-ranging ship by radio. In rescue operations, survivors from a ditched aircraft release one or more of the buoys, and searching aircraft or surface vessels obtain RDF bearings on the radio carrier at ranges of the order of 15,000 yd for surface vessels, and approximately five times that figure for aircraft. As a result of the experimental work conducted during the spring of 1945, an urgent and extensive program of equipping destroyers operating with fast carrier task forces was undertaken for the projected strike against Japan. Surface vessels, submarines, and aircraft were equipped with the necessary buoys and receivers and were trained and in readiness for operation at the time hostilities ceased. The program of experimental and operational tests continued and training manuals and movies for instructing personnel were planned for subsequent naval procurement.

The other phase of training which was concerned with the introduction of new combat devices likewise presented many occasions for extended tours and brief assignments of groups and individuals to naval activities. These activities can be illustrated more conveniently by considering them in terms of the device being introduced. A few representative instances of such training programs are given.

Bearing Deviation Indicator [BDI]

The BDI, which was developed by HUSL, required modification of training methods and assistance in introduction. At first this assistance was conducted on a very informal basis through occasional lectures given at training schools by members of the laboratory staff. Modifications of shore-based attack teachers to incorporate BDI were requested and the laboratory assisted in the design and production of these. ASWIS requested assistance in the preparation of lectures on the BDI and the laboratory assisted in this and in the training of

certain instructors on the ASWIS staff in the operation of the equipment. The Antisubmarine Warfare Training Center [ASWTC] at Norfolk also requested assistance in the preparation of BDI training aids and the laboratory assisted in the inauguration of a training course. A dynamic demonstrator was constructed, and later several units were procured for the sound schools to improve matériel training in this device. As the basic equipment appeared in larger quantities on naval vessels, it became evident that the informal lectures were not reaching a sufficient number of interested naval personnel. To meet the need for training men in installation and maintenance, a group of field engineers and sonar officers was sent to Harvard for a one-week course. Beginning in February 1944, six of these courses were conducted, covering trace interpretation, details of adjustment, operation, installation, the location of trouble, and conduct of tests.

Expendable Radio Sono Buoys [ERSB]

The introduction of radio sono buoys was another occasion for which training assistance was required. In the spring of 1943, the New London laboratory inaugurated a training program and furnished instructors in the ERSB school which was established by ComAirLant in Norfolk. They gave introductory training, trained instructors, and formulated outlines of courses, lectures, and demonstrations. A training device for the ERSB was designed and several units were furnished to air commands. Assistance was also given in the organization of training exercises and the evaluation of student performance. With the advent of the directional buoy, further assistance was given in introductory training, and a directional radio sono buoy trainer was designed and used for training in the laboratory. This was later furnished to the training activity at Norfolk and assistance was given in its incorporation in the air training program of that activity.

Magnetic Attack Director [MAD]

The training work undertaken by the Airborne Instruments Laboratory at Mineola was an example of aid given to the Navy in an entirely novel field. Naval personnel were not familiar with the MAD, and with the advent of this equipment the training problem became of great importance. The laboratory built training equipment, laid out curricula, and hired and trained instructors. The work was carried out in the laboratory essentially as an experimental project since there was no precedent in this field. Regular courses in the principles of operation of the equipment were begun in September 1943, and a more or less continuous series of courses was conducted until June 1944. Army personnel were assigned to the school from time to time, and it was found that the syllabus was equally applicable to both Services. Three separate courses were taught. The first was intended for pilots, and covered two weeks of material devoted to operating capabilities and limitations, coordinated use with sono buoys and radar, and practice in the recognition and discrimination of signals. The second course was for aviation radio men who functioned as operators of MAD aboard aircraft. This course was of two weeks' duration also and covered the recognition of signals and their distinction from spurious indications, adjustment and operation of the gear, and coordination with the pilot. The third course was for aviation radio technicians who were concerned with maintenance and repair. It was of five weeks' duration and was a comprehensive review of the electronic principles of operation and a thorough course in maintenance and troubleshooting. Nearly 350 officers and men from both Army and Navy were indoctrinated in one or more of these courses. As a by-product of the training activities of this laboratory, certain special courses were undertaken for training in the magnetic compensation of aircraft and the use of the magnetic attack trainer.

Bathythermograph [BT]

The initial installation of bathythermographs aboard naval vessels gave rise to one of the first instances in which training assistance was requested. The Woods Hole laboratory assisted ASWIS in 1942 in the training of a few student officers who were sent down to the laboratory for a few days at a time. They were given lectures and reading material, and shortly the curriculum was expanded to occupy about one

week and was attended on the average by ten men at a time. Other groups of BT officers were assigned to the laboratory for periods of a month at the request of the Bureau of Ships, and these men were given more extensive training in the use of the BT. Before the training of ASW specialist officers was terminated in 1944, approximately 600 men had received instruction through the efforts of the laboratory. In addition to this formal instruction program, a number of laboratory personnel from both Woods Hole and San Diego made extensive tours of the North and South Atlantic, the Caribbean, and the Mediterranean, to increase their knowledge of this device and the effectiveness with which it could be used. At a later stage, both laboratories provided training assistants who worked with the Operational Training Commands on both coasts, assisting in both the training and matériel problems which were encountered. The program with submarines was more extensive and will be mentioned in a later section.

Manuals and Publications

An instance of a somewhat different type of cooperative assistance was furnished in the field of matériel. In addition to the manuals prepared for school use and instruction, urgent need was felt by the district and Service forces, as well as shipboard maintenance men, for more adequate information on sonar gear. In some instances no manuals whatever were available, and in others the documents were fragmentary or outdated. The existing manuals were not standard in content, style, or technical level. It became increasingly evident in 1943 that faulty maintenance was one of the chief causes of inefficient sonar operation, and an urgent request was received to assist in the preparation of more adequate manuals and the establishment of a standard by which Navy suppliers could be guided. A considerable number of officers were assigned to the work, and through their participation a knowledge of the problems and techniques involved was disseminated within the Bureau of Ships. Approximately 12 manuals and equipment logs were produced, averaging about 300 pages apiece. These were printed under direct Navy contract and distributed by the Bureau of Ships.

One further publication undertaking is worthy of note. This was the *Training Group Handbook* assembled in January 1944. The major portion was secured as loose leaves from the *Manual for ASW Field Engineers,* as this manual was directly applicable to the problems encountered by training groups and assistants assigned to naval activities. The handbook contained reference material for the indoctrination and training of members of the civilian staff as well as data needed on assignments to the various naval establishments. It proved invaluable to all training activities and represented a most significant contribution to training by the Field Engineers.

11.7 ANTISUBMARINE WARFARE SONAR TRAINING DEVICES

11.7.1 Training Aids

One of the important contributions made by the contractors' laboratories to the training program was the design and procurement of training aids and devices. Training aids took many forms and were supplied not only to schools but to the Navy units engaged in training and they contributed materially to the effectiveness with which instructors could impart information to large classes of enlisted men and officers.

Profiting by industrial experience in visual education, a number of moving picture films were produced. Some were produced by the laboratories with advice and assistance from the Navy and in other instances films were procured by the Navy, utilizing technical experience furnished by the laboratories. These films formed part of the sonar curriculum at the school and were of even greater value in refresher training with the Navy and at advanced bases. Slide films were also made by the laboratories. These dealt chiefly with newer types of auxiliary equipment, such as the BT and RSB. The facilities of the laboratories were also drawn upon for producing lantern slides and an extensive library of these was built up which assisted materially in the school curricula. In

addition to visual aids of this nature, charts and animated demonstrators were built for the purpose of displaying surface vessel and submarine maneuvers.

These visual aids were supplemented by auditory ones, and the recording facilities of the laboratories were well adapted to the preparation of this type of training aid. For some purposes, lectures were recorded at one training activity and made available to another. The playing back of these lectures was also helpful on many occasions in improving instructors' presentations and techniques. In addition to this application, phonograph recordings of sea echoes and ship sounds formed the basis of training in echo and sound recognition. Extensive programs were carried out in the laboratories for the acquisition of representative echoes and ship sounds, and these were later edited and assembled in graded series adapted both to school and advanced-base instruction.

A wide variety of small, inexpensive devices were also produced which either assisted in training curricula or were aids to the operators or officers during different phases of their training or practice.

11.7.2 Representative Training Devices, Shore Phase

In addition to the demonstration devices and training aids considered above, considerable effort was expended in the development of training devices for large-scale student use during the shore phase of instruction within the schools. It is not possible in as brief an account as this to describe all of these devices that were used in the course of World War II, but representative ones will be considered briefly to illustrate the type of assistance rendered and the improvement in these devices that resulted from increased knowledge on the part of laboratories and schools as to the most effective manner in which they could be employed in training.

Primary Bearing Teacher

It was recognized during the spring of 1942 that a need existed for a simple primary single-student trainer for giving practice in the manipulations required of a sound operator in response to auditory stimuli. Work on a primary bearing teacher, which was later given Navy designation QFE, was begun in June 1942. It was submitted for evaluation by the Navy in July and a request was soon received for 50 of these devices, which were supplied through a subcontractor. They were completed in about 6 weeks and immediately put into use at both sound schools. Subsequently about 500 were built and used at various training activities.

Since sound school classes were large, there was no opportunity for students to obtain the necessary thorough drill in fundamentals with the other training facilities available to the schools. Although the primary bearing teacher was not intended to duplicate conditions of work on an actual sonar stack, it did permit extensive drill in the correct procedure for operating and reporting while listening for echoes. A crude approximation of a doppler effect was also provided. With these devices, a student's reactions could be brought to the point where they were largely automatic and correct operational habits could be developed before going on to advanced training.

In practice, three students were generally trained on this device at one time. The first of these was the control operator who reported on contacts, contact bearings, cut-ons, mid-bearings, target width, bearing drift, and doppler. The standby operator, using a checker's record sheet, checked for errors made by the control operator. The problem setter, or instructor, was generally a senior student who set the ship's course, target bearing, and doppler. After contact, he gave the appropriate commands while turning the ship smoothly to head for the target. When the students were all of more or less the same degree of competence, the three operators would change places until all became familiar with the various procedures.

Advanced Bearing Teacher

In point of time, the advanced bearing teacher, Navy designation QFD, antedated the primary bearing teacher, but in the normal curriculum and in the orderly development of

a training program it represented an advanced stage of training, presenting more realistic sounds and providing practice in more of the functions of the sound operator. Like the primary bearing teacher, however, it suffered from being an individual student trainer and from a certain artificiality in the controls and auditory signals.

This device was suggested in early conversations with officers of WCSS, and design and construction of a pilot model were undertaken early in 1942. By June 1942, three of the devices were in use at WCSS, and a month later two were delivered to FSS. Within the next few months, 20 more were obtained from a subcontractor. In all, about 170 of these devices were built and used by the Navy during the first two years of World War II.



FIGURE 3. Primary bearing teacher. *Left*, student's side. *Right*, instructor's side.

The advanced bearing teacher was particularly suited for continuing the training of students who had had several days' experience on the primary teacher. On the advanced teacher, their training was conducted under conditions more closely resembling those of actual operation. At the conclusion of their drills with this instrument, their habits were sufficiently well formed that they were prepared to make the most effective use of team training on the attack teachers and at sea. The student's side closely resembled the older types of QC sonar. The training handwheel was of the same size and had approximately the same friction and moment. Either long or short standard keying intervals could be used. The problem presented to the operator could be allowed to develop automatically or could be modified as desired by the instructor's intervention. Two ships, a submarine target and an attacking surface ship, were simulated by the device. The student imagined himself in the sound room of a destroyer seated before the QC stack, and he operated the controls as he would operate them there. When contact was established, he attempted to stay on the target as his own ship maneuvered to intercept the submarine, and he furnished the same reports that he would on board ship.

At the beginning of the problem, the submarine was 2,300 yd distant from the destroyer and had an angular width of 7½ degrees. Contact could be made at any true or relative bearing at the option of the instructor. The course of the destroyer could be altered by the instructor, if desired, as the problem progressed. The relative motions were such that the destroyer passed about 150 yd in front of the submarine, and at the point of closest approach the apparent width of the submarine was 24 degrees. Throughout the attack, realistic sounds characteristic of operating QC gear were produced, including the ping with its reverbera-

tion, echoes, and water noise. Means were provided for automatically changing the echo to produce the doppler effect appropriate to the chosen attack pattern. The echo automatically followed the ping after an interval which corresponded to the actual range of the submarine. Stronger echoes were obtained if the axis of the sound beam was directly on the target than if it was on one side or the other, and the echo strength diminished with target distance. By regulating the various controls provided on the instructor's side, as shown in the figure, the instructor could introduce many of the distractions and difficulties which the sonar operator would experience at sea. The instructor was able to set up the problem and let the run proceed automatically, or he could simulate a wide variety of other attack patterns by making one or more of the following adjustments: (1) the pitch of the echo with respect to reverberation, (2) the loudness of the echo with respect to reverberation, (3) the rate at which the reverberation decayed, (4) the loudness of the water noise, (5) the heading of the attacking ship, (6) the bearing of the submarine. The problem ordinarily ran for about 11 minutes.



FIGURE 4. Advanced bearing teacher. *Left*, student's side. *Right*, instructor's side.

PRIMARY CONNING TEACHER

The primary conning teacher, Navy designation QFH, is another instance of the advanced realistic type of single-student trainer, differing, however, completely in nature from the advance bearing teacher. It was intended principally to provide preliminary practice for conning-officer trainees in dealing with the relative motion problem presented in an antisubmarine attack by a surface craft equipped with standard echo-ranging gear. No sounds were produced by this teacher as it was not intended for training in echo recognition, but equivalent information of about the same character and reliability was presented visually to the trainee. In the usual operation of the attack teacher (QFA), unequipped at that time with BDI, it was found that the information essential for

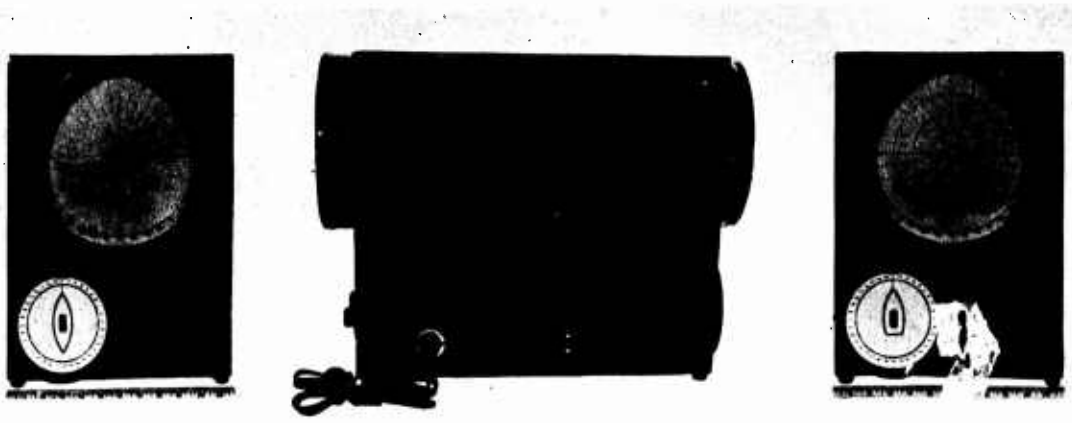


FIGURE 5. Primary conning teacher. *Left*, submarine side. *Center*, control panel. *Right* destroyer side.

plotting was too erratic and confused to provide a good basis for learning plotting methods. By means of the conning teacher, it was possible to hold extensive drills in plotting for an entire class with continuous increase in the level of difficulty. Students could thus be brought to the point where they could plot efficiently on the attack teacher during their training with that device.

The conning teacher was a device with which an ASW officer could acquire practice in making all the judgments necessary in conning an attack against a submarine. The surface vessel and submarine had complete freedom of maneuver, subject only to the limitations imposed by the tactical parameters of the vessels and the information properly available to them. The conning-officer trainee was seated at one end of the instrument, which is shown in the accompanying figure, and imagined his ship to be at the center of the coordinate screen which he viewed. The range (maximum value 2,000 yd) and the bearing of the submarine were indicated to him visually by a small round light spot which appeared intermittently on the screen. The frequency with which this spot appeared was approximately that at which he could expect to obtain information from a good sound operator. On the panel before him, the conning officer was provided with engine and rudder controls with which he could change the speed and course of his ship. Appropriate delays were incorporated in the rudder control to simulate the lag in the response of the ship to its helm. The rate of turning was also a function of ship's speed and was chosen to be appropriate for the class of ship that the instrument was intended to represent.

The opposite end of the machine was the submarine control station and was occupied by the competitor, or instructor. The submarine was imagined to be at the center of that screen on the course indicated by the course dial. The movement of the destroyer with respect to the centered submarine was again indicated by a small round light spot which appeared continuously, and the screen was calibrated by radial lines for bearing but was without circles for range. Controls for changing the speed and course of the submarine were provided, again with suitable delays in the turning rates. At the beginning of each exercise, or competition, the submarine positioned itself and, in the case of elementary exercises, the officer conning the submarine provided additional information to the ASW officer in training to simplify his operations. The exercises actually used varied all the way from the simple case in which the trainee was given the speed and course of a submarine which was not maneuvered, to those free competitions in which the instructor regarded himself as a submarine commander and employed all the evasive tactics at his command. It was possible to apply various criteria in evaluating the success of an exercise. The scoring of a mousetrap problem might be made on the ability of the conning officer to maneuver his ship so as to be on the correct bearing at the instant of fire, or alternatively the conning officer might be held responsible for the time of fire as well.

The conning teacher was used by various training commands to fulfill a number of different functions besides that for which it was originally designed. It was used for training in elementary and advanced plotting. It was used for both depth charges and forward-thrown attacks on straight courses and on maneuvering submarines. It was also used as a problem generator in CIC instruction. In one of the schools it was used as an ASW instructional device by assigning a full attack team of four members to each unit. The conning officer conned the attack as he would on an attack teacher, watching the gyro-compass repeater and true sound bearing and, acting as his own helmsman, manipulated the rudder and speed controls. The sound operator called off ranges and center bearings, as indicated by the light spot, keeping the true sound bearing continuously adjusted and recording intermittently the reading of the range dial. The plotting officer made a Halifax or time-range plot from the data furnished by the operator. The problem setter made the initial setting of the submarine and maneuvered the target as required by the problem.

The first five units of this device were completed in June of 1943 and furnished the sound schools and the Submarine Chaser Training

Center. One hundred and four additional units were later procured by the Navy and furnished directly to ASW training centers.

Tactical Range Recorder Teacher

The training devices that have been described above contributed materially to the rate at which trainees could receive the shore phase of their instruction, but they were essentially individual training devices, requiring the presence of an instructor for each student. As the shortage of instructors was one of the chief handicaps faced by the schools and other training activities, it was desirable to develop devices which were more economical of instructors' time. The devices previously described had the additional failing that they provided no permanent accurate record of the student's performance and therefore fell somewhat short of ideal training instruments.

The tactical range recorder teacher, Navy designation QFL, was the earliest of the group trainers which provided a permanent record upon which the performance of the student could be accurately scored. With the advent of the range recorder, an instructor at WCSS recorded on a phonograph disk the reverberations and echoes of a practice attack on a submarine. By means of a special electronic keying circuit and amplifier, this recording was played back to the range recorder, thus reproducing the traces originally made at sea. Recorders were not at that time sufficiently plentiful to permit the construction of a training device built around them. However, ASW officer of the Readiness Division of COMINCH recognized the importance of such a trainer, and a training assistant was assigned to collaborate with the USS *Sylph* to develop the idea in order that a trainer would be available as soon as range recorders could be furnished in sufficient quantity. On the basis of this work, one of the division's laboratories constructed five units, and later 50 units were procured through a Navy laboratory.

As the name implies, the trainer was intended to provide instruction and practice for the operator of the chemical recorder in evaluating traces and reporting at proper intervals the motion of the target and the time of fire. Recordings were made of practice attacks at sea using the laboratory facilities and were representative of the various types of attacks. Five albums containing approximately 50 records were furnished as part of the trainer.

A typical training unit consisted of five range recorders to which information was furnished by the playback and electronic system. The realistic reproduction of the recorder traces and the accompanying sounds was a primary aim in the design of the equipment. The record that was presented to each student enabled the instructor to assess accurately the student's performance and indicate to him, both at the time and in subsequent conferences, the errors perpetrated. Case studies were made at the training activities on the effectiveness of the device as an instructional aid, and assistance was given in the establishment of the trainer in school curricula. As in the case of all the other training devices, instruction manuals were prepared covering installation and maintenance as well as instructional use.

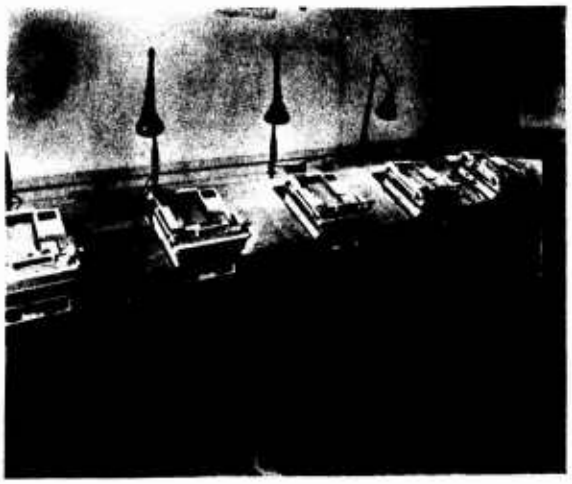


FIGURE 6. Tactical range recorder teacher, as installed at the U. S. Fleet Sonar School, San Diego.

This was the earliest and one of the most successful of group trainers and met with enthusiastic approval by all training activities.

Echo Recognition Group Trainer [ERGT]

Early in 1944, the WCSS recognized a growing need to establish a special training program in the recognition of target echoes as heard

over sonar gear. The size of the classes indicated that the trainer should be capable of accommodating 15 or 20 students, and it was essential that the recordings be highly correct in character. In addition, a permanent record should be kept of the accuracy of the student's judgment and the time required for him to formulate it. Finally, the trainer should be such that it would be unnecessary for the instructor to interrupt the auditory pattern of the exercise during its presentation. The first model of

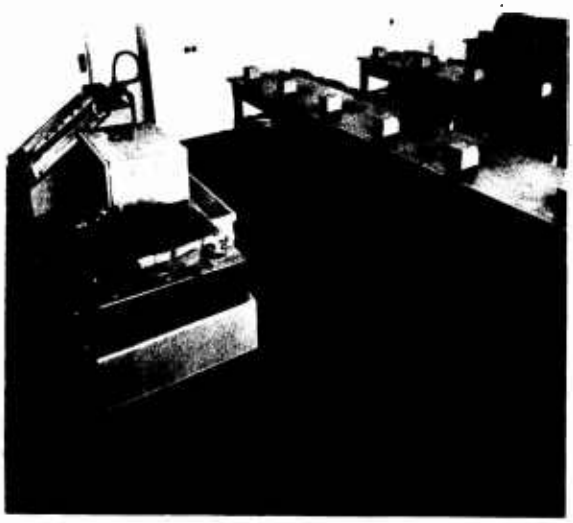


FIGURE 7. Echo recognition group trainer, as installed at the U. S. Fleet Sonar School, San Diego. The recorder, filters, amplifier, and playback system are shown at the left, and some of the students' stations at the right.

such a trainer was designed and placed in operation at the school in April 1944, its performance was carefully studied, and two additional models were later built for other training activities.

The trainer comprised a phonograph playback system, a number of student station keys, and a monitor recorder. The recordings and the exercises conducted with them were designed particularly to improve the abilities of the sound-officer and enlisted personnel in the following functions: (1) doppler judgment, including degree, (2) distinction between wake and submarine echoes, (3) detection of faint submarine echoes, (4) identification of cut-ons, and (5) proper reporting of judgments as made during an attack. In the operation of the training program, a number of students were presented with a carefully prepared sequence of sea recordings interspersed with related lectures. During the presentation of the recordings, each student registered his judgment silently by moving a station key. These movements were recorded simultaneously for all students and the instructor on the monitor recorder. When each selection was over, the instructor compared the students' records with his own in assessing the members of the class. A predetermined code allowed the instructor to interpret the broken and continuous lines produced on the record by the movement of the students' keys. In addition to the album of recordings, instructor's manuals and maintenance manuals were prepared on this device, and it formed an essential element in the training courses at the schools.

Training in echo recognition was found to be such an essential feature in operator and sound officer training that a request was received to modify the training in this function so that it could be given at advanced bases with a minimum of equipment. In response to this request, studies were made of the feasibility of using the same recordings and employing mimeographed forms which were marked in pencil by the student in lieu of the keys and the recorder. It was found that the training so provided was equivalent to that of the echo recognition group trainer, except that the time necessary for the student to reach his decision could not be made a matter of permanent record. It was considered that the training was satisfactory without this feature, and 20 albums of recordings and instruction manuals were prepared and issued at the direction of the Bureau to advanced bases during the winter of 1944.

GROUP OPERATOR TRAINER

As the classes of sonar operators increased in size, at both of the sound schools the allowance of advanced bearing teacher units was found to be inadequate. The demands made on the staff instructors by such unit-training devices were also prohibitive. In consequence, a request was received for the construction of a group trainer in sonar operation which would

enable one instructor to handle a class of approximately 10 students at a time. An opportunity had been afforded by the installation of the British mass procedure teacher at Key West to evaluate the possibilities of such a device and a counterpart of this British trainer was the first suggestion. It appeared feasible, however, to improve considerably on the mass procedure teacher, and the most desirable features of the advanced bearing teacher and tactical range recorder teacher were drawn upon in the design of the group operator trainer. Standard sonar gear was available in sufficient quantity by 1944 to permit its use for student stations. This afforded greater realism of instruction and also permitted the teaching of various stack adjustments which had not been possible previously with the advanced bearing teacher.

Each student station was provided with a standard QGB or QJB stack with a few of its circuits revised to correspond to those of the problem generator. The master station, or problem generator console, was provided with three panels. On the left-hand panel were the concentric bearing scales on which a bug indicated the true center bearing of the submarine. On the center panel, ten small identical receiving instruments indicated the respective bearings on which the students' projectors were trained. Below these instruments were control knobs which regulated the various sound effects, the depth of the submarine, and other factors of the problem. On the right-hand panel were a monitor bearing recorder, control buttons for the two-way communication system between instructor and students, and certain control switches. After the problem was started, the relative movements developed independently of the instructor and students. The cam arrangement controlling the problem was so constructed that the surface ship was conned properly for the attack. Six different attacks were included in the repertoire of the trainer and they were grouped in pairs representing attacks and reattacks. The instructor could select at will any one of the three pairs by an adjustment through the side of the console. The sound effects were more realistic than those provided by the advanced bearing teacher.

Units were installed at both sound schools in 1944 and were incorporated in the regular curriculum of the schools. From time to time requests were received for the incorporation of additional features such as the FXR-4. As the program represented a developing one from the fall of 1943, the maintenance and instruction manuals originally provided were considered as interim issues, and a final manual was not furnished until the termination of the laboratory's activities.

Underwater Sound Attack Teacher

Although NDRC had little part in the development or modification of the attack teacher, Navy designation QFA, no account of sonar training would be complete without a mention of it. As was stated in a previous section, it was recognized during the earliest days of the operation of WCSS that a shore-based device, portraying in the best synthetic manner the major features of an ASW attack, would be an essential training instrument. The attack teacher differs from the devices previously discussed in that it was originally designed as a training device for all members of the ASW team. The first model was built by the Mare Island Navy Yard using an old range keeper and on the basis of its performance a redesigned attack teacher was procured by the Navy from the Sangamo Electric Company in quantities sufficient for the schools and all other training activities of any size.

The equipment was designed to simulate in miniature the operation of sonar gear, and included the range recorder, the attack predictor, and conning stations. It consisted primarily of a mechanism integrating the functions of the various attack stations, providing appropriate sounds, and also projecting on a screen conventionalized images of the surface ship and target throughout their maneuvers. The resultant equipment provided a means for training sound operators in the manipulation of sonar gear and for instructing sonar officers and conning officers in the performance of their several functions. This simulation of supersonic echo ranging was achieved by a suitable arrangement of optical, electromechanical, and electronic apparatus. The simulated ocean consisted

of a screen upon which were projected the images of the surface ship and submarine, together with a band of light periodically traversed from the ship across the screen at a rate proportional to the velocity of sound and in a direction controlled by the sound operator. The path of the band of light represented the wave front of the sound beam, and when it encountered the ship image representing the target, an echo was returned to the sound stack. A



FIGURE 8. Console of the underwater sound attack teacher as installed at the U. S. Fleet Sonar School, San Diego. The rear of the console can be partially seen in the mirror, which was used to increase the projection path in this particular installation.

major feature of the conning controls was the correct simulation of the tactical parameters of the ships concerned and, in consequence, realistic training was given to the officers. The training device was a most complete and valuable one and formed the backbone of the shore phase of team training in ASW.

In the work of the training assistants with the schools and in the early advisory work of the committee for the Bureau of Ships, certain minor contributions were made to the design and operation of this trainer. Observations on the apparent beamwidth of the supersonic projector indicated certain modifications in the interest of correct presentation. An adjunct representing an assisting ship was designed and provided to WCSS to aid in the training on that type of attack. An auxiliary projector to provide the instructors and observers with an azimuth grid covering the synthetic ocean was found to be of assistance, particularly with the early models of this teacher, and a number of these were designed and furnished by a laboratory.

14.7.3 Representative Training Devices, Sea Phase

The sea phase of training in ASW operations is an essential advanced stage in any course to qualify operators and officers for combat operations. The attack teacher provided training in the integration of various members of the attack team ashore, but it was not sufficiently realistic to take the place completely of such team training aboard ship. The sea phase of training, however, presented additional problems which were found to be very difficult of solution under the conditions encountered at the schools. In general, only one operator at a time could obtain direct participatory training aboard ship, and in consequence the periods of actual operation for any one man were very brief. It was difficult for instructors aboard ship to assess properly the performance of the sound operator because of the many distractions and the dependence of his performance upon that of other members of the attack team. Few surface ships were available for training, and the sound gear was not of the most modern type during the early days of World War II. Still fewer target submarines could be provided for school operations, and these were of the older types incapable of deep submergence or rapid maneuvering. Finally, the assessment of attack success presented the greatest difficulties. The method in general use was that described in Section 14.2, but its precision was not sufficiently great to determine whether or not the charges would have exploded within

lethal range of the target. The training groups of the laboratories were able to make some contributions toward the solutions of these difficulties, but the sea phase of training continued to be the most difficult one for the schools to conduct effectively.

ANTISUBMARINE PRACTICE TARGETS

The lack of submarines for school operations in 1942 was so serious that a request was received for the development and construction of synthetic practice targets which would simulate the presence of a submarine to the attacking ship. The problem was studied in cooperation with the WCSS, and it was decided to attempt the development of a mobile electronic target which would be essentially nondirectional, return an echo of at least 2,000 yd, and exhibit doppler effect.

The various forms of practice target that were designed all employed the telephone receiver principle and consisted of a receiving transducer, amplifier, and transmitting transducer. On receipt of the signal from the echo-ranging vessel, the impulse was amplified and returned to the water by way of the projector and subsequently picked up as an echo by the sonar gear aboard the attacking vessel. Filters were incorporated to reduce the effect of extraneous noise and the amplification adjusted below the point at which regeneration would set in. The first model was mounted on a raft towed by a small surface vessel, and in later modifications the transducers were mounted directly beneath the keel of this vessel with the electronic and monitoring equipment on board. Tests made in the harbor showed that when the projectors were submerged approximately 6 ft deep, satisfactory echoes were obtained to 2,500 yd. On the basis of this success, 37 raft and keel installations were constructed for use at the schools during 1942 and 1943. They contributed materially to alleviating the situation brought about by the shortage of submarine targets.

Raft- and keel-mounted echo repeaters had certain shortcomings which were recognized early in their utilization by training activities. The small vessels involved could not operate satisfactorily under the various conditions encountered at sea. The transducers were shallow and, in consequence, the range was short and the lost-contact range unrealistic. Also, the presence of the small vessel prevented the attacking ship from having complete freedom to maneuver in the neighborhood of the target. The first modification to attempt to meet some of these disadvantages was the buoy type of echo-repeater target which consisted essentially of the same transducer and electronic components, but in which the transducers were suspended 50 to 100 ft beneath its surface by means of a cable supported by a small barrel buoy. The buoy target presented less of a hazard to the maneuvering of the attacking ship and the depth of the transducers provided adequate simulation of the depth of a submarine. This model, however, rested passively in the water and did not provide any doppler effect, but it was very economical in men and facilities and easy to keep in operation. Between 30 and 40 of these were designed and furnished to the schools and other training activities during 1943. Eighty-three units were subsequently procured directly by the Navy.



FIGURE 9. Echo repeater practice target, model SR-2. Navy designation OAS.

It had been recognized during these earlier developments that the eventual practice target should take the form of a towed, submerged body simulating more nearly the behavior of the maneuvering submarine. Work was undertaken in the autumn of 1942 on the development of such a target, and early in 1943, the SR-2 type shown in Figure 9 was developed. This consisted of a 330-lb torpedo-like body, containing the electronic amplifier and carrying two Rochelle salt crystal transducers in the

tail fins. A pressure-indicating unit was also included for depth indication. The transducers, which were identical with those used in the buoy model, were essentially nondirectional in the horizontal plane, thus making the target equally satisfactory for all bearings. The excess buoyancy of the unit was such that the target floated when at rest, but when towed at from 4 to 6 knots at the end of a 1,200-ft cable, it ran at a depth of from 60 to 90 ft. The towing cable had an insulated electrical conductor as its core and power was supplied through this conductor from the towing boat. A separate portable unit, including the power supply and remote control panel, was carried in and controlled from this boat. The operator had the gain at his disposal and was able to monitor the signals that were received and the depth at which the target ran. This type of target was first put in use by WCSS early in 1943 and after a few months of use was considered sufficiently practical and satisfactory to warrant procurement on a considerable scale for training activities. Good echoes were received at ranges as great as 4,600 yd in 600-fathom water and the laboratory constructed 16 units with successive refinements during 1943. One hundred and sixty-three units were later procured directly by the Navy.

The SR-2 was somewhat heavy for convenient handling, and before the practice target project was discontinued, a radical departure was made in the design of the SR-5. In this case, the body was a hollow, wing-type structure with excellent towing characteristics, and a total weight of approximately 100 lb. It was first tested in the autumn of 1943 at WCSS, and subsequently 16 of these devices were made by the laboratory and furnished to training activities. It was much easier to handle than the SR-2, but in other ways performed identically.

Evaluation of Attack Success

Although the determination of whether or not a practice attack had culminated in the successful delivery of the depth charge or other projectiles was most essential in training exercises, the problem presented in securing this information was never satisfactorily solved. Early in 1942, the problem of devising suitable equipment for this purpose was assigned to a contractor and, after an extensive period of development and test, certain units were procured by the Navy. The equipment consisted essentially of a hydrophone carried by the target submarine which recorded the acoustic impulse emitted by a small explosive cap thrown ahead by the attacking vessel. This cap was carried in a small body so shaped and weighted as to fall at a predetermined rate corresponding to the ordnance presumed to be in use. It was detonated by a pressure-actuated mechanism. The electronic equipment aboard the submarine utilized the acoustic signal produced by the cap to display on dials the range and bearing of this small explosion relative to the conning tower of the submarine. The range was inferred from the intensity of the impulse and was dependent for its precision on the uniformity of the explosive caps. This uniformity was found to be adequate for the purpose. The bearing was determined by the ratio of the responses of two crossed velocity hydrophones and adequate precision was secured. The equipment received some operational testing at the schools, Pearl Harbor, and certain other bases and it appeared to be adequate for the evaluation of attack success to a precision commensurate with the lethal range of ASW ordnance. The chief impediment to its effective employment was the difficulty in installing it on the various submarines available from day to day for school operations. Extensive upkeep periods were necessary on these older types of vessels and frequently other assignments diverted them from school operations. The electronic equipment was complex and not available in sufficient quantities to equip all of the submarines that might from time to time be called upon to serve as targets, and it was infeasible to remove and install the equipment during the brief interval available subsequent to the assignment of a particular vessel for school maneuvers.

An essentially similar device was developed independently by a Navy laboratory which depended for range determination on the interval between the arrival of the light and sound from a small underwater explosion. Certain difficulties were encountered in the production of satisfactory charges for this device,

but it also promised to meet the need for an accurate evaluation of ASW attacks.

In addition to the vegetable-crate water-slug method originally employed by the school, a photographic method was in use through 1943 and 1944 for evaluating the success of ahead-thrown attacks. The maneuvering submarine towed a buoy float at the end of a line that was as short as was permissible and the location of this buoy with respect to the submerged submarine could be inferred with a satisfactory degree of precision. The procedure was then to photograph from the crows' nest of the attacking vessel the splashes made by the entry



FIGURE 10. Shipboard antisubmarine attack teacher, model V. Model IV, Navy designation QFK, was very similar in appearance.

of the ahead-thrown projectiles into the water, and if there was any possibility of the attack being successful, the buoy would also appear on the photograph. Careful subsequent measurements of the picture and a knowledge of the preceding maneuvers enabled the instructor to assess the success with which the attack had been made. Occasionally some difficulty was encountered in securing satisfactory photographs under adverse weather and sea conditions but in general the procedure was found to be of great value. It had the drawback that the success of the attack could not be known until the photograph had been developed and studied and in consequence some training value was lost. It did provide a quantitative check, however, on the performance of the teams under training, and it was of the greatest value in assessing the sea phase of operations.

SHIPBOARD ANTISUBMARINE ATTACK TEACHER [SASAT]

It had been recognized in the earliest work in antisubmarine operations that the maintenance of a state of training represented one of the most serious problems of a commanding officer of an ASW vessel. Skills involved in an attack could be lost during the long periods of Navy assignment during which there were few opportunities to work with either submarines or practice targets. A shipboard device was needed which would permit the conduct of simulated ASW drill and which would also enable the commanding officer to give shipboard training to prospective sonar operators. Early in 1943, the commanding officer of the USS *McLanahan* visited one of the division's laboratories and outlined his proposal for the type of device he would like to have aboard his vessel. Within two weeks the electronic components were designed and assembled in a small cabinet and given a trial on this vessel. Many inadequacies were brought to light but the original installation continued in use by the vessel. Subsequently a project for the design and development of a shipboard antisubmarine attack teacher was undertaken, resulting in a series of successive models approaching more closely the desired type of equipment.

The only model that was procured to any extent during World War II was known as SASAT A, Navy designation QFK. Thirty units were built during the winter of 1943-44, and subsequently 100 units were procured under direct Navy contract. The instrument, which is shown in Figure 10, injected an echo into the standard sonar gear of such a character and at such a time as to conform to the echo that would have been received from a maneuvering target-submarine during a real attack. A range dial on the instrument controlled the time interval between the emission of a signal by the sonar gear and the receipt of the simulated echo. In order that the recorder trace should present a realistic slope, a range-rate dial auto-

matically controlled the range dial in such a way that it increased or decreased at a rate appropriate to the maneuver. The echo length could also be controlled in such a way as to simulate the proper character for beam, bow, or stern attacks. The amplitude of the echo could similarly be controlled to simulate near or distant targets. The pitch of the echo was controlled by a doppler dial, and concentric bearing dials enabled the instructor to indicate the course of the ship and set the relative bearing of the target. In addition, provisions were automatically made within the apparatus for increasing the target width as the range decreased, attenuating the echo with range and with the angular training of the sonar head. In the final model of this device, dual signals were generated to provide a realistic simulation of split projectors. Thus the device could be used with the range recorder, the BDI, and the attack predictor.

The situation presented to the sonar operator by SASAT A was highly realistic and his equipment would respond to all the adjustments available to him. The controls available to the shipboard instructor were adequate to simulate at his will any maneuvers he wished to portray. However, the relative motion problem, which he had to solve in order to present a completely realistic situation to the operator and officers, made considerable demands on his ability and dexterity. A circular slide rule to assist him in his work was designed and furnished with each equipment, but it was obvious that any final acceptable design should be more completely automatic in the generation of the problem. Instructor's manuals were supplied with each equipment, and they not only contained directions for its operation but also provided tabular material which could be used by the instructor for the generating of typical runs.

In addition to this device, a somewhat similar piece of equipment known as the QFG was procured by the Navy. The design of this was based on the modified harbor defense trainer, but it proved somewhat less well adapted to shipboard work.

In an effort to design a completely automatic attack teacher, one of the division's laboratories worked for a considerable period, at relatively low priority, on SASAT B. Certain progress was made toward the solution of the various problems presented by a completely automatic trainer, permitting freedom of maneuvering to the ship and providing an accurate record of the positions of the ship and synthetic target, but the device did not reach the stage of service tests and evaluation before personnel were diverted to more urgent assignments.

14.8 SUBMARINE SONAR SELECTION AND TRAINING

14.8.1 Opportunities for Assistance

By the summer of 1943, the relative priority of the prosubmarine and antisubmarine efforts justified the diversion of considerable effort on the part of the division to the technical needs of the submarine service. A very small amount of training work had been done in association with the medical officer of the Submarine Base, New London, during 1942. At this activity certain pioneer work had been undertaken in audiometry, and it was thought that this might have some bearing on ASW operator selection procedures. The problems, however, were found to be quite different, and although a minor program of assistance continued at the Submarine School, New London, no considerable assistance was rendered to that activity until the division's interests as a whole were oriented toward submarine problems. In spite of the active participation of the division's contractors in antisubmarine work during the preceding years, little was known about the organization of the submarine service or its technical requirements. In consequence, considerable time was required in the summer of 1943 to acquaint the division as a whole and the training committee and training groups of the contractors in particular with the organization of the submarine service in order that the proper contacts could be established and opportunities for the rendering of assistance developed.

Elementary training in all phases of submarine operation was centered at the Submarine

School at New London, which was a shore-based establishment under the direction of the Bureau of Personnel. It operated closely with ComSubLant and his staff, which by their proximity and intimate association determined the general nature of the curricula offered. This was in distinction to the ASW schools for which the Readiness Division of COMINCH and later the Tenth Fleet performed an analogous function. The major Navy training establishment, at which operational training and evaluation were conducted, was at Pearl Harbor under the command of ComSubPac.

The geographic separation between New London and Pearl Harbor rendered the free and frequent interchange of ideas and personnel a matter of considerable difficulty. The Submarine School, partially by the nature of the exigencies of this service, was somewhat insular and, in consequence, less familiar with the recent developments in sonar training at the large and newly established surface schools. The principal Navy training command was not only remote but also lacked liaison with the sound schools. The geographic situation was likewise a handicap to the laboratory groups working on assignment at Pearl Harbor, and had prevision been available, the division might well have established a laboratory at that location much earlier in World War II. The submarine force, however, was composed of eager, aggressive officers with an experimental outlook and ingenuity in extemporizing, and these characteristics went far to alleviate the handicaps imposed by the geographic separation between Pearl Harbor and the development laboratories.

Sonar techniques are of particular importance to the submarine because when submerged it is dependent upon them almost exclusively for the receipt of information. A wide variety of sonar aids can be utilized in the various maneuvers of exploration, approach, attack, and evasion. The technical developments that took place concurrently with the establishment of training programs and the improvement of training methods were more considerable than in the case of ASW, and in consequence a larger fraction of the training effort was devoted to training in the use of new gear. Secrecy and security are a prime concern to a submarine; hence emphasis was placed on listening rather than on echo ranging. In later developments of submarine sonar gear, including the fathometer, power levels, frequencies, and beam patterns were carefully considered from the point of view of security, and this consideration was emphasized in all training programs involving the use of gear emitting sonic or supersonic sounds. A further significant difference between the work with submarines and with surface ships was the smaller number of the former. In consequence, more effective assistance could be rendered by the laboratories in the construction of limited numbers of devices and in pilot procurement through subcontractors.

The smaller number of submarine personnel made it somewhat easier to provide training facilities and the higher degree of training and skill commonly encountered aboard submarines provided a broader basis upon which special training programs could be erected. Except for the operations in the Pacific, the proximity of the division's laboratories to naval training activities was again a favorable factor in the establishment of close relationships and the rendering of assistance. The New London laboratory was adjacent to the Submarine School and the training activities of ComSubLant. The training group at that laboratory was able to render effective aid in many branches of sonar training as well as in fields quite remote from underwater sound.

At a meeting of a naval board attended by civilian training assistants in July 1944, it was recommended that submarine sonar training be transferred to WCSS in order to take advantage of the extensive experience gained by that establishment in ASW training and the special devices and experienced instructors there available. In conformity with this recommendation, the sonar training program was transferred in the autumn of 1944, and the proximity of the San Diego laboratory again presented a very favorable opportunity for close collaboration and assistance. The proximity of that laboratory to squadrons of the Pacific Fleet was also found to be of the greatest value in gaining familiarity with the requirements of the subma-

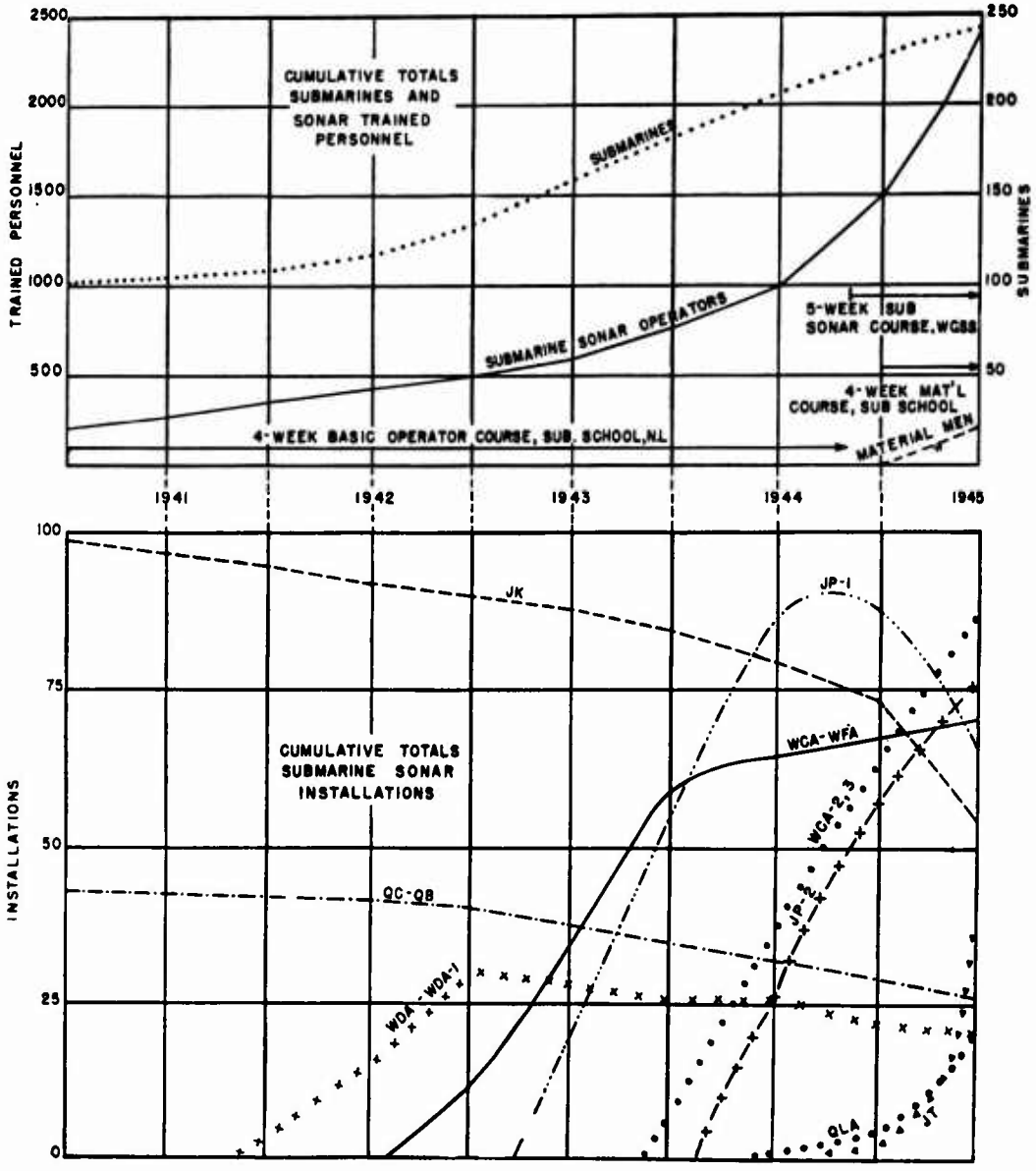


FIGURE 11. The above charts show for submarines what Figure 1 illustrated in relation to surface vessels. The noteworthy increase in trained enlisted sonar men is shown, the curves used being reasonable interpretations of figures made available by the Submarine School, New London, and the U. S. Fleet Sonar School, San Diego. The improvement in quality of training as experience in this field was gained, further increased the effectiveness of the sonar complements.

The figures on the total submarines and sonar installations were made available through the excellent cooperation of Code 5815, BuShips. The introduction of the combination sonic-supersonic listening gear is indicated in the growth of the JP and JT curves (JK gear was supersonic only). The remaining curves for standard echo-ranging gear (except QLA, which later was frequency-modulated PPI gear) indicate the increase and decrease of the various types throughout World War II.

It is noted that until 1942 most of the submarines in service were O, R, and S boats, whereas subsequently fleet-type vessels largely undertook the combat patrols.

rine service and in maintaining close relations with its training activities. Training assistants from the division's laboratories were assigned to Pearl Harbor and advanced bases and rendered as effective aid as they could under the handicaps of remoteness and difficulties of communication and transportation. The observation of the laboratories' activities in the submarine training field re-emphasized the great advantages that result from close proximity.

11.8.2 Submarine Training Program

During 1944 and 1945, the laboratories of the division devoted extensive efforts to the assistance of submarine sonar training activities. This assistance took many forms but roughly paralleled the type of work performed in the ASW program. In consequence, it will not be described in such great detail, but representative activities will be considered, with particular emphasis on those aspects which presented problems that were not common to the ASW program.

The submarine sonar operator's job differs from that of the surface vessel operator both in the gear used and in the conditions under which operation takes place. The need for a special submarine sonar operator's manual was early apparent, and on receipt of a request for it, a standard handbook on the operation of all types of sonar gear was prepared. The manuscript was completed in September 1944, and 5,000 copies were issued by the Bureau of Personnel and distributed to the submarine service.

Assistance was rendered to the new-construction submarine training program at New London through the development of a two-week sonar operator's course. The first week covered lectures and operation of equipment on pier installations. The second week, on the sonar-radar barge, was devoted to the operation of equipment. A four-week course for submarine sonar matériel men was outlined in collaboration with the instructors of the sonar matériel course at the Submarine School, and assistance was also given in the preparation of material for lectures and laboratory exercises. On the receipt of advice that the sonar training program would be transferred to WCSS, the laboratories concentrated on cooperating with that activity in the devising of curricula, lectures, demonstrations, laboratory exercises, and training devices. By the autumn of 1944, the training program was ready to be placed in operation, and the laboratories continued to study the effectiveness of the training methods, introducing new techniques, and modifying the training equipment as inadequacies became apparent.

The laboratories assisted in the design of sound training barges at New London, San Diego, and Pearl Harbor. These were equipped with a large number and variety of sonar gears appropriate to submarine installation and also contained radar and radio equipment. Excellent training could be given on them not only in sonar operation but in integrated sonar-radar training. At Pearl Harbor, training assistants worked with personnel officers in classification, selection, and training, also in studies and statistical analyses of personnel records. This informational background was used for the establishment of entrance standards for the training command courses in order that the training facilities could be used to the best advantage. A preliminary survey of the auditory capabilities of the prospective sonar men was carried out in an effort to develop suitable criteria for sound discrimination ability. This work was continued and amplified by the training group working at WCSS and contributed markedly to the eventual success of the enlarged sonar training program.

Submarine Sonar Training Devices

A large number of submarine sonar training devices were developed but many of these closely resembled analogous equipment previously in use by the schools. The primary listening teacher, Navy designation QFF, resembled closely the primary bearing teacher and differed only in the presentation of screw sounds in place of echoes. Similarly, the advanced listening teacher bore a close resemblance to the advanced bearing teacher. The added experience gained by the laboratories in the design of such equipment, however, enabled the production of a more highly refined instruc-

tional device. Submarine conning officer attack teachers were modified to include a sound injector for the purpose of providing target noise at the proper sound level and correct bearing. Similarly, a few sound injectors were built and furnished submarines for use in refresher training and practice. The need for this type of device is somewhat less with the submarine than with the ASW vessel since targets are encountered more frequently by the submarine



FIGURE 12. Sound recognition group trainer, as installed at the U. S. Fleet Sonar School, San Diego. The recorders, console, and turntable are seen at the lower right, and some of the students' stations can be seen at the left.

and a greater opportunity for realistic practice is thereby presented.

SOUND RECOGNITION GROUP TRAINER [SRGT]

Profiting by the experience in ASW work with WCSS, it was recognized that realistic group trainers would be of maximum effectiveness in the expanded submarine sonar training program in contemplation in 1943. In consequence, the design of two new modern group trainers was undertaken for this program, and in many ways they represent the culmination of design experience in the field of training devices. One of these was the sound recognition group trainer for the provision of closely guided instruction in the recognition and interpretation of sounds heard over submarine sonar equipment. It resembles the echo recognition group trainer in that it consists of a phonograph turntable and central recorder console, together with a plurality of student stations. Twenty stations were provided in the units of the SRGT that were built and installed in submarine training activities. Two units were employed at the West Coast Sound School and one at the Submarine School, New London.

In this trainer, an edited and graded series of sea recordings is presented to the class and students register their judgment on the selection to which they listen. In order that a variety of operating conditions may be simulated, the output of the phonograph pickup can be presented either through a standard JP or standard WCA receiver or, at the option of the instructor, through an amplifier having a flat frequency response from 60 to 10,000 c. The student's judgments appear as two-digit numbers on the paper of a monitor recorder at the instructor's position. Each student listens through headphones and indicates his judgment by depressing one of 70 appropriately labeled pushbuttons at his station. When a pushbutton at a student's station is depressed, a two-digit number appears in facsimile in the column on the recorder paper assigned to that particular station. Each monitor recorder presents eleven columns, ten for students and one for the instructor. Some of the phonograph recordings include 40- or 70-c tones which are made inaudible to the students by means of suitable filters. These tones automatically actuate the instructor's styli on the monitor recorder to indicate the presence of certain target sounds, thus providing a standard with which the student's judgments can be compared. These tones are also used for operating a range-indicating device during single-ping ranging drills. A microphone and amplifier are provided in order that the instructor may communicate with the students while they are wearing their headphones. The illustration indicates the arrangement of the equipment in a classroom. Numerous controls are provided for adjusting the sound level, the choice of amplifier characteristics, and the insertion of filters.

GROUP LISTENING TEACHER

The second modern group instructional device for submarine sonar training was developed from the advanced listening teacher. This trainer bears a resemblance to the group op-

erator trainer in that the student is presented with actual sonar gear and the problem is developed and sounds generated automatically by a central console to which the stacks are connected. The group listening teacher gives simultaneous instruction to a number of operators on different types of equipment. Model CXKG is for the training of groups of students in listening techniques on WCA and JT equipment. Model CXKG-1 is for training on WFA sonar equipment. Under pressure, an interim model with no Navy designation was designed and built in a period of about 6 weeks to accommodate the first submarine sonar class at WCSS in November 1944. The master station of that unit consisted of an adapted advanced listening teacher and the student stations originally consisted of JP, WCA, and WEB sound stacks. The revised and improved models of the CXKG series were undertaken in December 1944 and were not entirely complete before the transfer of the program to Navy auspices.



FIGURE 13. Group listening teacher console.

The WCA half of the CXKG was, however, complete, and it is representative of the other models of this equipment, consisting of a master station shown in the illustration (Fig. 14) and five duplicate student stations housed in small booths grouped around the master console. The instructor sits at the latter and can monitor the performance of students through the glass doors of the booths. The master station generates sounds to simulate two surface vessels and a submarine, in addition to appropriate water noises. The instructional material is provided in the form of three 20-minute runs which range in difficulty from elementary to advanced situations. Two of the runs are concerned with attack situations in which torpedoes are fired. A third run presents the problem of evasion in which the submarine maneuvers to escape from two ASW vessels and successfully eludes attack. A fast reset control is included so that the instructor can select or repeat any particular part of a problem for concentrated drill. Provision is made for the simulated firing of torpedoes to give training in a sound attack. The master station contains a cam control, mechanical problem generator, and various electronic circuits for sound effects, control, and monitoring. The student stations consist of standard WCA stacks adapted for use in the trainer.

JP LISTENING EQUIPMENT

The introduction of JP listening equipment required the assistance of the laboratories in the provision of introductory and training equipment. A complete course of instruction in this device was provided and a set of training aids was prepared in connection with it. These included demonstration material on amplifiers and miscellaneous parts, visual aids, such as lantern slides and slide films, and also handbooks and pamphlets for instructors and operators. Phonograph recordings were also prepared and an enlarged JP amplifier mockup was provided for the submarine school. Training kits were furnished to the principal submarine training activities at New London, Portsmouth, Manitowac, Key West, San Diego, Hunter's Point, Pearl Harbor, Midway, and Subic Bay. Training assistants visited most of these activities and assisted in the inauguration of training programs, participating frequently in the lectures and demonstrations until naval personnel were sufficiently acquainted with the gear to take over the instruction.

FM SONAR [QLA]

With the advent of QLA installations, need for similar training assistance became apparent. As these installations were made in the

Pacific, this training program was concentrated in that area. One phase of this activity was the training of matériel and maintenance men in the laboratory. Classes of six or eight at a time were assigned, beginning in the early spring of 1945, and were given a 6 weeks' course in maintenance and operation. This activity continued after the transfer of the program to Navy sponsorship. Maintenance manuals were prepared and instructions given in the laboratory, afloat on laboratory vessels, and on QLA-equipped submarines assigned to the area. Operator instruction occupied three days of the submarine sonar training curriculum at the WCSS. A moving picture film was prepared by the laboratory and used both at the school and at advanced bases to introduce the operator to this new type of sonar gear. An instruction manual was prepared and furnished the school, and the design of an electronic trainer was undertaken and later completed under Navy auspices. The introduction of and training in this device were also carried on by engineers and training assistants at bases in the Central

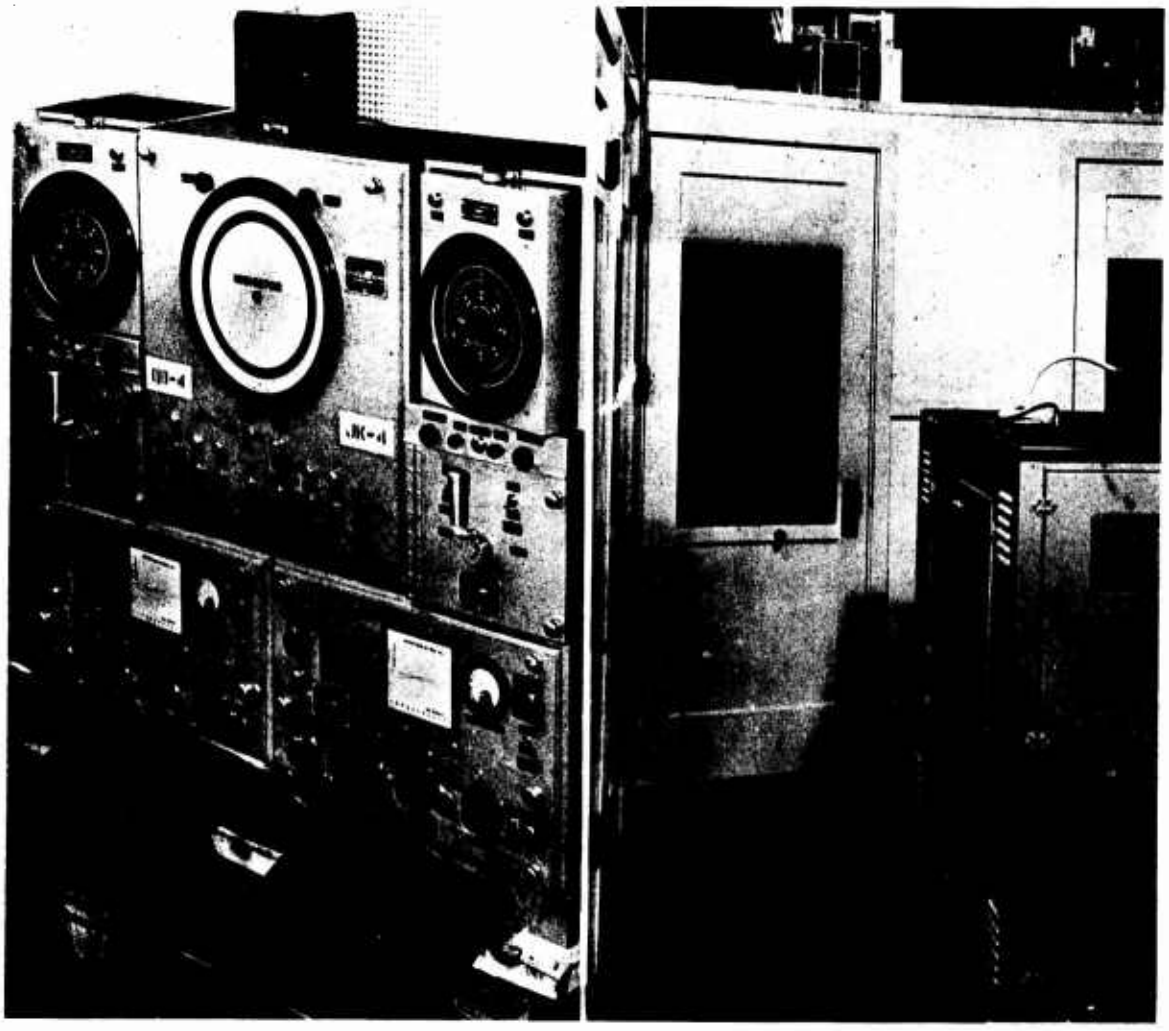


FIGURE 14. Group listening teacher. *Left*, a representative WCA stack for students. *Right*, a view of the room in which the teacher was housed at the U. S. Fleet Sonar School, San Diego. The rear of the console can be seen at the right. It was surrounded by booths housing students' stations.

Pacific, utilizing the training material prepared by the laboratory for use there and at the school.

Noise Level Monitor [NLM]

The noise level monitor was another device requiring assistance in operational training. A brief lecture course and auxiliary slides and charts were prepared at the laboratory to provide actual operator training in reading and recording NLM measurements. A NLM trainer was designed for use at major training activities. This trainer permitted two sources of recorded sounds to be fed into a single NLM unit, thus simulating the effect of background noise with auxiliary noise superimposed upon it.

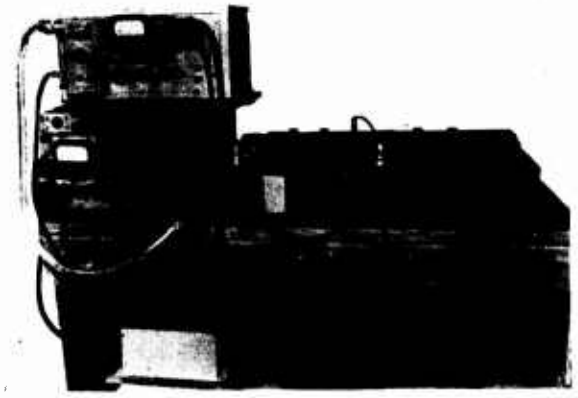


Figure 15. Noise level monitor trainer.

Torpedo Detection Modification [TDM]

The torpedo detection modification of standard gear also involved a training problem. Lecture outlines covering operation and maintenance, together with suitable slides and an operator's manual, were prepared by the laboratory. A slight modification of the QFL (tactical range recorder teacher) made it possible to use this training device for teaching TDM operation. A series of records of torpedo runs was made for use with this trainer.

NAD Beacons

The NAD beacons may also be considered as directly related to sonar gear, and their introduction involved an extensive matériel training program and participation in operational training and tests. A series of classes was assigned by SubTrainPac to the laboratory for training in maintenance and upkeep. The instruction period averaged 6 weeks, and covered all aspects of beacon testing, repair, and operation. Manuals were prepared for these students, and lectures were formulated and delivered by laboratory personnel.

Bathythermograph Program

The bathythermograph training program for submarines may also be considered under this same general heading. Prosubmarine instruction in this device began in a small way on the east coast as part of the study of the submarine model BT as an aid to diving. As each submarine was fitted with the BT, a member of the laboratory staff was sent to adjust it and determine the compressibility of that particular vessel. Opportunity was thus afforded for individual training by these representatives. As the three persons engaged in this early work became acquainted with the submarine service, it became easier to find opportunities for more formal instruction. On returning to the base after a cruise, a group of officers would be assembled and a class would be held. It was gradually recognized that such instruction should be formalized and given to all submarine officers, and requests were received for the establishment of a series of lectures for groups in training at the Submarine School. Early in 1944, a request to expand this program was received, and a special BT training group was assembled to concern itself with training involving the BT on both surface and submarine vessels.

In view of the greater importance of this device to the submarine, emphasis was placed on the submarine phase of the work, and three types of activity were undertaken. The first of these was the training of submarine BT pilot instructors to be assigned to Atlantic and Pacific submarine commands for improving the effective utilization of the BT. A group of 6 or 8 men was trained, and at one time or another most of them participated in work with submarine training activities. The work of these instructors centered largely at New London and Pearl Harbor but from time to time they

visited a large number of advanced bases. They were particularly helpful in the introduction of training aids and literature and in general instruction in subsurface oceanography, interpreting range charts, bottom sediment charts, and submarine supplements to the sailing directions, as these were issued by the Navy and reached the submarine commands.

Other training aids were also designed and constructed by the laboratories. Some of these were merely lecture demonstration kits, but a more considerable piece of equipment was the BT adjunct to the Askania diving trainer. This was an optical and electronic device which, on the insertion of a BT card into a receptacle, would bring about the proper reaction of dials and controls to the inhomogeneity of the surface layers represented by the BT trace. Only one unit of this equipment was constructed and it was used at both San Diego and Pearl Harbor. A similar modification was later made in the standard diving trainer as procured by the Navy.

A third phase of the BT training program was the provision of manuals and other training aids by laboratory groups. In general, this material was assembled and edited and the necessary illustrations drawn and dummies prepared for submission to the Bureau of Ships for approval. They were reproduced by offset lithography in color and issued to the Navy. The first of these manuals was entitled, *Workbook for the Prediction of Maximum Echo Ranges*, NavShips 900,050. This included the most recent information available on the prediction of maximum echo ranges, the reading of BT slides, the utilization of sound ranging charts, and the preparation and sending of the sonar message. The second manual was entitled, *Herald Ranges*, NavShips 900,070. It was prepared specifically for harbor defense officers and other personnel concerned with the design, operation, and location of harbor defense gear. The manual discussed effect of oceanographic factors on the operation and location of harbor echo-ranging and listening devices. The largest undertaking in this field was the preparation of *Use of Submarine Bathythermograph Observations*, NavShips 900,069. This manual was prepared for submarine officers and enlisted men concerned with sonar gear and diving. It presented a comprehensive survey of the effect of oceanographic factors on sound conditions and on the operation of submarines. It also discussed the uses of the submarine BT as an aid in predicting sonar conditions and ballast adjustments, and covered the tactical implications of such information. The manual represented very careful thought in organization and preparation on the part of both the contractor and the bureau. A number of other manuals were projected but not completed before the summer of 1945.

A further unofficial publication to aid the pilot instructors and other technical personnel associated with the BT was the *Manual for BT Pilot Instructors*, distributed in 1945.

Finally, this group prepared a *BT Slide Kit*, NavShips 900,083, to give additional instruction to sonar officers and sonar men in the reading and interpretation of BT traces. It consisted of photographic reproductions of ten varied but typical BT slides chosen from a collection of over 30,000; a booklet of instructions, questions, and answers; and a viewer and special grid for reading the slides.

14.9 RELATED TRAINING PROGRAMS AND DEVICES

The major attention of the training committee of the division and the training groups of the contractors was given to antisubmarine warfare during the first years of World War II and to prosubmarine sonar devices during the latter period. The official field of the division was somewhat broader, including as it did all phases of subsurface warfare, and some training projects extended into fields somewhat remote from sonar. In the case of certain radar training assistance and development in the field of CIC training, the extension was actually beyond the field of subsurface warfare. Such programs in which instruction material was prepared or extensive participation occurred are briefly described.

Radar Operator's Course

Assistance in the development of a basic radar operator's course at the New London

Submarine School was undertaken in October 1944, by a training group. The Applied Psychology Panel, NDRC, collaborated in this work. Assistance was furnished in planning laboratory and classroom facilities, and in outlining a 2 weeks' training course. Instruction material was prepared, and examinations of both written and practical types were designed and introduced.

Submarine Interior Communications Training Program

A request was received from ComSubLant for assistance in the training of telephone talkers, since the problem of interior communication had proved to be one of considerable importance and special difficulty. Work had been done by other NDRC groups on interior communications in aircraft, and at a conference in New London, representatives of the Harvard Psycho-Acoustic Laboratory, the Applied Psychology Panel, the contractors' training groups, and naval liaison met to determine what assistance could be rendered the submarine force in this field. Men were furnished by the other NDRC activities, and the division's laboratory acted to coordinate the activities of all groups interested in submarine interior communications and to maintain liaison with the Navy.

The program fell under two headings: (a) the analysis and standardization of interior communications, procedures, and phraseology; (b) the establishment of a training course for personnel using interior-communications equipment. Lists of standard commands were collected and tested for intelligibility, procedures were reviewed and corrected, and a basic 4-hour course was developed and tested with classes of submarine officers and men. Later the interior-communications training program was extended to include the Submarine School.

A *U. S. Fleet Telephone Talker's Manual, Submarine Edition,* and a chapter on interior communications for the ship's organization booklet were prepared. A glossary of standard submarine phraseology was also assembled, as was a pamphlet of standard submarine communications procedures. Recordings and instructional manuals for the submarine telephone talker's training course were also furnished. This doctrinal and training material was likewise furnished to advanced bases where communications instruction was given, and training officers were coached in its use.

Periscope Attack Trainers

In several instances the training groups and development laboratories assisted in the design and production of training devices giving both shore and shipboard practice in periscope attacks. The principal device in this field was the periscope range trainer (see Figure 16) which was a device to be used ashore for instructing submarine personnel in the use of the periscope. By means of this trainer, practice could be given in the identification of targets and the determination of their range and aspect. Six units of this device were completed in April 1944 by one of the laboratories, and consulting services were furnished in connection with the subsequent production order for 25 by the Navy. This device gave valuable shore training in the use of the periscope, and the models constructed by the laboratory were installed at New London, Portsmouth, Mare Island, Midway, and Pearl Harbor.

In addition to the periscope range trainer, a request was received to assist in the much-needed modernization of a few strategically located installations of the basic shore-based training device known as the submarine conning officer attack teacher. This trainer was designed shortly after World War I. In it, single targets were moved manually along the track and the attack problems that could be presented were far from realistic. Redesigning involved the construction of a new carriage for the target and an auxiliary control cabinet operating with a modified Mark I TDC. Target and screen ships, as well as the car and conning tower, and another repeater unit in the classroom showed the relative bearing, target speed, range, and angle-on-the-bow for the instructor's information. With the modifications thus introduced, a target ship and 7 screen ships, or 5 target ships, or any combination within these numeric limits could be portrayed. Manual control of the screen ships and lighting could be effected through an auxiliary control cabinet. Seven of these modification units were con-

structed by the laboratory and distributed to New London, Portsmouth, Mare Island, Pearl Harbor, Midway, and Subic Bay.

In addition to the shore-based periscope trainers, a proposal for the construction of a shipboard periscope attack teacher emerged as a result of conferences at Pearl Harbor in the autumn of 1943. Long submarine patrols afforded occasions during which practice could be obtained in the conduct of periscope attacks if a sufficiently realistic and compact device could be supplied to each vessel. The combination of realism, accuracy, and compactness presented a difficult design problem, but work on this device was undertaken by one of the laboratories early in 1944. An observer would be presented with a realistic field of view through an orifice at approximately eye level and provided with controls simulating those of periscope operation. Various ship types could be presented as images on a film, the angle-on-the-bow being varied by the substitution of different frames during periods of occultation. The lighting effects would be chosen by the instructor to suit the problem being presented. Variation in range and true and relative bearing would be brought about automatically in response to simulated ship controls by mechanical means and the various motions so integrated as to present on dials at the side of the instrument the actual range bearing and bow angle in order that the progress of the attack could be recorded and its success evaluated. In the late spring of 1944, this NDRC project was discontinued and the design information furnished a Navy supplier.

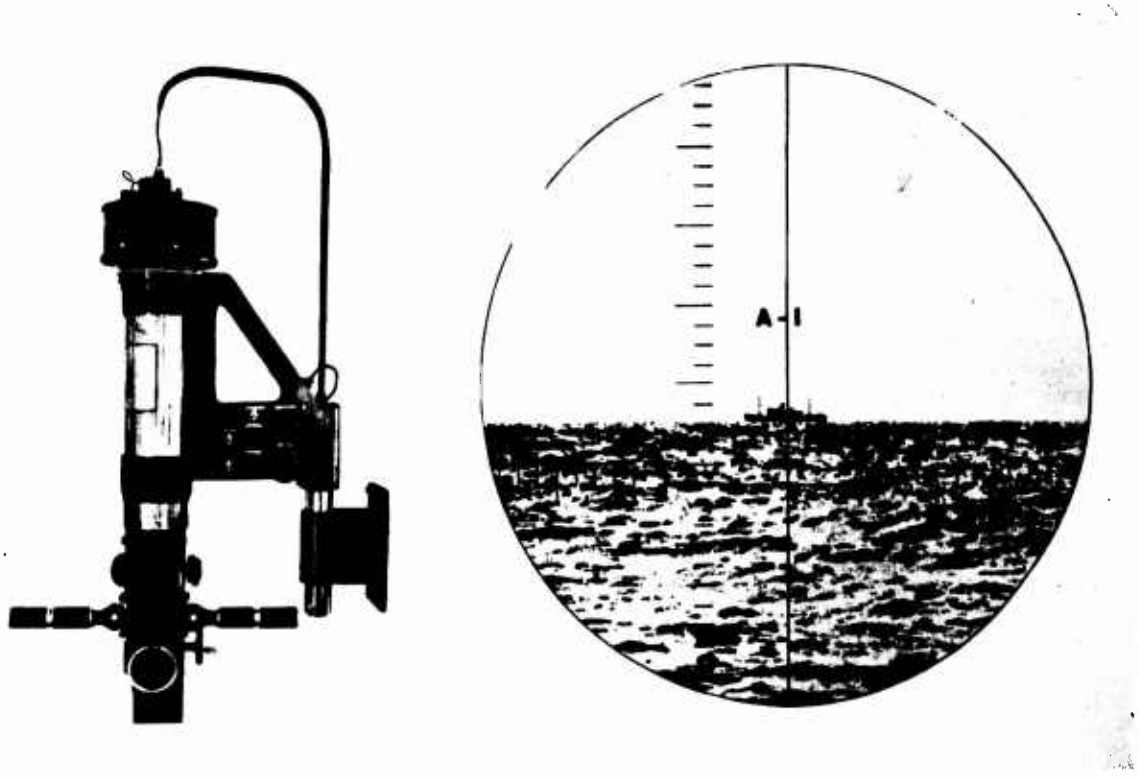


FIGURE 16. Periscope range trainer. *Left*, the trainer. *Right*, a representative field of view as seen in low power.

CIC TRAINER

In the autumn of 1943, the chairman of the Selection and Training Committee visited the submarine and destroyer commands at Pearl Harbor for the purpose of determining how the previous training work of the division could be directed more effectively toward the solution of

problems encountered by the Pacific Fleet. The relative infrequency of encounters with Japanese submarines rendered ASW training of lower priority than training in surface and antiaircraft actions. At the request of ComDesPac, conferences were held with the commanding officer at the Pacific Fleet Radar Center, which was at that time engaged in the development of methods for the more effective integration and utilization of radar and other information in the conduct of surface and antiaircraft actions. It was evident that an opportunity existed for the furnishing of training assistance, and as a result of the discerning analysis presented by the officers of the Radar Center, general specifications were established for a trainer, and its immediate development was requested. The concept of the Combat Information Center was developing at that time under the pressure then existing for more effective assimilation of available information aboard ship. The proposed device was called the CIC Trainer.

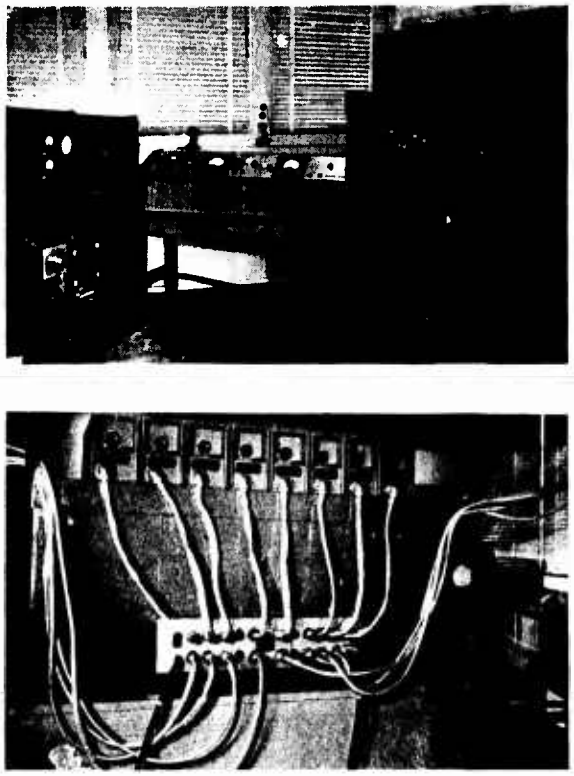


FIGURE 17. CIC trainer and display system, as installed at COTCPac, San Diego. The upper picture shows the rear of the projectors and the control central at the right, in the background are some of the conning and fire control stations, and at the left is an SG radar receiver on top of the panel containing the pickup scope and other electronic components of the trainer. The lower picture shows the front of the projectors as seen from the screen and some conning stations. The monitoring radar may be seen at the right. The CIC room with DRT and radar repeater as well as the principal conning station were in rooms directly beneath that shown in the figures.

The project was assigned to a contractor's laboratory and the work was carried out in close association with the Operational Training Command of the Pacific Fleet which had its headquarters in the buildings of the WCSS. Following the recommendations that emerged from the initiating conferences with the destroyer command, the trainer was intended to fulfill two general purposes. The first was to facilitate and improve the training of the officers and men who composed CIC teams and, to a lesser extent, the training of associated officer specialists in torpedoes, gunnery, and navigation. The second purpose was one of demonstration and exposition, for displaying to observers the conduct of a naval engagement under modern conditions. It was hoped that this not only would be of value to observing CIC teams and to senior officers in assessing trainees' performance, but that it might also provide greater insight to group and force commanders in the tactical and strategic potentialities inherent in the scope, accuracy, and speed characterizing information obtained by radar.

It was recognized that the training would be most effective if standard shipboard equipment were used by the CIC team. In consequence this principle was adopted, and the surroundings and radar presentation were made as realistic as possible. The problem of reconciling complexity and flexibility was met by the adoption of a unit principle in construction. In this way a trainer could be built up to the complexity required by the problems handled at a particular training activity, without necessitating the provision of more extensive facilities than necessary at advanced bases or elementary training centers. Following this principle, it was also possible to grade the exercises. Initially, simple problems calling only for standard procedures could be presented in order to intro-

duce junior or auxiliary personnel to elementary maneuvers. In other applications, classical actions or situations could be initiated or reproduced in part with subsequent freedom of maneuver for one or more ships to provide demonstrations and intermediate training. In the more advanced stages, duels could be conducted between two CIC teams, starting with an arbitrary configuration of ships and permitting complete freedom of maneuver subject only to the limitations imposed by actual ship speeds and turning radii. Accurate records could be made of the developing action at all stages for subsequent analysis and evaluation. A final feature was the accuracy which was provided in the initial positioning of ship or plane units and in the generation of course and speed. Although it was recognized that actual maneuvers at sea were subject to many navigational factors introducing uncertainty, plotting was an important phase of CIC training, and accuracy in the generation of the problem was essential for refined plotting and for the reproduction of maneuvers.

The principal work in this general field was the construction, testing, and operation of an experimental model of this trainer installed at the WCSS and used by the CIC training group of COTCPac. This trainer controlled in a realistic manner the motion of eight optical projectors for displaying on a screen the maneuvers of ships and planes and presenting the resulting configurations to the CIC radar receivers. A projector could be used to simulate a ship, a plane, or a torpedo, and in these various services the image was given an appropriate conventionalized form. The motion was brought about by the traversing of the projecting lens in a plane perpendicular to its axis. This motion was controlled by a conning station having appropriate speed and turning parameters for the unit to be represented. In the case of a torpedo, the projector was moved as a slave to the ship in which the torpedo was loaded, and, on firing, it was liberated and assumed a predetermined course, speed, and run.

In the first installation, the SG radar alone was used, and in consequence it was only appropriate for ships and low-flying planes to appear. The coordinates of the projecting lenses were integrated through a control central and, by means of auxiliary electronic equipment, presented as potentials to the radar receivers in such a way that realistic presentations appeared on the scopes in response to the various controls. In addition to these features, which represent the most essential ones of the trainer, gun fire could be portrayed by means of slits and expanding diaphragms at the focal plane within a projector. Auxiliary sound effects were produced by battle recordings, and intercommunication circuits between the various stations provided the necessary realistic contact between participants in the problem.

The trainer was used in a wide variety of ways but most extensively in the training of a single CIC team. In this application, the group commander conned his flagship, which resulted in the maneuvers of one of the projecting images. A record of these maneuvers was furnished automatically to the DRT, and the CIC received radar information on the location of all other targets in the area. By voice communication, the group commander directed officers at other conning stations in the maneuvering of other vessels in the force. One or more enemy vessels were maneuvered from another conning station which could be supplied with appropriate radar information. Low-flying planes could be introduced at will by the officer in charge of the problem. Practice was also given in shore bombardment work by using one or more of the projector units as headlands or other readily recognizable radar targets.

The equipment was used by COTCPac during the spring of 1945 and maintained in service by the laboratory staff. Some study of the training afforded was made by the training group at the WCSS, and valuable experience was gained upon which the design of further production units was based. The construction of three additional units was undertaken under NDRC auspices but not completed before the contract under which the laboratory operated was assigned to the Navy.

14.10 CONCLUSION

The principal work of the division in the field of training was carried out by either the Selection and Training Committee or the train-

ing groups associated with contractors' laboratories. The Training Committee and training groups performed complementary functions, and the majority of the situations encountered offered opportunities for both agencies to render effective service. The committee was essentially a central advisory group of specialists, and the training groups were decentralized bodies of varying composition through which contractors' facilities and personnel were applied to the solution of specific training problems. The centralized organization of the Training Committee and its liaison with Navy offices and bureaus and with the other divisions and panels of NDRC were invaluable in preliminary surveys of fields of activity and in the initial formulation of problems and attacks upon them. On the other hand, members of the committee could not give their full time to the conduct or oversight of the programs widely distributed along both coasts and in forward areas. The training groups working immediately out of the laboratories, or maintaining close connection with them, formed intimate local associations and conducted programs of selection and training in collaboration with schools and Navy commands.

The training groups enjoyed a considerable freedom of initiative and liaison and the experience that was gradually built up enabled them to render local assistance with the greatest benefit. Their decentralization was somewhat of a handicap which was surmounted to some extent by intergroup reports and correspondence and frequent visits between the individuals composing them. The absence of formal naval recognition through the issuance of orders to training assistants occasionally interfered with their effectiveness but was not always an unmitigated disadvantage. The partial and fragmentary information available to such civilian contractors' employees likewise reduced their general effectiveness, but this situation was inherent in the principle of compartmentation that was imposed.

The most important observation that can be made on the operation of the training program is the crucial role played by the proper choice of participating personnel. The personal ability of a man in a key position may well make all the difference between the success or failure of the particular phase of the program with which he is charged. He must not only be technically competent, but obviously so, in order that he may gain the support of the naval officers with whom he is associated. He must have sufficient initiative and ingenuity to develop opportunities for the exercise of the talents of himself and his associates, and the results that he achieves must be presented in sufficiently concrete form for local Navy appraisal. The practical approach and an understanding and reasonable frame of mind go far toward smoothing out the conflicting daily demands on personnel and facilities. Finally, it should be mentioned that discretion and local loyalty promote the assimilation of civilian assistance by naval activities and greatly facilitate cooperation.

The successful operation of the training groups can be largely attributed to the support given them by the contractors' laboratories which furnished shops, recording equipment, photographic and duplicating services, and staff specialists. The civilian organization would have been unable to function without independent facilities and the ability to obtain rapid procurement of the various items needed in the course of its work. Reliance on Navy facilities would have been quite impractical for many obvious reasons. The prestige associated with the laboratories was also in many instances of value to the training groups in the establishment of initial contacts. Another important factor was the provision of travel and communication which are essential for adequate liaison between widely dispersed groups. One visit is worth innumerable letters and reports, particularly when the program is developing rapidly and the status is represented by fragmentary data, personal opinions, and other tangible factors.

A clear understanding of the complementary roles played by groups of civilian scientists and naval activities in a collaborative effort is particularly conducive to the success of such an undertaking. The responsibility for the acceptance and application of methods, techniques, or devices is that of the naval command. In this the scientist recommends, advises, and assists as the occasions warrant. On the other hand,

the direction of the civilian scientific effort is not the province of the naval officer. If this responsibility is assumed by him, there is then no need for duplicate scientific direction, and indeed it should be recognized that under such circumstances the caliber of civilian ability that should be associated with project direction cannot be retained. The general scope of a joint undertaking should be laid out by Service and civilian personnel in broad terms to achieve the ultimate objective agreed upon, and subsequent collaboration should be carried out in a spirit of mutual helpfulness but with the retention of independence of initiative and action on the part of both naval and civilian groups.

On those occasions when this procedure was not followed, a marked reduction could be observed in the effectiveness of the combined efforts as judged by the results that were achieved on other occasions when the proper balance of responsibility was maintained. In some cases, joint efforts were initiated to accomplish quite reasonable objectives, but the failure to appreciate the conditions necessary for success or the inability to bring these conditions about led to desultory progress or, on occasion, to abrupt cessation. In other cases, close and effective programs of collaboration were carried on between civilian scientific groups and naval commands which extended over the entire duration of World War II and increased in scope and value with successive changes of command and administration.

Programs of civilian assistance are best arranged on the basis of very considerable local autonomy. It is, of course, essential that decisions on objectives and general methods be made by central bureaus and integrating agencies, and such groups must be furnished with periodic reports in order that the benefits accruing may be effectively and widely disseminated. On the other hand, the local administration in day-to-day contact with the work is in a better position to make appropriate decisions for the effective promotion of the program. Attempts to circumscribe local operations too closely, to specify details, and to designate the movements or activities of individuals invariably handicap and frequently seriously endanger the success of an undertaking. Here again, a nice balance must be maintained between civilian, advisory, and participatory functions, on the one hand, and central and local naval commands on the other. The establishment of a civilian technical group by higher authority initiates a permissive association which must be sympathetically accepted by the local command if an effective contribution is to result. The situation is a voluntary one requiring good will and tact. Any recourse to authority would remove that freedom and flexibility which is necessary for the conduct of research and experiment and the immediate incorporation of its fruits in an urgent training program.

The induction of civilians to this type of work requires a period of indoctrination in naval customs and procedures since ignorance of these matters may otherwise cause considerable embarrassment. The assisting and advisory function of the civilians frequently requires emphasis on those occasions when in their excess of zeal they may tend to press for official action in too minatory a manner. An awareness of their own limitations of knowledge and experience must, however, be tempered by sufficient resilience and tenacity to surmount the first few negative reactions that frequently precede naval acceptance of novel procedures.

The problems of the naval officer to whom civilian collaboration is offered merit some diffident comment as well. To the regular officer, such a proposal presents all the earmarks of irregularity and heterodoxy, and he tends to react with some skepticism. If, however, his first dubious and tentative essays at utilizing these services do not embarrass him but promote the execution of his mission, requests for further assistance multiply with great rapidity. At this stage there is some likelihood that requests may be presented as orders, and willingness is expressed to take over completely the direction of the civilian group, employing it on routine matters. If this tendency is successfully and tactfully resisted and the direction of research and experimental programs retained in competent civilian hands, the way is open for a most fruitful collaboration.

Precedent would be of great help in winning wars if each were fought like its predecessor, but, like all habit, it is an impediment to the

acceptance of new ideas. To the extent that it is a basis for many naval decisions, it must be recognized as repressive, but its baleful effects may be to some extent overcome by the marshalling of facts and the cogent presentation of an argument. The effort to secure the adoption of new training methods and techniques during a war may seem to impede the operation of combat operations. However, the advantages of making such changes in the full stride of a naval effort, when the hinging of success on adaptability renders the Service most receptive, far outweigh the disadvantages. The argument that it is possible to introduce new methods and procedures at any other time may well be questionable. The Navy is well aware of the difficulties and delays in the long path of the development, testing, proving, manufacturing, installing, and training for any new instrument or device. The slender peacetime budget with its close scrutiny by persons unfamiliar with the technical requirements of research further add to the Navy's conservatism.

This leads in conclusion to the question of the desirability of continued civilian participation in naval training programs. This question might be considered in two aspects. The first is the benefit that might accrue to the Navy during peace, and the second is the advantage that might later appear on a declaration of war.

The possible effectiveness of civilian participation in either advisory or participatory capacities during a period of peace would depend to a considerable extent on the naval policy pursued. Prior to World War II, naval training was a craft apprenticeship leading to a wide range of individual competence, but of a strictly standardized and rigidly specified type. The man of many enlistments was a jack-of-all-naval-trades at the particular level at which those trades were frozen at an earlier retrenchment. Naval techniques alter but slowly during peacetime, and a static system results which is highly resistant to change. The impact of war, however, disrupts this system, bringing in new military methods and requiring the mass production and education methods which produce specialists in old as well as new techniques. These men have narrower ranges of individual competence, but are basically more flexible and receptive to changing circumstances and requirements.

A service that might be performed by civilian participation in naval training programs in peacetime would be that of maintaining the germ or nucleus of the system of mass education of specialists that must be resorted to by the Navy at the onset of a major war. Periodic visits of interest and inspection to naval units and activities by civilian training advisors would serve to give them some picture of the Navy's day-to-day needs and problems. They would be but poorly qualified on such a basis to make recommendations in which they would have any great confidence, and in consequence, it is improbable that any important effect would be produced between wars by small-scale civilian participation in training matters. Also during such an interval, there is little motivation for the Navy or civilians, no compulsion to experiment with new methods, and, most important, no crucible of combat in which the success of new proposals can be unequivocally assessed.

Considering the second point, namely, the value of a continuing program of peacetime civilian participation to the naval training at the onset of a war, certain definite advantages could be anticipated. The maintenance of a suitable civilian connection would serve to educate specialists who were then to a considerable extent familiar with naval devices, procedures, and problems. They would understand the nature of the hibernant naval organization and could continuously study the methods and personnel techniques by which it could be conditioned to the absorption of large numbers of additional personnel in war. These civilians could also establish contacts with naval officers and, in discussing such problems, get to know and be known by them to the extent that their role would be appreciated, and they would be able to contribute immediately and effectively should the cataclysmic occasion arise. One might conclude, however, with the cautionary remark that civilians are in no sense immune from the conservatism of age, and early retirements should be encouraged from such naval advisory groups to insure youthful and energetic consideration of the Navy's problems and participation at need in its activities.

Chapter 15

FIELD ENGINEERING

By *Timothy E. Shea*

15.1 INTRODUCTION

IN PEACETIME, the Armed Services and industry spend years in testing, proving and refining new devices or equipment, before releasing them for general use. They maintain huge proving grounds and employ elaborate systems for analyzing operational experience. Carefully controlled experiments, duplicating operational conditions, are performed under the direct observation of engineers who are then able to make suggestions for changes or corrections in the design.

In wartime, however, when there is a more urgent demand for new and improved devices, it becomes necessary for the engineer to leave his laboratory and go into the field. The battlefield becomes the proving ground. Since modern war has become to a large extent a war of gadgets, the advantage lies with the nation that can most quickly develop new or improved weapons and counterweapons. Because of war's urgency, the periods of development and utilization must often overlap.

Equipment for fighting men whose lives may depend upon its performance must meet a dual requirement. It must be dependable and rugged enough to operate beyond normal maintenance periods. In the case of the gear dealt with by Division 6, it might have to be designed to withstand the effects of pressure when submerged, or the corrosion of salt water, or the effects of tropical fungus growths, or the pounding of ship or airplane vibration, or the shock of depth-charge explosions.

While meeting such stringent requirements, the equipment must at the same time be adaptable to manufacturing techniques common to mass production; it must be capable of easy repair or replacement of parts; and it must be accompanied by adequate technical information. It must be installed and maintained properly. It must not be too difficult to operate and not be tricky in performance. It must be designed to be readily integrated with other shipboard or airplane equipment.

The engineer and research worker have a personal as well as professional and patriotic interest in the proper design of war matériel, for, the shortcomings of a single piece of new equipment may not only cause a fighting man to lose confidence in its effectiveness, but also cause him to lose confidence in researchers and the whole research program.

But the interest of the engineer does not end with design. In developing new equipment or devices, there is a complementary responsibility upon him to see that installation is correct, that technical information for operation and maintenance is adequate, and that operation is not only satisfactory but carries out the basic ideas which lay behind the development originally. This is also true of techniques; the applications must be appropriate.

THE JOB OF THE FIELD ENGINEER

The responsibility of getting new equipment into effective use is threefold. The operator asks that someone help him to obtain new tools. The developer designs the tools. Between the needs of the operator and the work of the developer there is a gap which the field engineer must bridge.

In bridging the gap, the field engineer must be concerned with problems of installation, operation, and maintenance. He becomes an appraiser and serves as liaison agent. He carries to the operator an appreciation of the problems of the developer; he brings back to the laboratory the operator's opinions on service requirements and operating conditions. The better these two groups mutually understand each other's problems, the better it is for the whole process of development and application. The operations of the field engineer foster a close union of thinking between the developer and the operator.

Therefore, in wartime, when equipment is proved on the battlefield, the field engineer becomes responsible not only for installing a new device, testing it for malfunction and maladjustment, but he must also help train personnel

to operate and maintain new devices, so that they will gain the maximum benefit from their equipment.

In the case of antisubmarine and prosubmarine warfare, operations are conducted on the threshold of an instrument's performance. Since first contact is extremely important, it is necessary to extract the last ounce of performance from the equipment. Equipment must be in good condition and personnel must be able to operate it efficiently. Training and intelligent understanding of the use and limitations of equipment is important. This, of course, implies the coordination of men and equipment. All the men using the equipment must operate as a team.

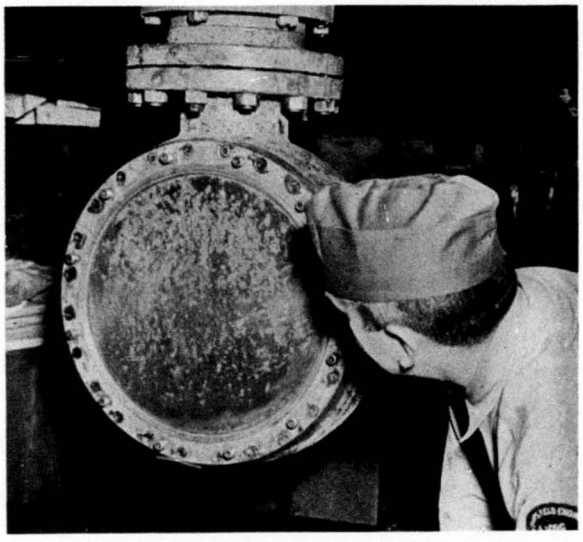


FIGURE 1. Field engineer inspecting projector in dry dock.

Men are usually trained to use equipment at the training centers. But the coordination and integration of the equipment is accomplished in actual service. There are many different kinds of equipment, made by different manufacturers, at different periods. It becomes the duty of a properly trained field engineer to weld this equipment into a coordinated mechanism, and, in some cases, it is his duty to weld both the equipment and men into an efficient team.

In carrying out his manifold duties, the field engineer becomes a diagnostician and a doctor. Often he is a specialist, but to treat emergency cases he must also be a general practitioner with wide experience and knowledge of his subject.

Field engineers, recruited from American industry and the university laboratories, played a vital role in the antisubmarine warfare of World War II.

15.2 ORGANIZATION OF THE GROUP

By 1942, the development and research projects of Division 6 were well under way throughout the United States. For instance, the Harvard Underwater Sound Laboratory [HUSL] in carrying out research on the improvement and modification of existing sonar gear, had installed auxiliary electronic devices aboard ship, and measured their performance. The furnishing of engineering service and operational training by HUSL was a logical and necessary part of the research program.

During the latter half of 1942, and the first half of 1943, HUSL engineers made about 70 installations of *bearing deviation indicator* [BDI] equipment, and in this process they discovered many cases of malfunction and maladjustment of equipment that had been previously installed. They made the necessary improvements and recommendations for corrections. Whenever possible, they acquired first-hand accounts of equipment performance from the operating personnel. This information was valuable in making adjustments and adding improvements to the gear in service, as well as revising BDI specifications.

During 1942, experience with BDI installations revealed that some of the streamlined domes installed around sonar projectors were interfering seriously with the establishment of normal beam patterns. HUSL had been studying beam-pattern characteristics and had developed a useful device, the *sound gear monitor* [SGM] for determining the beam patterns. Therefore, the Atlantic Fleet administrative staff requested HUSL to carry out tests to measure the sonar directivity patterns for destroyers.

Original instructions for sonar domes from

the Bureau of Ships (BuShips) had specified that they should be filled with antifreeze, antirust solution. Seventy vessels were tested and the investigation showed that the solution caused a waxlike deposit in the sonar domes which interfered with and tended to distort the beam pattern. HUSL engineers made recommendations for correction and later BuShips' instructions were revised to provide for another kind of antifreeze, antirust solution. HUSL engineers were able to detect and correct this trouble because of their wide knowledge of mechanics, chemistry, and acoustics. This is one example of how field engineers were able to "grease the wheels" of war operations by employing their diversified experience and knowledge.



FIGURE 2. Checking a BDI installation.

NEED FOR ASSISTANCE

By 1943, Division 6 of NDRC had become closely integrated with naval operations, design, and research, acting as a consulting body, inventing and improving weapons and assisting in personnel training.

Although a great deal was being accomplished in developing new devices for detecting, locating, and destroying the enemy, it became apparent that more attention should be given to the problems of installation, operation, and training in the effective use of new antisubmarine warfare weapons and devices. Also, experience showed that the performance of older types of devices often could be substantially improved.

Experience in peacetime had proved the need for coordinating the development, manufacture, installation, and operation of new devices. As the German U-boat threat increased, the need to bridge the gap between laboratory development and application of new devices grew more urgent.

Several Division 6 laboratories had already found that they must render field engineering service if they were to do their job right. The research and development activities of these various groups created a problem in coordination, evaluation, and use.

PROPOSED ORGANIZATION

By early 1943, it had become clear that these various field engineering activities should be coordinated under one direction. Also, the Navy needed even more technical assistance in design, installation, maintenance, operation, and training methods.

Two ways in which the Navy and NDRC could meet the demand for this increased field engineering service were (1) the staffs of research laboratories could be expanded so that more men could be sent from the laboratories into the fields; (2) a special group of engineers, independent of the laboratories, could be recruited and trained in field engineering.

If more men were sent out from the research laboratories, the research program undoubtedly would be hampered. Competent laboratory men might be wasted on field work for which they were inexperienced or unqualified.

Specially trained field engineers seemed desirable. Preliminary discussions between the NDRC and the Navy were held and it was subsequently agreed that NDRC would set up a group of civilian engineers to render field engineering service to the Navy.

Obviously, the functions of field engineering should be closely integrated with naval operations and research. In forming the group, the

Navy and NDRC were confronted with at least three plans of integration: (1) civilian engineers could be commissioned as Navy officers and serve as officer-engineers; (2) keep their civilian status and operate directly under NDRC; (3) keep their civilian status and operate under Navy jurisdiction through existing organization lines.

The first plan was discarded because it was agreed that engineers working as Navy officers would lose a certain freedom of movement essential when speed and flexibility are at a premium. The second plan was discarded as unworkable. The third plan appeared most satisfactory to both the Navy and NDRC.

Just as it was necessary to integrate the NDRC laboratories under civilian direction with the organizational methods of the Navy, so it seemed necessary to integrate the field engineers with the Navy.

Since field engineers deal with design information, and the bureaus are responsible for design in the Navy, it followed that the field engineers should operate through and for the bureaus on design matters. Also, since the naval operating forces are the sole customer-users of designed equipment, the thinking of field engineers must be identified with the objectives and situations of the operating forces. For these reasons it was decided that the group should be under the cognizance of the Bureau of Ships and that their orders and reports should be handled through Navy channels.

This plan was agreed upon by the Navy and NDRC, and early in 1943 the Field Engineering Group was formally established under BuShips.

The Navy Directive

On April 27, 1943, Rear Admiral E. L. Cochrane, Chief of the Bureau of Ships, issued a directive to all ships and stations announcing the formation of the Field Engineering Group by the Bureau of Ships, with the assistance of the NDRC, and with the cooperation of the Bureau of Ordnance, the Vice Chief of Naval Operations, and the Commander-in-Chief.

The directive was issued on May 1, 1943, as Navy Bulletin C-157 and defined the purpose, scope, and mode of operation of the new group.

The purpose, as stated by Admiral Cochrane, was:

> (1) to directly serve the naval shore establishments and through them the fleets and forces in this interest (of improving the technique of installation, maintenance and operation of antisubmarine equipment); (2) to gather and publish information for service use on antisubmarine equipment; (3) to permit the National Defense Research Committee to obtain first hand contact witn the problems of antisubmarine warfare in order to increase its usefulness to the Navy.
>
> [Personnel for field engineering service was to be] selected from experienced civilian engineers, well-qualified by training and temperament to make themselves effective in work with other personnel, [to be] obtained from the ranks of NDRC and loaned to the Navy for this extremely important work.
>
> [Field engineers while on duty were to be] directly under naval jurisdiction and . . . make their reports to the Chief of the Bureau of Ships, via the naval officer to whom they report. The personnel involved [were to be] governed by such directives as . . . in effect or published from time to time with Naval approval.

To permit effective liaison in all antisubmarine warfare matters, the bureau assured the availability of representation from the engineering service to other interested bureaus, the chief of Naval Operations, and the headquarters of the Commander-in-Chief.

> [It would be the Bureau of Ships' responsibility] to disseminate the information and data collected from the field to the interested bureaus, offices, commands, manufacturing establishments, and research and development institutions.
>
> [The bulletin then stated] it is expected that the Bureau of Ships will use the talents of field engineers to the fullest extent in composing reports and directives concerning the subject.

Field engineers were to report to the chief of the Bureau of Ships, for assignment to field engineering duty "in matters on installation, maintenance and operation" at the following activities within established naval districts: Navy yards; industrial managers; naval stations; naval operating bases; naval schools; inspectors of naval matériel; laboratories conducting antisubmarine warfare investigations; interested bureaus or offices of the Navy Department.

When the field engineers were assigned to an activity within a naval district they would op-

erate under existing organizational lines. The bulletin stated:

In the case of an engineer, for example, assigned to a Navy yard, the commandant will direct him to report to the radio material officer during such time as he may be engaged in work involving projects in radio, radar and underwater sound material. Simultaneously he may be directed to report to the ordnance officer for work in connection with depth charges or other ordnance weapons. [And finally,] in order that effective help in problems of antisubmarine warfare may be obtained from field engineers by the Navy, all commanding officers are enjoined to make full use of this service at each opportunity presented and to offer these engineers every possible assistance.

The directive referred only to antisubmarine warfare, but the scope of the Field Engineering Group later included assistance and training not specifically mentioned by Admiral Cochrane.

15.2.1 Formation of the Group

On the basis of the Navy directive, the Field Engineering Group was organized and administered by Columbia University Division of War Research [CUDWR], under an OSRD contract. T. E. Shea had general charge of the group, which was directed first by J. W. Kennard and later by Woodman Perine.

In assigning the task to CUDWR, Dr. John T. Tate, chief of Division 6, wrote Shea a letter of guidance specifying certain basic principles which should govern the activities of the group. Excerpts from the letter follow:

I have noted the issuance by Admiral Cochrane of the Bulletin announcing to all ships and stations the establishment and mode of operation of the Field Engineering Group which Division 6 of the National Defense Research Committee is making available to the Navy.

I am asking that you assume, under Dr. E. H. Colpitts, Chief of Section 6.1 of Division 6, responsibility for the conduct of this enterprise insofar as the responsibility of the National Defense Research Committee extends. It is my understanding that this responsibility will include the selection, training, and indoctrination of the members of the group, the establishment of its internal organization, and, subject to the policies laid down in Admiral Cochrane's bulletin, the delineation of the responsibilities and methods of operation of the group.

Since the task of the Field Engineering Group for which you are responsible will, of necessity, impinge upon matters which lie in several different areas of functional responsibility in the Navy and in the National Defense Research Committee, it will be essential that you rigidly adhere to and respect the lines of responsibility and duties of the several branches of the Navy and of NDRC. The success with which this can be done will, to a large extent, determine the usefulness of the Field Engineering Group.

For your guidance, I am setting down my understanding of the basic principles of operation of this group:

1. The group as a whole is to interest itself broadly in anti-submarine detection equipment, specialized anti-submarine ordnance, related conning aids, and other associated devices used in detecting and attacking submarines. This includes equipment of existing types as well as newly developed equipments or equipments to be developed in the future.

2. The group will render assistance to the Bureau of Ships, Bureau of Ordnance, Commander-in-Chief [Readiness], and other Navy groups in the rectification of specific installation, maintenance or operating troubles.

3. The group is to keep in mind that installation, maintenance, and operations are to be improved not alone by the correction of spot situations, but even more importantly by discovering through analysis of experience troubles of a recurrent or persistent nature and the institution of corrective actions of a general nature. This latter work is, of course, merely the concluding part of any practical development engineering work, insuring that equipment is suitable to the use intended. Where justified, recommendations for such corrective actions are to be made by the group through the Bureau of Ships to the appropriate Bureaus or Offices or to the appropriate National Defense Research Committee groups.

4. The group will note that a close inter-relation exists between the performance of equipment and the type and training of the personnel which maintain and operate it. The group will interest itself, therefore, in operations with the special aim of obtaining insight into ways of improving adaptation of equipment to the existing background and experience of its users.

5. Individual members of the group will realize that their effectiveness depends to a large degree on the manner with which they handle themselves in their everyday relationships with Naval personnel in informal dealings, and will accordingly endeavor to conduct themselves with the maximum of tact and discretion consistent with getting their jobs done.

6. For the purpose of providing members of the group with Naval sanctions and entrees, the field assignments of members of the group will be under authorizations and instructions from the Chief of the Bureau of Ships. The Navy directive covering this group states that 'Field engineers, while on duty, will be directly under Naval jurisdiction.' I understand

this to mean that they must conform to all rules and regulations of the station to which they are assigned and generally conduct themselves as on loan to, and for the time being an integral part of, the Navy organization.

7. It is important that the collection and distribution of information derived from the endeavors of this group be coordinated with the effort of the various Naval branches. You are therefore to see to it that such information is centrally collected and its distribution is centrally supervised in such a manner that the responsibilities of the various Naval agencies are properly served. It is for this reason that the Navy directive covering this group refers to reports being rendered to the Chief of the Bureau of Ships. It is expected that all such reports will flow in the Bureau of Ships to the one whom you may designate in the Field Engineering Group, so that he may digest them and recommend appropriate action and so that there may exist in one place as comprehensive a view of the field situations and their related problems as possible. It will, in this connection, be the particular responsibility of the head of this group so to arrange matters with the Bureau of Ships that an adequate flow of development criticisms and suggestions accrues to the National Defense Research Committee groups on matters of concern to them.

8. In this latter connection, you will especially bear in mind that the National Defense Research Committee laboratories will be looking to your group, subject to proper channelizing through the Bureau of Ships, for the obtaining of valuable constructive development criticisms and suggestions.

9. A general liaison will be maintained with the Bureau of Ships and the Field Engineering Group by this office to the end of insuring that the National Defense Research Committee is providing for this work facilities and assistance of the types needed for it, and that the scope of the activities of the group are such that the National Defense Research Committee's participation in it is a logical and natural one.

Steps were promptly taken to organize the group on the basis of Admiral Cochrane's directive and the division chief's letter of guidance. The headquarters office was established in the Underwater Sound Installation and Maintenance Section of the Radio Division, Code 983, in the Bureau of Ships. The director and his assistants were located there. Business management, personnel and procurement of equipment and supplies were handled by a small staff at 172 Fulton Street, New York City. Field headquarters, including the training and information bureau, were established at the New London laboratory of Columbia University.

The next step was to recruit civilian engineers for training. Since only a few men at the New London laboratory and other Division 6 main laboratories could be spared for work on the new project, it was necessary to look elsewhere for personnel with the required experience and personal qualifications.

Recruiting of Personnel

The chiefs of both the Bureau of Ships and Division 6 recognized certain factors involved in the integration of the functions of field engineering with the Navy. Some of these were:

1. The Navy is necessarily a complex organization, based principally on considerations other than those involved in performing technical work in a specialized field.

2. The Navy had expanded rapidly in both matériel and personnel.

3. Operations are paramount, and matériel and training are but a means to an end.

4. A process of orientation and adjustment of civilian engineers to Navy conditions and practices is necessary and this takes some time to accomplish.

5. It also takes time for naval officers to understand how best to use civilian assistance.

6. The application of electronics to naval operations had increased greatly and learning the techniques, equipment, and methods of use had created a huge problem.

7. The tremendous dimensions of the war, geographically and in relation to national production capacity, had disarranged the orderly procurement and distribution of matériel and personnel.

There were other factors which have a bearing on the problem of effective utilization of civilian engineers. Because of these factors, and because of the nature of field engineering, certain characteristics which field engineers should have were determined.

These included: (1) good technical ability, (2) emotional stability and adaptability to a variety of work and conditions, (3) ability to criticize equipment constructively for operations, (4) practical ability to use tools and a "nose for trouble," (5) eagerness and aptitude for passing on to others the knowledge and experience acquired, (6) ability to work through organization channels, (7) ability to command

the confidence and respect of commanding officers, (8) resourcefulness and an ability to handle emergencies, (9) a strong sense of responsibility to people, a "feeling for service."

The age of 35 to 40 years was considered ideal since men of that age would be old enough to have the necessary experience and young enough to stand the pressure.

After a survey of the scientific and industrial fields, it appeared at first that the communications and power industries had a reserve of electronic and mechanical engineers whose industrial experience gave them the necessary know-how for the job. It was soon discovered, however, that the communications field had already been drawn upon heavily, so a substantial number of engineers were recruited from power companies and other sources.

The group was formed around eight men from the New London laboratory of Columbia University, who had already been doing some field engineering. These men were immediately given special training for their new job and the Personnel Branch started recruiting additional engineers.

Industrial and other organizations were urged to lend some of their best men to the group, and the companies released the men wanted on leaves-of-absence.

Wartime recruiting was difficult not only because of the heavy demand for qualified engineers by the Armed Forces and manufacturers, but also because the necessity for security made it impossible to explain the requirements in full detail.

These requirements, determined when the group was formed, were based on an analysis and estimate of the nature and extent of the job to be done and they were altered very little during the life of the group.

Men with field and appraisal experience were preferred to men with only developmental experience. Special efforts were always made to secure qualified men who were tactful and experienced in handling people.

Eighty-one engineers were recruited from telephone companies, radio broadcasting systems, power companies, schools and colleges, manufacturing companies, and government agencies. Their experience in these fields ranged from 4 to 24 years, averaging 15 years. Thus men of similar caliber but with widely varied specific experience and background were secured.

15.2.2 Training and Indoctrination

As the men were recruited and accepted, they were sent to the New London laboratory for training and indoctrination. The field engineer's training included: (1) a comprehensive introduction to the fields of underwater sound and antisubmarine warfare, (2) indoctrination in Navy customs and traditions, and (3) training in the Navy's organizational structure and operating methods.

Later, training courses were broadened to cover airborne ASW equipment and the pro-submarine warfare equipment developed for the Pacific Fleets. In conducting these courses, lectures were given by laboratory staff members, naval officers representing the Bureaus and Fleets, personnel from other research laboratories, representatives of manufacturers, and later, by experienced field engineers.

The naval training centers made available ASW practice equipment for the trainees. The group went on many trial operations conducted at sea and made visits to factories, naval bases and stations, and research laboratories. Some field engineers were employed for months on laboratory developments so that they could learn all the details of certain newly developed pieces of equipment. Engineers usually spent a brief period in the Bureau of Ships to learn bureau procedures and to meet the personnel. The period of training varied from several months to more than a year, depending on the need for the engineer's services and his individual capabilities.

To show how this work differed from that of a laboratory or manufacturer's group, here are excerpts from an initial lecture by T. E. Shea in the engineers' training course:

> In its work, the Field Engineering Group must especially adopt a detached and unbiased point of view with regard to devices and their use. The natural enthusiasm of development people for devices on which they have worked, which enthusiasm is one of the driving forces of development people, has as such no place in the thinking of the group. It is as tools for the

Navy to use that the group must have enthusiasm for these—and as practical tools actually becoming available.

On the other hand, the group must realize that new devices can be appraised only when conditions for appraisal are right, and as shortcomings in design and performance are removed or improvements incorporated. The group can therefore stimulate and make more productive the work of laboratories by applying to their product the acid test of just, practical, and imaginative analysis. . . .

This group cannot do more than a fraction of the work that is to be done. Its objects must therefore be (1) to look back on having done a lot of good for a lot of vessels, and as the latter can be reached; (2) a shortening of the time required for given vessels to achieve efficient operating situations. . . .

In their capacity as field engineers, members of the group will . . . interest themselves broadly in all phases of anti-submarine warfare equipment, and are to seek out opportunities to help Naval personnel, formally or informally. Often this may result in unexpected ways by the simple process of familiarizing themselves with the existing equipment and personnel situations, and discovering whether it is satisfactory. They are looking for trouble only if it exists but will find out whether it exists by getting around and getting acquainted.

They should be cautious: (1) not to excite desire for as yet undeveloped equipment which the ships cannot have for some time; (2) not to excite pessimism regarding equipment which may not be all that it ideally should be; (3) not to preach doctrines in respect to use of equipments which are unsanctioned.

In other words, the aim is to do the best we can with the equipment and personnel we have, until and unless we can get replacements. They should constantly be on the lookout, and report on, situations seeming to require action as a class. . . .

The field engineers should secure the acquaintance of such manufacturer's representatives, and exchange mutual help. They can help us by information on their equipment. We may be able to assist them with BuShips or otherwise on problems. The better they can do their jobs the less there is for us to do—and this should be our aim.

The Manual

An important part of training field engineers was the unique volume, *The Field Engineering Manual.* For convenience, a wide variety of information on installation, maintenance, and operations was collected in a single volume in order to digest essential information from Navy publications, to permit continued study by engineers, to enable them to keep up to date on new equipment as it was released, to provide information in compact form not otherwise available, and to provide material suitable for informal or formal training of naval personnel.

Very little material produced by others was used as originally published and much information was developed on new devices from the ground up, and was issued ahead of the manufacturers' regular instruction books. An example of this is the attack plotter guide, discussed in another section.

Field Training

The first group of field engineers to go out under Navy orders to various Navy yards did not have the benefit of advanced field training. Subsequent groups were first assigned to work with and assist senior field engineers who had already been on the job. It was of considerable value to all of the men to have this active and informal help in getting acquainted with actual operations in Navy yards and stations before undertaking the responsibility alone at a new activity.

Refrfsher and Special Training

To insure the continuing usefulness of the group to naval operating forces, men were brought back from time to time to laboratories and factories to receive refresher training on equipment in the final stages of development or in production. In each case they returned to the field bringing up-to-date and current information on new equipment about to arrive in the Navy. This refresher training program, in reverse, made it possible for the engineers to convey the field point of view to the laboratories and factories.

15.3 OPERATIONS OF FIELD ENGINEERS

15.3.1 Scope of Activities

When the group was formed in 1943, men were assigned, as directed by Admiral Cochrane, to the various Navy yards in the continental United States, under cognizance of the radio material officer (RMO) and in several cases under the ordnance officer, to fill the most pressing needs at that time.

Engineers were assigned to give technical assistance to RMO's making installations of

sonar equipment. Having an experienced engineer from industry who had the installation, maintenance, and field point-of-view was an advantage, since most civilian employees in the yards were not familiar with the practical shipboard use of echo-ranging and sound equipment.

During this period, the field engineers made in-the-water checks of sound gear and cleared up difficulties arising from the adaptation of new devices to existing equipment. This surface ship activity naturally evolved into certain assistance to operating bases in the continental United States.

At the operating bases, field engineers were asked to assist in tactical operations, in training, and in the evaluation of equipment, and informally made modifications in operating techniques.

Having had some experience in Navy yards and operating bases, it was natural that engineers should begin to collaborate with laboratories and manufacturers, exchanging information on sonar and ordnance development. The engineers were building up an experience which could be used to mutual advantage in planning equipment and suggesting programs for schools and training activities. Because of the interest of the bureau and through the engineers' personal contacts, training activities and training centers accepted their assistance. The engineers could give a kind of help not readily obtainable from either officer or enlisted personnel.

During and following the transition from antisubmarine warfare to prosubmarine warfare, the men assisted in prosubmarine warfare much as they assisted in antisubmarine warfare.

It may be that it would have been well to have set up the forward area coverage sooner, but perhaps this final phase of field work could only have been done after gaining previous experience elsewhere.

As time passed, opportunities developed to serve outside the narrowly defined limits of the original directive and this led to such activities as distributing technical bulletins to Navy personnel, establishing formal training schools, and developing certain testing techniques which were adopted as standard procedure. Examples of these types of additional services are discussed in Section 15.4.

As the organization grew in numbers and experience, additional assignments were made, until in the final year of operation, there was a heavy concentration of men with the forces afloat.

Field engineers served at 68 establishments and headquarters in 14 naval districts; in 8 sea frontiers; with 4 Fleets and groups in the Atlantic; 8 Fleets in the Pacific; at 16 schools and training activities; and at 6 laboratories.

They served at Navy yards, operating bases, Navy commands and with the forces afloat from North Africa and Europe, through the Caribbean, across the United States, through the Pacific islands to Australia.

During a typical week, 60 engineers would be on field assignment and at least 50 of them would move during the week. At any time of the day or night, an engineer might receive orders to pack his gear, catch a plane and report within 24 hours to a base 3,000 miles away. Within the United States they traveled by means of public carriers, but most of their overseas transportation was provided by the Navy.

The men usually traveled alone or in pairs, but on one occasion it was necessary to send 15 men on one ship to Pearl Harbor.

Their casualty and sickness record was excellent. No engineer was killed on duty and only a few were injured in accidents. This does not mean they were not exposed to risks. More than one engineer escaped death by having been "bumped" from a plane that later crashed.

The need for strict security measures to protect vital information is obvious. But so far as is known no attempts were ever made to steal data and all material issued to the men in the field was returned or accounted for when the group was terminated.

15.3.2 Information Branch

From the first, it was recognized that an information service must be maintained to keep the engineers fully informed on developments affecting their work, thus assuring their value as consultants to the Navy.

Technical information was compiled from

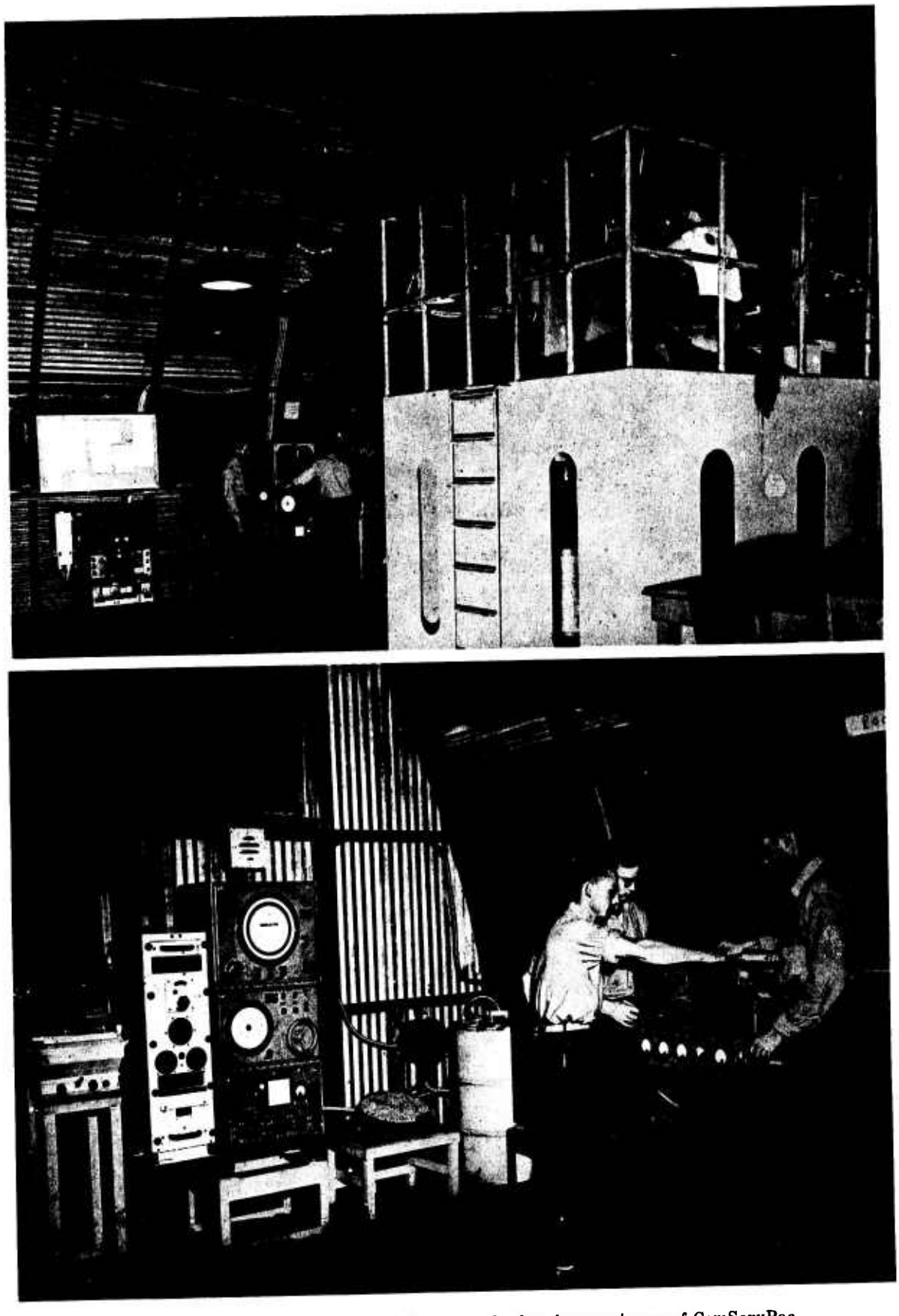


FIGURE 3A, B. Views of sonar maintenance school under cognizance of ComServPac.

every available source. A complete library and file of instruction books were established, and the field manual was begun. The information branch was organized to provide this service and to act as a clearing house and source for assisting the engineers in the field.

Information flowed to the engineers from three principal channels: (1) the manual; (2) *In-Between* and special bulletins; (3) correspondence and wire communications.

The manual has been described in another section. *In-Between* was a monthly house organ which contained items of general interest, technical items, news about the work and life of the men at all stations, and administrative news.

Innumerable requests for information on specific equipment or special problems confronting individual engineers were received at the New London information branch. Each request was answered as promptly, completely, and accurately as possible. In many cases, members of the information office would have to get the answers from other laboratories or manufacturers.

An example will illustrate how this service operated. The field engineer assigned to the submarine base at Perth, Australia, discovered that submarines on war patrols and other operations in the Philippines area, were operating with high sound levels, making them subject to easy detection by the Japanese. At first, the field engineer not only had trouble in locating the source of the high sound levels, but he also had trouble in persuading the submarine officers to improve their boat conditions, such as rattling deck slabs, vibrating plates on superstructures, squeaky shafts, and noise due to wear and tear. The field engineer decided that he needed a sound recorder to record the boats' sound and then play it for the skippers and electronics officers.

He cabled the New London information engineer to rush a recorder to Perth. To speed delivery, the information engineer cabled the field engineer at Pearl Harbor and asked him to ship his recorder to Perth and at the same time told him that a new one was being shipped from the mainland to replace the one to be shipped to Perth. The sound recorder did the job expected of it. The submarines operating out of Perth were made significantly more silent.

For another example, the radio material officer at Pearl Harbor had a tremendous job of keeping the sonar equipment of hundreds of ships in operation. One of his continuing problems was to determine if one piece of equipment could be substituted for another. For instance, were the electronic characteristics of two pieces of equipment the same? Also, at advance bases a table of sonar projector characteristics was urgently needed that would show the interchangeability of parts. The RMO knew about the Field Engineering group, and asked the engineer attached to CINCPAC to provide the information. The engineer cabled New London, and within a few days the projector characteristics table was produced and several hundred copies were printed and flown to Pearl Harbor for distribution to all essential Pacific locations.

15.3.3 Operations Statistics

Because of the far-flung and diversified nature of the Field Engineering group's work, the heavy demand for its services, and the personnel shortage, it was never possible to make statistical studies of the work performed.

For example, there are no figures to indicate how field engineering improved the efficiency of submarine or ship sinkings, since it was never possible to isolate all the factors involved in an ASW operation. Neither was it possible to determine how much field engineering increased ASW crafts' operating efficiency. When a ship arrived at a yard for repairs, a certain number of days were allotted for making all repairs, and at the end of that time the ship returned to sea duty whether ready or not. During this time the field engineer might be called upon to check and repair the entire sonar system, and he had to complete the job in the allotted time. So, field engineering did not necessarily help speed the return of craft to war patrol. But field engineering did increase the efficiency and coordination of the men and weapons.

A specific example will indicate the impossi-

bility of measuring the work of any one field engineer. A certain engineer, who had just completed his training, was sent aboard a ship at Boston to assist in installing a stop-gap model of an attack plotter. When the job was completed, he was invited to go on the shakedown cruise. During the cruise, he checked, tested, adjusted, and repaired not only the sound equipment, but practically all other shipboard equipment. He was virtually shanghaied by the ship's crew for several weeks. Finally, he left the ship at a Navy base at Bermuda, but here he found waiting for him more jobs than he could handle. Each day for several weeks he went out on vessels in ASW practice operations, working as a free-lance mechanic and troubleshooter, wherever he was needed. Obviously, it was impossible to measure the results of the thousands of jobs done by this man.

Many of the jobs done by field engineers were determined by whether the man had the flexibility and versatility (which depended on his particular training and background) to handle on-the-spot jobs that suddenly developed. In many cases an engineer would be assigned by a commandant to fix a specific situation and in doing so he would discover several other difficulties which needed clearing up.

Thus to classify and measure the work of any one man, or the group as a whole, would be extremely difficult without a large statistical staff, which the group never had. An understanding of what field engineering accomplished may, however, be gained through consideration of some examples of the kinds of work the group did.

The examples are grouped under four classifications. The material has been abstracted from more than 400 engineering reports made through Navy channels, as well as from correspondence and informal reports.

15.4 THE FUNCTIONS OF FIELD ENGINEERS

Although the problems of field engineering were complex and varied, it was possible to divide the functions of the group into four categories: (1) giving staff assistance, (2) detection of fundamental equipment difficulties, (3) introduction of new equipment, and (4) development of new systems and techniques of using equipment.

The story of the development, production and installation of the *attack plotter* [AP] is a good illustration of the varied and specialized functions of field engineering.

An attack plotter, as has been already noted, is a visual conning aid used in antisubmarine attacks and is now standard equipment on destroyer escorts and other ASW craft. This device, based on a course-plotting application of the cathode-ray tube, was developed by the General Electric Company under an NDRC contract. The New London Laboratory in 1942 had appraised it in comparison with two other plotting systems, and recommended its production. At about the time the Field Engineering group was organized, Bureau of Ordnance contracts for manufacture were let.

Here was a new and complicated electronic device. There would be design and production problems, problems of distribution, installation, and problems of integrating it with all other shipboard equipment. Men would have to be trained to use it.

To operate successfully, the AP had to be coordinated with three other information systems aboard ship. In most cases these systems were manufactured by different companies, installed and maintained by different personnel. Therefore, introducing the AP would require engineers familiar with all antisubmarine equipment.

The field engineers were able to foresee the problems and take action in advance to solve them. And when the units came off the production line, the engineers were ready to help put them to work.

As a part of their training, the engineers were sent to General Electric plants. They studied the theory and design of AP's, and assisted in designing and testing circuits and certain components. They worked with the company engineers, studying part replacements and adjustments. They even helped to draw circuit diagrams. When the AP was ready for sea trials, the field engineers made the arrangements and supervised the tests. Engineers as-

signed to the factory sent technical information to the engineers in the field who were working on introductory plotter problems.

Meanwhile the company was preparing an instruction book on the Bridgeport model. But production of plotters ran ahead of the manufacturer's editorial work and AP's were reaching the Fleets without instruction books. At the same time the Information Branch of the Field Engineering group was preparing a manual for its field men. Because of certain differences in the stop-gap and production models being manufactured at Pittsfield and Bridgeport, different engineering information had to be provided for



FIGURE 4. Checking attack plotter chassis under the guidance of a field engineer.

the two different models. Instruction manuals were urgently needed by the Navy personnel and field engineers who were receiving the new equipment.

The field engineers had followed the development and production of AP, and were assigned to compile technical information for the GE manual. Since it could not be issued in time to meet the demand, they issued interim instruction bulletins. This interim instruction material was shipped with the first 100 plotters, and additional copies were distributed by the Navy and group both to naval personnel and field engineers.

Even after the company's manual was published, many ships continued to use the preliminary instruction material as an operating guide, because of its convenient form.

Among the first groups of trainees, several men who specialized in the theory and design of the AP, and company engineers, who had developed the device, formed the nucleus of a teaching staff for new engineering trainees and Navy personnel.

By the end of 1943, AP's were flowing to the Fleets in great numbers and every field engineer had had some experience with installation.

Field engineers on duty in the plants alerted the men in the field on the date of arrival of the new plotters. Engineers in the field at first encountered difficulties, mostly of a minor nature, in installing and using the new devices. But the plotter experts still at the GE plant were able to send information to help clear up these difficulties.

With any device of this kind, which takes information from a variety of sources aboard ship, difficulties are encountered which increase with the number of systems involved. Although the plotter had been well designed and well built, certain operational difficulties were encountered at first and field modifications had to be made. Because field engineers had been specially trained, they were able to make these modifications promptly and suggest corrections or changes to the Bureau of Ships which forwarded them to the manufacturer.

But AP units were reaching the Fleets faster than the engineers could handle them. Between October 1943 and April 1944 about 500 AP's were shipped out, and only 53 field engineers were available to introduce the equipment as it arrived. These men also had many other duties and could not devote all their time to the new device. Also, very few manufacturer's field representatives were available to assist in installing the equipment and instructing personnel how to use it.

To speed up the installations, plotter experts were sent out as flying squadrons to all locations installing the AP. One such squadron of two men traveled 15,000 miles in less than a month, visited 26 Navy and civilian yards and ASW training centers and gave instruction to

more than 200 installation and maintenance men.

Practically every member of the Field Engineering group worked on the AP problem, and it is safe to say that the field engineers or personnel whom they had trained supervised the installation of every AP in the Fleets.

In handling this one problem, the group performed all of its four major functions. It gave assistance to naval commands and training staffs. It detected and corrected fundamental difficulties in the first AP's. It introduced the equipment to the men of the Fleets and in doing so, developed new systems and techniques for antisubmarine warfare.

Other examples of the work of the Field Engineering group may be mentioned.

15.1.1 Staff Assistance

Field engineers offered technical advice to the various staffs and served as general consultants, appraisers of equipment, organizers of installation and maintenance procedures, and advised on training instructor personnel.

The engineers' contact with the Fleets had revealed to them a serious and urgent need for better trained and better informed personnel. Naval operations were badly hampered during the first part of World War II by lack of training facilities, inadequate technical information and inadequately trained instructor personnel. Here was another problem for the Field Engineering group.

As soon as the group was organized, it went to work to establish better naval training facilities. It had ships assigned to training activities and sent urgent reports to BuShips on the need of more and better training facilities.

Before the engineers could become instructors, they often had to become familiar with a whole new field of knowledge in a few days. For instance, one group of engineers took a two-hour course on how to man sound gear and fire control, and how to helm and conn the ship. The men who had been recruited proved adaptable in learning tactical as well as operational and electronic problems. They could discuss tactical and operational problems with the skipper, answer questions on operation of gear, and instruct the crew on adjusting sound range recorders and improving the accuracy of target-hitting and depth-charge dropping.

In 1944, ComServPac requested the group to help prepare a curriculum for sonar maintenance at the Pearl Harbor Radar School. This school was to train qualified radar technicians to maintain shipboard sonar equipment. Some students came from the Radar School, and others were taken from ships, were trained, then returned to duty.

The school opened on November 1, 1944, and field engineers served temporarily as instructors until new instructors were available from the ASW Training Center.

Since the students who came from the ships knew what type of gear they would have to work with when they returned, it was possible to concentrate on information of immediate use to them. The school concentrated on gear widely used by the Navy rather than on new equipment—at least until new equipment was installed in considerable quantity.

The sonar course proved highly effective, not only because the men could now use their ships to better advantage on war patrol, but the additional training enabled them to repair equipment casualties at sea.

Field engineers also gave underway instruction to submarine crews. At Pacific submarine bases, the engineers would go out on every submarine for one or two days instructing crews on the operation of electronic equipment.

They even organized a storekeeper training course, to instruct the men on the classification and recognition of parts and equipment. At one time, repair and reconditioning of ships at the Brooklyn Navy Yard was being seriously impeded by the storekeeper's lack of knowledge as to what certain gear looked like. If a radio material officer ordered an OAX, the storekeeper might waste several precious hours trying to locate it. So the group devised a system which helped the storekeepers to locate and recognize thousands of parts and pieces of equipment.

The assistance given to staff commands was varied and extensive. Operating through the

Bureau of Ships, at Navy yards and stations or with the forces afloat, field engineers: (1) modified an AP teacher for improving training facilities at the WCSS; (2) made circuit modifications and additions and changed RCA sound gear so it could be used with a HUSL BDI on

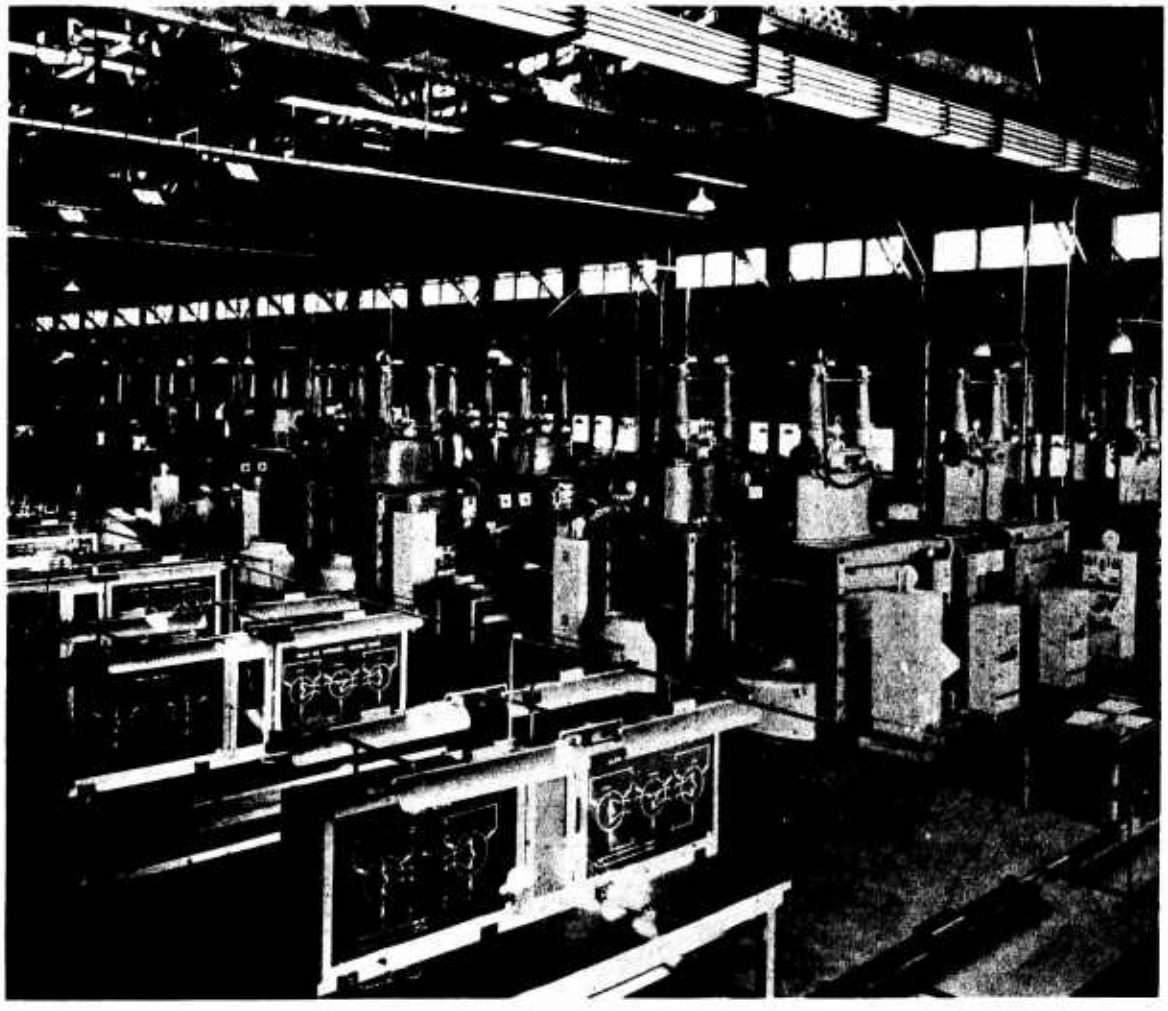


FIGURE 5. Shore sonar laboratory at Navy Training School, Navy Pier, Chicago.

ASW training ships; (3) redesigned the arrangement of sonar equipment in DE sonar huts, making the equipment more accessible and easier to maintain and operate; (4) introduced equipment and techniques of checking ship's sonar equipment on arrival or departure; (5) at the Chicago Navy Pier and the Treasure Island Training Schools, assisted with planning the layout of equipment, procurement and installation of equipment, planned the curriculum, trained instructors; (6) planned and directed an *expendable radio sono buoy* [ERSB] school for air force personnel at ASW headquarters in Oahu, and at the same time aided in solving problems of launching certain devices, designed a floating triplane radar target, and established a communications system for aircraft and ground station coordination; (7) supervised training and the development of attack techniques at the Submarine Chaser Training Center, Miami; (8) assisted in improving the use of sound equipment, repaired equipment, and trained personnel on destroyer escort shakedown cruises.

15.4.2 Detection of Fundamental Difficulties

An important part of the field engineer's duties was to locate and diagnose equipment difficulties of recurrent character, making changes or corrections in the field, then suggesting design changes to the manufacturer through BuShips to correct such difficulties. This work required the closest cooperation of field engineers, manufacturers, laboratories, and naval officials.

Field engineers "put out thousands of fires," soldered many connections and made other emergency adjustments, but their fundamental job was to improve equipment. If a tube burned out they would fix it, but they were more concerned with determining from circuit design why the tube burned out. They went to the crux of difficulties to determine how the manufacturer could alter or improve the design or production of equipment.

The group's modification of the *bearing deviation indicator* [BDI] is a good example of detecting difficulties. The BDI was developed after echo-ranging gear, and the first units were ineffective because the power transformer produced a 60-c hum. A field engineer discovered that the hum could be reduced by relocating certain components in the equipment. His modifications were sent to BuShips and later were published in BuShips' official radio installation bulletin [RIB].

To detect fundamental equipment difficulties, a variety of experience and specialization was often necessary. For instance, one field engineer who was an experienced mechanical engineer had specialized in ASW ordnance. He was assigned to a destroyer escort to determine why a hedgehog (Mark 10 projector) was difficult to train under sea conditions when fully loaded. Discovering that faulty lubrication of the trunnion bearings under full load was causing the increase in friction, he suggested minor modifications in the lubricating points. His recommendations were accepted by the Bureau of Ordnance and distributed to the Fleets as ordnance alterations.

Familiarity with all ASW devices was also necessary. In some cases, separate ASW devices, designed to operate integrally with other shipboard equipment did not always work as expected. For instance, one model of echo-ranging gear when connected would not produce a trace on the recording paper of the range recorder to permit adjustment (no trace to zero zero). The range recorder was used for dropping depth charges and when not in proper adjustment would have range errors of 20 yd or more. A trace was needed to determine the range accurately. Field engineers detected the inadequacies, put the equipment in proper operation, and sent suggestions for modification of the echo-ranging gear to the manufacturer through BuShips. Later the design section and manufacturer found a way to make the necessary changes in design.

Wherever the field engineer went, he brought his wide experience to bear on problems in a highly complex war organization. A field engineer was able to increase the effectiveness of a harbor defense system because he could apply his knowledge of shipboard echo-ranging gear to a land defense system. The projector training system of a harbor defense equipment needed simple repairs. The field engineer assigned to clear up the trouble devised a different type of training control which he made from spare radar parts. His improvements were highly satisfactory and provided more accurate, trouble-free operation. While making the repairs, he made additional improvements in order to increase the effectiveness of the defense system. At that time the Navy's harbor defense engineers had not had the opportunity to study shipboard sound equipment. The field engineer was able to improve the defense system because he could apply his experience with echo-ranging gear to equipment used in a different field.

15.4.3 Introduction of New Equipment

As has already been seen, the field engineers introduced many new pieces of sound gear to the Fleets. The attack plotter and the bearing deviation indicator have been mentioned. Other gear introduced included: (1) appliqué components for *maintenance of true bearing*

[MTB]; (2) console-type echo-ranging gear; (3) JP and JT submarine sonic listening systems; (4) WFA submarine sonar; (5) *depth charge direction indication* [DCDI]; (6) the submarine *noise level monitoring* system [NLM]; (7) the *torpedo detection modification* of WCA-2 sonar equipment [TDM].

In the field of ordnance, field engineers assisted in introducing the forward-firing hedge-



FIGURE 6. Installing noise level monitor unit in forward torpedo room of submarine.

hogs and mousetraps. Also, numerous training aids were introduced.

In dealing with the early major problem of adapting and improving the existing underwater sound equipment, rather than introducing complete new sound systems, field engineers converted or adapted a total of 85 types of equipment. In most cases the job was done with little or no interference with operations.

The adaptation of the attack plotter to the attack teacher equipment (used in all sonar training schools) is a good example of the application of a new development to an existing complete system.

The AP was designed to produce on a fluorescent screen the geographical plot of an entire ASW operation, showing the course of the submerged target, own-ship's course, and other features, such as the predictor line. This operation requires inputs from echo-ranging equipment, the gyro-compass and the ship's pitometer log.

The attack teacher is a shore-based synthetic device used for training personnel. To adapt the attack plotter to it was a difficult problem.

When the AP was being designed and tested at sea, the Navy realized the need for training personnel to use it. The obvious way was to attach the AP to the attack teacher. Various ways of associating these two devices were discussed, and a field engineer was assigned to study the problem and coordinate research. He had had previous development laboratory experience and at one time had operated an early model of an AP while on sea duty. One of five possible methods of attaching the AP to the attack teacher was selected, and the engineer devised the *attack aids adapter* [AAA] as a practical method of integrating the plotter and attack teacher.

Although the Navy training schools were eager to put this new device to work, it was impossible at first to manufacture them on a production basis. So five AAA's were built and sent to the Fleet training schools. It was many months before AAA units were produced in any quantity, so the preproduction units of the AAA made it possible to instruct Navy personnel in the use of the AP much sooner than expected. Here again, the field engineer had helped bridge the gap between development and use of equipment.

During World War II, as all existing devices were further modified, the teaching equipment in the schools fell far behind, and it, too, had to be modified. The field engineers helped to modify much of the teaching equipment.

The story of two field engineers who were ordered to help install a bearing deviation indicator, maintenance of true bearing equipment, and an attack plotter on a ship at Pearl Harbor tells how engineers helped to introduce complicated devices to ASW crews.

During the latter part of May 1944, several BDI, MTB, and AP units arrived in Pearl Harbor to be installed in ASW craft. The units were checked and adjusted by the field engineers. The first ship selected for the installation of

these three associated units was one with an excellent ASW record, so every effort was made to finish the job quickly and return the ship to active duty.

The BDI units were of early manufacture and required field modification as there was no time to send them to the mainland for revision. Because the crew was unfamiliar with the equipment, arrangements had to be made so that these three units could be disconnected from the sonar gear in case of failure or damage. The field engineers furnished all the technical information and devised a system of disconnecting the equipment which the Navy yard produced.

The two field engineers made the modifications, checked and tuned the equipment, corrected the errors, and finished the job several hours before the ship's scheduled sailing time. To do this they worked for a continuous 36-hour period. The ship's subsequent report, a confirmed sinking of a Japanese submarine, furnished ample reward to these men and their associates who helped to introduce this complicated equipment.

15.4.4 Development of New Techniques

Invariably, field engineering work led to the development of new systems or techniques of testing, appraising and operating equipment, and instructing personnel. Even ASW tactical operations were influenced.

When field engineers were testing or inspecting shipboard equipment or training radio technicians and sound men, they frequently found that the men did not use the sonar equipment efficiently because they did not know how to tune it properly.

The group developed several methods of tuning echo-ranging projectors and receiver-amplifiers to peak performance. They evolved empirical methods for general application of these methods to all ASW vessels. Cards as visual aids to enlisted men were developed which were suitable for easy dissemination and use in the sound rooms and these were printed in BuShips official publications. Two such cards were *How to tune a receiver*, and *How to tune your QC driver*. The cards were provided for shipboard coaching work and were convenient to use either lying-to or underway and helped to insure proper functioning of the equipment under any circumstances.

The importance of such a contribution may be difficult to understand. But to the field engineers who saw so many inadequacies in the life-and-death business of fighting submarines and who observed these inadequacies in personnel as well as equipment, the widespread use of this simple method of assuring proper operation of vital equipment was extremely important.

Another kind of assistance was the development of a system of measuring the sound conditions of submarines operating at various depths and speeds. The New London Laboratory had collected data at Pearl Harbor on the noise produced by submarines as a direct result of cavitation and had made studies to link the noise with the speed and depth. As a result, it was concluded that a definite relation could be established between speed and depth, and cavitation, which would vary only from boat to boat.

Field engineers assigned to ComSubPac evolved field methods of making cavitation measurements. Procedures were developed for laying out operating schedules and preparing the gear for test runs. Considerable practice was required to distinguish cavitation from other noises.

The data or "boat signature" was compiled for each submarine tested, and a chart was prepared showing the record of noise level before and after propeller cavitation at various speeds and depths. These were curves of speed versus depth showing the boundary or threshold between cavitation and the absence of cavitation. These charts were then presented to the submarine skippers.

Since propeller cavitation and other noise sources vary from time to time, particularly in war patrols when depth charges are dropped or when operating in shallow water, this method of measurement was extremely important. Skippers were able to operate under certain conditions with at least a greater peace of mind when they had this information. Thus,

field engineers even helped to improve tactical operations.

15.5 SUMMARY

This unique cooperative effort of the men from the laboratories, factories, naval commands, and forces afloat efficiently accomplished far more than anyone expected in the beginning. Because the engineers had been carefully selected and trained they were able to grease the wheels of ASW operations and weld the men and equipment into a single, highly efficient team. This could not have been done if all hands had not worked together. This cooperation, in summary, enabled the field engineers to:

1. Speed up the use of many new devices that played an immeasurable part in winning the antisubmarine war in two oceans.
2. Discover the facts on the inadequacies of old and new devices and report them to the men whose job was to correct and improve equipment.
3. Expedite the development of new equipment and methods by reporting the improvements urgently needed.
4. Train thousands of enlisted men and officers in schools, laboratories, and in the sound rooms aboard ship.
5. Supervise the installation of new and complicated equipment on ships, submarines and planes, and improve methods of operation and maintenance.
6. Sell the men of the Fleets on the kind of work done by research organizations and field men and thus win the personnel's confidence and understanding of the purpose and usefulness of new devices.

From the beginning, the field engineers knew that the group's life would extend no longer than the period of emergency, and if the work were to be continued, someone else would have to be trained to carry on. Whenever they repaired a situation, before they turned to another job, they always trained Navy personnel to carry on.

Early in the spring of 1944, the Navy proposed that an organization within the uniformed Navy be developed as a permanent solution to the problem of making specialized engineering talent available. A subordinate command at the Naval Research Laboratory founded such an organization of officer engineers to serve as an installation, maintenance and operation group.

During the last year, the Field Engineering group trained 30 especially selected Navy sonar officers to form the nucleus of the Navy's permanent field engineering group. Today, the Sonar Section of the Electronic Field Service group, operating under the Naval Research Laboratory, closely corresponds with the wartime Field Engineering group. Thus, the work of field engineering is being continued in peacetime.

There are good reasons for the continuation, since both in the Armed Services and in industry, there will always be the problem of coordinating the manufacture, installation, maintenance, and training in the effective use of newly developed instruments of warfare.

If the nation ever faces another emergency, how could field engineering be improved? The men who worked so closely with the group at headquarters and in the field have had many suggestions. But it appears that most of the difficulties the group encountered in doing its job can be traced to its late start. When the organization was formed, the crisis was at its peak and there was no time for refinements. If there is another emergency, such a group undoubtedly should be formed, trained, and put to work as quickly as possible. Since the Navy now has a permanent field engineering group within its ranks, it should be easier in the future to expand and train additional personnel more quickly.

This raises the question of whether the Armed Services should again recruit civilian engineers for integration with the forces. This question cannot be answered here. But the success of the Field Engineering group should indicate that there will always be a place for civilian assistance. Civilians, operating under Navy jurisdiction, have a greater freedom of movement, freedom from routine duties, fresh contact with industry, and other advantages not always available to officers in the Services—advantages which are essential when speed and

flexibility are at a premium. By using field engineers with wide industrial experience, the Navy's research and development program is not limited to control experiments on the proving grounds, but can be extended to the operations of the Navy itself. The advantages of developing and improving equipment under actual operating conditions have been described in previous sections of this chapter.

When all hands, Service and civilian, are striving to win the same objective, and if each understands the functions and responsibilities of the other, then the result should be team work. And after all, it is team work that counts.

APPENDIX

Appendix A

NAVY DEPARTMENT

Refer to: QB/A16(A)

Bureau of Ships
Washington, D. C.

April 10, 1941

Chairman, National Defense Research Committee,
1530 P Street, N.W.,
Washington, D. C.

Dear Sir:

I have investigated the report of the Colpitts Committee and have noted particularly that it recommends the formation of a committee to investigate the problem of submarine detection.

Inasmuch as your organization was formed for the specific purpose of handling such problems, it is requested that you undertake this study, and I shall be pleased if you will let me know what arrangements I should make to cooperate with your organization.

Very sincerely,
(*Signed*) S. M. ROBINSON
Rear Admiral, U. S. N.

Copy to:

Rear Admiral H. G. Bowen, USN,
Naval Research Laboratory,
Bellevue, Anacostia, D. C.

Dr. F. B. Jewett,
195 Broadway,
New York City

Appendix B

MEMORANDUM

PLAN FOR HANDLING THE PROBLEM OF A COMPREHENSIVE INVESTIGATION OF SUBMARINE DETECTION

Foreword

This memorandum is in response to the request contained in the letter of April 10, 1941, from Admiral S. M. Robinson, Chief of the Bureau of Ships (copy attached), to the Chairman of the National Defense Research Committee, asking that the latter body undertake the investigation of submarine detection in cooperation with the Bureau of Ships. It is in conformity with discussions which Dr. Bush and Dr. Jewett had had previously with the General Board of the Navy and with Admiral Robinson at their request.

Pending final discussion with the Navy as to details of organization and allocation of responsibility in cooperative undertaking, this memorandum is a recommendation of what NDRC thinks advisable. It is recognized that the plan suggested represents the outline of a basic organization which may be modified readily as new conditions arise. These new conditions may come either from developments on the scientific or on the military side.

To facilitate consideration of what follows there is attached (Appendix B) a rough chart of what now seems best for NDRC organization in order to make maximum use of the facilities, both human and material, which should be applied to the scientific research and initial development aspects of the problem.

Objective

The objective sought is:

1. The most complete investigation possible of all the factors and phenomena involved in the accurate detection of submerged or partially submerged submarines and in anti-submarine devices. While the detection of submarines operating as surface craft permits the use of physical phenomena other than those adaptable to underwater detection (e.g., micro-waves), this memorandum is concerned primarily with the latter problem. NDRC is already largely engaged in developing the possibilities of these other phenomena in the location of surface craft and results in the general field will undoubtedly be applicable to the surfaced submarine.

2. The development of equipment and methods for use of promising means for detection to the point where their final embodiment in form satisfactory for naval operation can be undertaken by the regular Bureaus of the Navy.

These investigations will involve study of the characteristics of ships as they relate to the optimum employment of promising methods and equipment. This aspect concerns the desirable characteristics of ships employed for detection purposes and of submarines themselves, considered as targets.

While primarily concerned with problems of offense, the investigations will necessarily involve considerations of defense.

Facilities Required

The facilities required are:

1. A central control group in NDRC to provide reasonable coordination of research work; to arrange for special work with existing laboratories and Government facilities; to maintain liaison with British development, etc.

2. A suitable staff of the ablest scientists, engineers and designers available for work directly on the problems involved. The scientists are mainly physicists and mathematicians; the engineers mainly electrical and mechanical.

3. A suitable number of assistants for laboratory and test work.

4. Access to university, industrial and governmental laboratories for specific research and development work, which can better be done in existing laboratories than in specially established laboratories.

5. One or two special laboratories located at or near naval stations where marine facilities are available for test purposes and where submarines are normally based. Preferably these stations should be chosen with regard to easy access to existing university and industrial laboratories, and to sources of supply of apparatus and equipment.

6. An oceanographic laboratory for the conduct of basic transmission measurements in ocean water under different conditions; for the collection of average transmission conditions in

areas of prospective naval operations as a guide to research and development work and subsequent use of detecting gear, and for the development of simple equipment and technique for measuring transmission characteristics quickly at any time and place.

What NDRC Can Provide

Both because of the authority vested in it by the Council of National Defense Order of Establishment, and because of its nation-wide contacts with civilian science through the National Academy of Sciences, the National Research Council and the scientific societies, the NDRC can provide 1 and 2, part of 3 if necessary, 4 and 6.

Note: No. 6 is already provided for in the existing NDRC contract with the Woods Hole Oceanographic Institution. When this contract was entered into it was contemplated that ultimately one or more of the oceanographic institutions on the Pacific Ocean would be brought into the cooperative program.

NDRC is empowered to employ personnel, to make contracts with university and industrial laboratories, and to transfer funds to Government agencies which are in position to do research work on NDRC problems.

It is in position to locate and secure the services of the most competent scientists and engineers needed for any work it undertakes.

What the Navy Should Provide

Because of the fact that the special laboratories (5) should be located at or near naval stations; that much of the testing equipment needed is of a marine or naval character; that a considerable part of the assistant personnel required (3) can best be drawn from the enlisted or civilian ranks of the Navy, and because NDRC is not well equipped to organize and police such a specialized operating force, it appears that the Navy should provide a specialized laboratory, much of the assistant personnel, and such of the equipment needed as is available to the Navy; further, that the responsibility for regular operation and policing should be undertaken by the Navy.

Special Laboratories

a. Character of Laboratories.

A special laboratory or laboratories contemplated in (5) are to be scientific research and development laboratories operated by NDRC either directly or through some local scientific institution acting as contractor for it, as seems simplest and best.

The contractor scheme is one which the NDRC employs generally and has found to be satisfactory. Under it NDRC retains full control of operations but by making use of the contractor's established machinery for handling financial matters, etc., it is relieved of the necessity for setting up non-scientific agencies. Under this arrangement the contractor performs the necessary service functions at actual cost without profit.

If these special laboratories are set up as contemplated, with the Navy furnishing part of the research and development personnel, the necessary police and guard personnel, the responsibility for the non-scientific operation of the laboratories, the contractor will be concerned only with matters, including the payment of bills, for which NDRC is responsible.

Since under its Act of Establishment the NDRC is authorized to cooperate with but not to supplant existing agencies of Government concerned with instruments and instrumentalities of warfare, the research and development work at the special laboratories will be carried only to the point where regular production of promising devices can be undertaken by the Navy in accordance with its established procedure. The laboratories will, however, always be available for assistance, and it is assumed that the time and manner of transfer of development work will be by mutual agreement.

It is assumed that wherever devices show definite promise of practical utility, the Bureau of Ships will be brought into intimate participation with the further work of initial development. In this way final standardization will be facilitated and expedited.

b. Naval Participation in Laboratory Operation.

In order to insure that the research and development work be carried on with maximum efficiency, it is assumed that the Navy will detail an officer familiar with submarines and with the requirements of research and development work, together with whatever assistance by way of officer and enlisted personnel it may deem necessary, to act in cooperation with the scientific director of the laboratory.

While this officer will be to a large extent a member of the scientific force, his primary function, in addition to his purely operational duties,

will be to arrange for the provision of naval facilities needed in the conduct of the work; to provide for liaison with the local naval forces, etc.

c. Number of Laboratories to be Established.

While the research and development work contemplated to be done by NDRC might be carried on in a single large laboratory, it seems best to contemplate two laboratories working in reasonable cooperation under common direction.

The reason for this arises both from the distribution of potential scientific facilities and the distribution of naval interests on both the Atlantic and Pacific seaboards.

A single laboratory would make it difficult to utilize fully and effectively all of the facilities which are available for utilization.

On the scientific side there are large concentrations of men and facilities on both coasts. Exact knowledge as to these and facility of usage will be most effective to a laboratory located in the region. In other words, the attack will be more powerful through two laboratories than through a single one which would have to use auxiliary facilities at a distance or move men too far from their permanent locations.

This latter item is important because men can be used effectively at the special laboratories on a part-time basis if they are in position to employ their existing facilities on portions of the main problem.

d. Character of the Work at the Two Laboratories.

While the general character of the research and development work at the Pacific and Atlantic Coast laboratories will be similar, it is thought that there should be some differentiation, and the attached chart, Appendix B, indicates this.

Because of its closer proximity to Washington and to the large number of facilities available for completing the final stages of development, it would appear that the Atlantic coast laboratory should have primary responsibility for the final stages of research and development on promising equipment which may arise from the work in either laboratory, and that if possible the director of the Atlantic coast laboratory should be a man who has had large industrial research experience, and particularly experience in the development of equipment designed to meet naval requirements.

Per contra, the Pacific coast laboratory might have primary responsibility for the carrying to completion of fundamental investigations which the work at either laboratory indicates to be promising and might best be directed by a man of wide experience in fundamental research who has specialized in a branch of physics most likely to be involved in the submarine detection problem.

Tentative selection of two such men for the directorship is indicated on the chart, Appendix B.

e. Location of the Laboratories.

Consideration of all the factors, both scientific and naval, indicates that the laboratories might well be located at New London and San Diego. Both of these locations seem to fit in well with the distribution of scientific and naval facilities. Because of adverse winter weather conditions in the North Atlantic, which are likely to interfere with tests and experiments in the open ocean, it may be that a laboratory established at New London might have to be supplemented by a small testing unit at some place like Charleston, South Carolina, Navy Yard.

NAVY DEPARTMENT

Refer to:
QB/A16(A)

Bureau of Ships
Washington, D. C.

April 10, 1941

Chairman, National Defense Research Committee,
1530 P Street, N.W.,
Washington, D. C.

Dear Sir:

I have investigated the report of the Colpitts Committee and have noted particularly that it recommends the formation of a committee to investigate the problem of submarine detection.

Inasmuch as your organization was formed for the specific purpose of handling such problems, it is requested that you undertake this study, and I shall be pleased if you will let me know what arrangements I should make to cooperate with your organization.

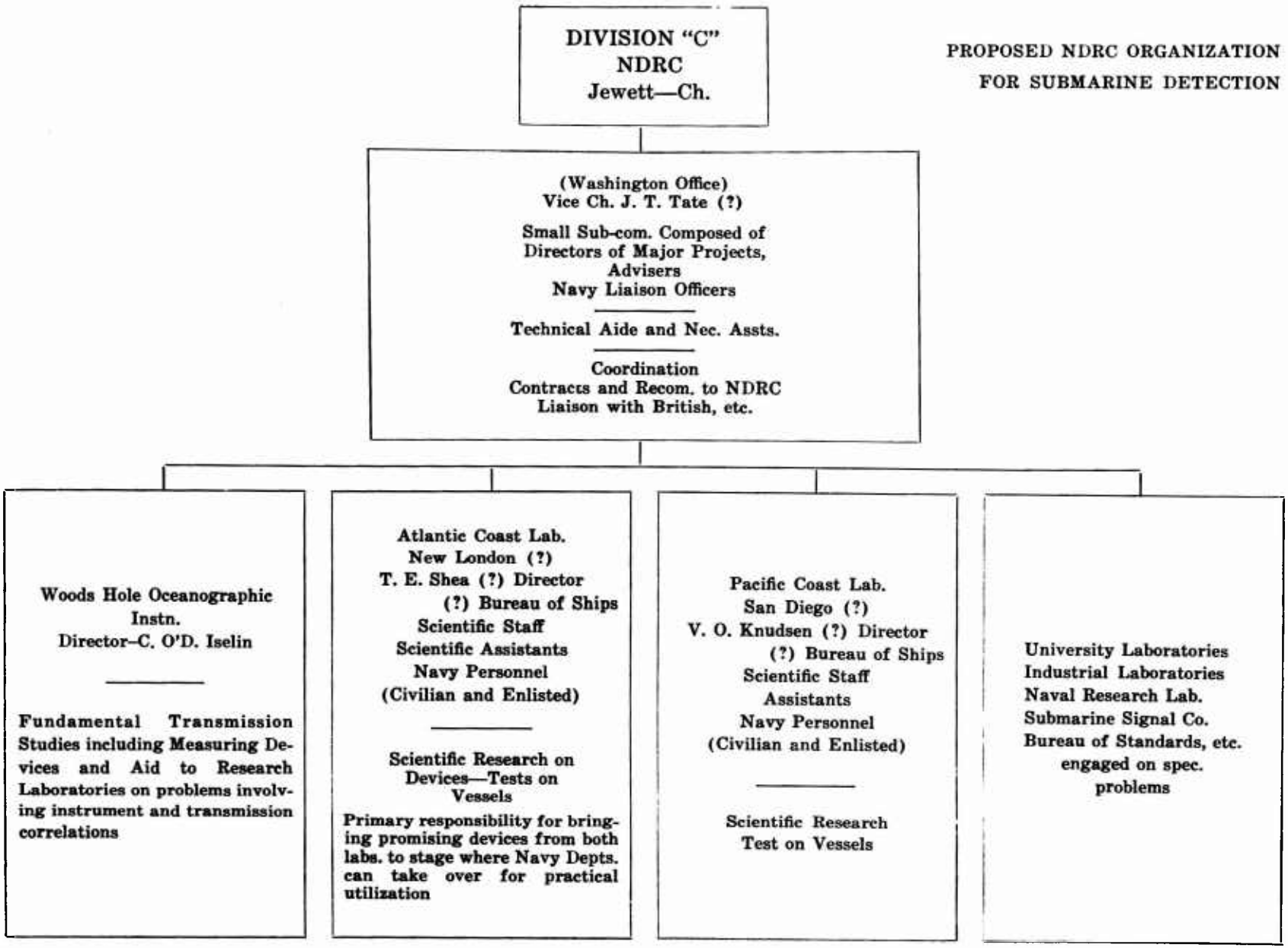
Very sincerely,
(*Signed*) S. M. ROBINSON
Rear Admiral, U. S. N.

Copy to:

Rear Admiral H. G. Bowen, USN,
Naval Research Laboratory,
Bellevue, Anacostia, D. C.

Dr. F. B. Jewett,
195 Broadway,
New York City

PROPOSED NDRC ORGANIZATION
FOR SUBMARINE DETECTION



April 18, 1941

Rear Admiral S. M. Robinson
Bureau of Ships
Navy Department
Washington, D. C.

Dear Admiral Robinson:

This is in reply to your letter of April tenth (your reference QB/A16 (A)), requesting that the National Defense Research Committee undertake a study of anti-submarine devices and asking to be advised as to what arrangements you should make to cooperate.

Enclosed herewith is a memorandum which outlines the general form of the set-up which we think best for a major attack on the problem. As the memorandum indicates, the proposed arrangement involves intimate cooperation between the Navy and NDRC and answers your question as to the form of that cooperation.

This memorandum has been considered by the National Defense Research Committee and is approved by them. If you concur, we will proceed to organize the special committees or sections contemplated, and to put the plan in operation as promptly as possible.

Very truly yours,
(*Signed*) V. BUSH
Chairman

Copy to:

Admiral Bowen
Dr. Jewett

Appendix D

NAVY DEPARTMENT

Bureau of Ships

Washington, D. C.

Address
Bureau of Ships,
Navy Department
and refer to No.
QB/A16 (A)

18 April 1941

Chairman, National Defense Research Committee,
1530 P Street, N. W.,
Washington, D. C.

Dear Sir:

I have just received your letter of April 18th giving a suggested set-up for handling the problem of a comprehensive investigation of submarine detection.

The plan seems to be satisfactory, and I shall be very pleased to get the necessary arrangements for carrying it out started in accordance with our conference this afternoon.

Very sincerely,
(*Signed*) S. M. ROBINSON
Rear Admiral, U. S. N.

Appendix E

NATIONAL DEFENSE RESEARCH COMMITTEE
of the Council of National Defense
1530 P Street, N.W.
Washington, D. C.

April 21, 1941

MEMBERS OF THE NATIONAL DEFENSE RESEARCH COMMITTEE.

Gentlemen:

Admiral Robinson, Chief of the Bureau of Ships, has approved the plan which we placed before him in regard to a comprehensive and cooperative attack on the problem of submarine detection. Dr. Jewett's Division is hence proceeding actively to put the plan into effect.

Very truly yours,
(*Signed*) V. BUSH
Chairman

Appendix F

Outline of Fundamental Research Work on Under-Water Acoustics

March 18, 1941
Revised April 1, 1941

Mr. O. E. Buckley:

Our recent discussions on submarine detection and signaling, acoustic mines, and other related military problems involving the use of sound waves in water, have brought attention again to the need of fundamental research on under-water acoustics. It seems to me that to provide a background for accomplishing specific military objectives a broad program of research work along these lines is badly needed. Stimulated by these recent conferences, I have attempted to put down briefly my conception of what such a program should comprise.

The work has been classified under the following headings:

1. Measurement tools and techniques.
2. Development of instruments for converting electrical vibrations into hydroacoustic vibrations—hydroacoustic generators.
3. Development of instruments for converting hydroacoustic vibrations into electrical vibrations—hydroacoustic detectors.
4. Development of hydroacoustic generators and detectors having highly directional properties.
5. Study of transmission characteristics of water.
6. Study of the boundary conditions and methods of locating submerged objects.
7. Theoretical and experimental search for materials having high absorption for under-water sounds.
8. Study and development of hydroacoustic sources having very great intensities.
9. Exploration of noise and transmission conditions around ships in motion.
10. Exploration of noise and transmission conditions in oceans and harbors.

1. *Measurement Tools and Techniques*

A great deal of the work done in air acoustics can be applied here. Vacuum tubes, amplifiers and oscillators, cathode ray tubes, etc., can be immediately applied both in the audio range and the ultrasonic range of frequencies. The development of devices for creating and picking up sounds in water having frequencies from zero to 100 kilocycles, and possibly higher frequencies, is needed. For part of this range satisfactory instruments are already available; for the other part further developments are necessary.

2. *Hydroacoustic Generators*

As a background for experimental work on hydroacoustic generators, theoretical consideration of what constitutes the ideal should be undertaken. Criteria should be set up for determining how near any model approaches this ideal. Formulae should be developed to show how the various material factors affect the efficiency of any proposed generator. Experimental work should proceed with crystals, magnetostriction devices, as well as with electromagnetic devices. Also a search should be made for other properties of matter which seem more ideally suited for under-water work than those now being considered. Particular attention should be paid to instruments which would stand the pressures encountered at very great depths.

3. *Hydroacoustic Detectors*

The work on hydroacoustic detectors should proceed along the same lines as those outlined for generators.

4. *Development of Hydroacoustic Generators and Detectors Having Highly Directional Properties*

Work similar to that underlying the development of directional microphones in air is indicated here. Also the theoretical and experimental work on development of arrays of detectors for obtaining sharp directional properties is included under this heading.

5. *Study of Transmission Characteristics of Water*

Although the transmission characteristics of air have been studied for centuries, it has been only in the last decade that the frequency selectivity of the air was discovered and understood. It is difficult to confine the low frequencies in a sharp beam and, on the other hand, very high frequencies are absorbed so rapidly that they can be transmitted only a short distance. This limits the useful frequency region for long

distance transmission to a small range of frequencies between 500 and 1500 cycles. Careful measurements in water may reveal a similar best frequency region for long distance transmission. Also the effect upon transmission of different physical conditions of the water is not thoroughly known. This is a large field for research but it is very vital for an understanding of under-water acoustics.

6. *Study of the Boundary Conditions and Methods of Locating Submerged Objects*

The boundary conditions of the water will play an important part in determining the transmission possibilities just as is the case with sounds in the air. A particularly important phase of this subject will be the determinations of the best methods of locating the direction and distance to submerged objects. Pulsing methods similar to those used with radio detection of distant objects should be studied. Particular attention should be given to methods of creating very intense pulses for a short interval of time.

7. *Theoretical and Experimental Search for Materials Having High Absorption for Under-Water Sounds*

Wherever there is a boundary to a body of water containing acoustic waves, reflections occur. It is important to find methods of reducing these reflections to a minimum. The experience with air waves will be helpful here. Tanks equivalent to reverberation chambers will probably be useful. Also tanks having a minimum reflection from the walls, corresponding to a dead room will be one of the first things that is necessary for accurate measurements. Theoretical studies along the lines of acoustic filters in air may reveal combinations of materials which will be useful.

8. *Study and Development of Hydroacoustic Sources Having Very Great Intensities*

A study, both theoretical and experimental, to determine the maximum amount of acoustic power that can be put into water should be made. Such intense sound sources may have great military importance. They might be used to explode acoustic mines, or even might have damaging effects upon ships. For example, the depth bomb now used against the submarine is only an intense acoustic source. Such intense sound sources could be used for producing masking effects upon other sound waves which the enemy are trying to use. There will probably be many uses for such sources, but the plan here is to consider the development of such sources entirely apart from their practical application.

9. *Exploration of Noise and Transmission Conditions Around Ships in Motion*

The work here is evident from the title. No doubt work along this line has been done, but only in a fragmentary way. A comprehensive survey of such noises in all directions from the ship should be made, paying particular attention to conditions in very deep water.

10. *Exploration of Noise and Transmission Conditions in Ocean and Harbors*

Work along this line should follow the outline given for 9.

To make the progress on this study that its importance warrants, a special laboratory should be set up adequate for twenty to thirty scientific workers with an equal number of helpers. It should be set up close to a large body of water where there is sufficient space to allow for large tanks of water which could be brought under laboratory control. Also, it is evident that a ship should be fitted out to carry out the work of exploring the noise and transmission conditions outlined above. The crew for manning the ship should be, of course, in addition to the numbers given above for carrying on the scientific investigation.

H. FLETCHER

March 27, 1941

SUGGESTED PROGRAM ON MEASUREMENT MEANS AND TECHNIQUE FOR UNDER-WATER WORK

1. Design and construct under-water microphones sufficiently stable and uniform to serve as secondary standards. Calibrate in terms of one or several, selected as prototype standard. Be prepared to furnish one or two instruments to each experimental group working on problem in order to provide a common reference.

2. Proceed with establishment of an absolute calibration system, including primary standard microphones for under-water measurement.

3. Design and construct series of under-water secondary standards to cover range from 0 to 50 kc.

4. Design and construct suitable under-water radiators having determinable and stable output for use in quantitative measurement work.

5. Design and construct directional devices for measurement purposes.

6. Select and design suitable auxiliary apparatus including such things as amplifiers, detectors, recorders, oscillators, filters, cable for connection to under-water experimental devices.

7. Be prepared to act as advisors on above matters to various groups working on the problem.

Appendix H

PRELIMINARY MEMORANDUM ON MAGNETIC DETECTION OF SUBMARINES FROM MOVING SHIPS OR AIRPLANES

L. B. Slichter December 14, 1940

I *Induced magnetic moments of submarines.* Magnetic measurements upon four submarines of the U. S. Navy indicate that the vertical component of their induced magnetization is of the order of 1 to 2.5 $\times$ 10^5 C.G.S. per ton of displacement. These measurements refer to undegaussed submarines. The effective magnetic moment at large distances from degaussed submarines is unknown, but it is estimated by those familiar with present degaussing procedures that degaussing is 80-90% complete. Available measurements are summarized in the table below. Here the first three boats were measured in the magnetic latitude of New London. The *Sailfish* measurements refer to a vertical field of .53 gauss and a horizontal field of .19 gauss (i.e., the magnetic latitude of Norfolk). In the table, the symbols M_z, M_H, and M'_H denote respectively the vertical component of magnetic moment, the horizontal magnetic moment, and the permanent horizontal magnetic moment. In the case of the *Sailfish*, the permanent moment represents the residual value after demagnetization.

TABLE. Induced Magnetic Moments of Submarines.

Name	Tons	Length	M_z	M_H	Permanent M'_H	M_z per ton	Date
D-2	337	135′	3×10^7			$.9\times10^5$	1918
G-4	470	158′	5×10^7	4×10^7	6×10^7	1.1×10^5	1918
L-11	550	168′	10^8			1.8×10^5	1918
Sailfish	1450		3.5×10^8	2×10^8	5×10^7*	2.4×10^5	1940

*After demagnetizing.

II *Size of German Submarines.* The German submarines are of four sizes: 250 tons, 500 tons, 900 tons; also ocean going submarines of approximately 1800 tons. We may therefore expect the magnetic moment M_z to be approximately 2.0×10^7 for the smallest size and 4.0×10^8 for the largest sizes, before degaussing. After degaussing, the corresponding magnetic moments will presumably be 2×10^6 and 4×10^7 C.G.S. Clearly, further data concerning the magnetic moments of submarines are needed, especially for the smaller sizes, and after degaussing.

III *The balanced coil method of detection.* The balanced fixed coil type of magnetic detector is believed to be the best magnetic method for detecting submarines from a moving boat or plane. This method was especially studied by Professor Ernest Merritt at the Naval Experimental Station in New London in 1918. Under modern conditions, however, the sensitivity which was then achieved can be multiplied by a large factor of the order of a thousand. In this method two equal coils are used; one mounted in the bow, the other in the stern of the chaser.* They are connected in opposition and are rigidly mounted with axes closely parallel. Thus, the coils are theoretically balanced against the effects of roll and pitch in a uniform magnetic field. When the chaser (plane) is underway, the coil pair responds to anomalies in the earth's magnetic field in accordance with the formula:

$$E = 10^{-8} NA \frac{\partial^2 Z}{\partial x^2} v_x \Delta x \qquad \text{(Eq. 1)}$$

where E = voltage differential on coil terminals, in volts.
A = effective area of a coil, cm^2.
N = no. of turns per coil.
Z = the component of the magnetic field perpendicular to the plane of the coils, in gauss.
v_x = ship's velocity component, cm./sec.
Δx = separation of coils, in the direction of x.

It is assumed that the distance to the source of the anomaly is large compared to Δx, as it normally will be near the limits of range of the equipment.

IV *Magnetic anomaly due to submarines.* At points in a horizontal plane at height h above the submarine, the vertical component, Z, of the magnetic anomaly due to the submarine's vertical magnetic moment, M_z, is expressed by the following formula:

$$Z = \frac{M_z}{r^3}\left(3\frac{h^2}{r^2} - 1\right) \qquad \text{(Eq. 2)}$$

* For obtaining direction, three coils may be used.

Here, x represents radial distance in the horizontal plane from a center directly over the submarine (i.e., from the intercept of the dipole axis and the horizontal plane), and $r^2 = x^2 + h^2$. There will also be a contribution to H_z due to the horizontal magnetization M_H of the submarine, but this is generally smaller. Its contribution will be neglected. The second derivative, $\frac{\partial^2 Z}{\partial x^2}$, is

$$\frac{\partial^2 Z}{\partial x^2} = -3\frac{M_z}{r^5}\left(\frac{35x^2h^2}{r^4} - 4\right) \quad \text{(Eq. 3)}$$

V *Natural fundamental limitations upon sensitivity of detection.*

(1) *Time-fluctuations in earth's field.* The coils must be balanced against differences at the two coils in the time-fluctuations of the local earth's field. Experiments on land and in Boston Harbor indicate that two identical coils separated distances of the order of 500′ to 900′, with an NA (see Eq. 1) as large as 10^{10} C.G.S. may be balanced to $\frac{3}{10}$ microvolt in locations remote from artificial sources of electromagnetic disturbance. Thus, the effects of normal fluctuations in the earth's magnetic field may be balanced out with high precision in these magnetic latitudes. It will later appear that such fluctuations do not appear to set natural limits to the sensitivity of detection with techniques now available. (In high magnetic latitudes, magnetic storms are more frequent and intense. It is not known what limitations, if any, these will impose.)

(2) *Fixed geographic anomalies.* The applicability of the method and the sensitivity which it will be feasible to use will be influenced by the magnetic character of the sub-oceanic geology, and by the depth of water. In water of depth 600′ to 2000′, geologic structures may be expected to produce anomalies of order 10^{-14} to 10^{-11} in $\frac{\partial^2 Z}{\partial x^2}$. (The normal latitude variation of the earth's field produces values for $\frac{\partial^2 Z}{\partial x^2}$ of about 1.5×10^{-18}.) Experience and knowledge of the geological conditions will aid in predicting the sensitivities feasible to use. In deep water, topographic effects, and disturbances due to sunken ships will have a much longer "wave length" than a nearby submarine, and may be distinguished by this fact. Actual tests seem necessary to determine the geographical scope of application of the method. It is probable that in some areas it will be severely restricted in sensitivity by the geologic background. In other areas it is expected that the geologic background will be found to offer little interference.

VI *Instrumental defects.* The following is a list of the types of instrumental defects to which the method is subject. Plans for compensating for these defects are listed in the section following.

(1) *Error in parallelism, and effect of roll and pitch.* Let the error in parallelism (angle between planes of coils) be ϵ, and let the carrier ship rotate with amplitude θ_0 and period P; i.e., $\theta = \theta_0 \sin\frac{2\pi}{P}t$, where θ is the angle between the horizontal and the coil planes, which are assumed nearly "horizontal" when at rest. In a field of vertical component Z and transverse component H (in gauss), the resulting induced e.m.f. in volts due to rotation is

$$E = 10^{-8} NA\,\theta_0 \frac{2\pi}{P}\cos\frac{2\pi}{P}t\left[Z\left(\epsilon\cos\theta - \frac{\epsilon^2}{2}\right) + H(\epsilon\sin\theta + \epsilon^2)\right] \quad \text{(Eq. 4)}$$

If, ϵ = 1 sec. of arc, $= 3\times10^{-4}$ radian,
$Z = .5$,
$H = .2$,
$NA = 4\times10^{10}$,
$\theta_0 = 1/2$ radian (30°),
$P = 6.28$ seconds,
then, $E = 3\times10^{-2}$ volts, which is very large and must be reduced by compensation.

(2) *Thermal expansion of coils.* The spurious e.m.f. due to differential thermal expansion in the two coils is

$$Et = 10^{-8} N Z_0 \frac{\partial A}{\partial t}. \quad \text{(Eq. 5)}$$

With a coefficient of linear thermal expansion of 2.3×10^{-5} (aluminum),

$$E = 10^{-8} Z_0 NA\,(4.6\times10^{-5})\frac{\partial I}{\partial t} \quad \text{(Eq. 6)}$$

where $\frac{\partial T}{\partial t}$ is the time rate of change of the differential temperature. Thus, for $Z_0 = .5$ and

$NA = 4\times10^{10}$, ten microvolts correspond to $\frac{\partial T}{\partial t} = 1\times10^{-3}$ c/sec.

Conclusion. Coils must be compensated against differential temperature changes.

(3) *Thermal contact e.m.f.s.* We are informed that thermal e.m.f.s. offer difficulties when detection voltages are of order 10^{-7} or less. For detection voltages of order 10^{-6} or greater it is believed fluctuations due to thermal e.m.f.s. may be reduced to a satisfactory level.

(4) *Disturbances due to the Ship.* Three types of local disturbances arising from the ship itself need consideration. (1) Movement of large iron parts such as anchors or swinging davits, tiller, and rudder mechanisms must be suitably restricted, or the parts must be made of non-magnetic materials. (2) The change in magnetic permeability with temperature of iron parts near the receivers may be of significant magnitude. (3) The effects of change in induced magnetization of the ship, with changing course, need special study.

In an airplane, or in a semi-non-magnetic ship, the problem of local disturbances is obviously much simplified.

The problem of local disturbances is obviously a complex one. In the work at New London it was found that a steel ship could be used as effectively as a wooden one, but this result has little if any bearing on the present scheme, since we are now contemplating sensitivities a thousand fold greater than were then feasible to use. In brief, it has been estimated that in a wooden chaser of 110′ length, the influence of engine is small, even for extreme values of the instrumental sensitivity, provided its temperature change is of order 2°C/sec. or less. Similarly, preliminary computations indicate that the temperature effects in local iron masses are small provided the temperature changes are less than .1°C per sec., and the ratio $\frac{\omega}{r^3} < 1/4$ where ω = wt. in lbs., and r = distance from coil in feet. Thus, at 3 ft. uncompensated masses should be less than 7 lbs.

The effects of change of course of the ship are difficult to estimate. They may be reduced by locating the coils parallel and near to the "magnetic axis" of the ship, and by automatically degaussing for changes in orientation. The pitching of the ship, however, will undoubtedly introduce severe difficulties. The best way for making progress in the study of the method is to use semi-iron magnetic ships, or airplanes.

VII *Compensation of errors.* Errors due to lack of parallelism were compensated by Merritt in 1918 by a system of three auxiliary coils with planes mutually perpendicular. This procedure may be further improved by the approximate neutralization of the normal component of the earth's field at each coil. This could be done by use of an auxiliary winding on each coil, carring a current proportional to the cosine of the angle between the axis of the coil and the vertical. The effect of that part of the horizontal component of the earth's field transverse to the axis of roll could also be neutralized—but the mechanism would have to take into account the orientation of the axis of rotation with respect to the magnetic meridian, and the normal intensity of the earth's horizontal component. If 99% or more of the total component of the earth's field normal to the plane of the coils were successfully eliminated, the influence of roll and pitch and also of temperature changes would be correspondingly reduced. In the examples cited in section VI, there would remain a residual voltage of 3×10^{-4} volts due to pitch, which must be further reduced by compensating coils to 1×10^{-5} in the design contemplated (see section IX). The differential temperature change permissible (see Equation 6) would also fall within easily attainable limits, i.e., .1° Centigrade/sec., for a detection threshold of 10^{-5} volts.

VIII *Short period fluctuations.* Spurious fluctuations due to vibration of parts or torsion in the ship may be eliminated by the introduction of suitable filters, provided the disturbances are not of period comparable to that of the signal to be observed. In the case of an airplane mount, the duration of the signal pulse will probably usually be between two and six seconds. In the case of a ship, about three times longer. (See sec. IX.)

IX *Detectability and range.* The factor $v_x\Delta x$ in Eq. 1 will be about the same size in either plane or ship installations. Thus, on a plane at 200 m.p.h., with a coil separation of 30 ft., $v_x\Delta x$ is 10^7 C.G.S.; on a boat at 20 knots, with coil separation 300 ft., $v_x\Delta x$ is also 10^7 C.G.S. The "wave length" of the response when passing directly over a submarine is about one and one-third times the height above the submarine. Thus, a boat at 20 knots (30′/ sec.) above a submarine submerged 300′ would ex-

perience a response impulse of about 13 seconds duration. An airplane, at 500′ above sea level, traveling at about 200 m.p.h. (300′/sec.) would experience an impulse of only 3½ seconds duration. At 100′ submergence the time intervals would be 4⅓ and 2⅔ seconds, respectively.

Because of the shorter time intervals involved with an airplane mount, and the need of minimizing weight, it seems essential to use a transformer on the coil-pair output. Some preliminary consideration has been given to the question of a proper transformer, and some preliminary model tests have been made. But the general question of the design of sensitive receiving equipment has been little considered.

However, to illustrate in a crude way the order of magnitude of the ranges which might reasonably be expected, the following somewhat arbitrary example is set up.

Assume (in Eq. 1)

1) $v_x \Delta x = 10^7$

2) $NA = 8\times10^8$ (Coil diameter—1 meter, 100,000 turns No. 36 enameled wire, wt. 78 lbs., resistance 415,000 ohms, inductance about 20,000 henries)

3) Transformer factor, f, = 50,

so $NAf = 4\times10^{10}$

4) Assume that the threshold value of voltage on the first tube of the amplifier is 10^{-5} volts. Let the detection voltage, E, (Eq. 1) be ten times the threshold, or 10^{-4} volts.

Substituted in Eq. 1, the above values give

$$\frac{\partial^2 Z}{\partial x^2} = 2.5\times10^{-14}$$

5) After de-gaussing, let (a) $M_s = 2\times10^6$ for smallest submarines, and (b) $M_s = 4\times10^7$ for the largest.

In Equation 3, the maximum $\frac{\partial^2 Z}{\partial x^2}$ occurs at $x = 0$, and is there

$$+\frac{12\,M_0}{r^5} \text{ when } \frac{\partial^2 Z}{\partial x^2} = 2.5\times10^{-14},$$

we find (a) r = 159 meters = 520′

or (b) r = 285 meters = 935′.

Thus under the assumptions made, the detection range is of the order 500′ to 1,000′.

A measure of the area coverage in exploring an area for submarines is the product of the range attained by the speed of the searching vessel. Since air craft travel at ten fold the speed of destroyers, the ranges above are equivalent to 5,000′ and 10,000′ respectively, on surface craft, in terms of area explored per unit time. When one takes into account, in addition, the relative first costs and costs of operation of a ship and an airplane, the efficiency and economy of search by the magnetic method on planes may exceed that by standard methods on ships, despite the highly restricted range of the magnetic method.

Balanced Coil Method of Detecting Submarines

Summary

A brief sketch of the problem of magnetic detection of submarines by the balanced coil method is here given. The range of the method is inherently short. Modern instrumental techniques should enable ranges on degaussed submarines of the order of 500′ to 1,000′ to be attained. The chief difficulties are not, apparently, fundamental and natural ones set by unavoidable background disturbances, but are those arising from local magnetic disturbances in the ship or plane. The sensitivity of detecting apparatus may be a limiting factor, if local disturbances are well eliminated by care in compensation. Apparently, little research on the method has been carried on in this country since 1918, and it is believed that enough work should be done to establish the true limitations and possibilities of the method. Even the short ranges which it is estimated could be achieved with present apparatus may be important in searching for submarines by airplanes. Since the problem is primarily an instrumental problem, it seems reasonable to expect that distinct improvements can be made through research.

Appendix I

September 19, 1940.

Proposed Study of Oceanographic Aspects of the Sound Ranging Problem

Introduction

The research program outlined below is designed to supplement certain investigations on underwater sound transmission now in progress (or planned for) at the Naval Research Laboratory, where work is for the most part directed towards improvement of the instrumental technique, and towards the determination of the relationship between a given distribution of density in the surface layer and the effective range of various types of equipment. It is now proposed that this work be closely correlated with a thorough study of the oceanography of the surface layer with the ultimate aim of developing a method for forecasting the sound transmitting characteristics of the waters in any part of the ocean, at any season and in any type of weather.

The oceanographic part of this investigation will be centered at the Woods Hole Oceanographic Institution because some trained personnel and equipment are immediately available there and because the strategical value of the expected results makes it advisable to carefully select the investigators and to keep their finding secret.

Objectives

1. Immediate preparation of a manual, for use by both officers and enlisted personnel, summarizing a) the existing oceanographic knowledge relating to sound transmission, b) the physics of sound in sea water, and c) the results available in the sound file of the Naval Research Laboratory.

2. Training of several pairs of observers and providing them with sufficient oceanographic background to collect on a large scale the necessary data from a) Naval ships, b) Coast Guard cutters, c) commercial steamers and d) available oceanographic research vessels.

3. From these observations areas will be mapped which can be considered a) reliable, b) unreliable, and c) safe only when seasonal and diurnal factors are fully taken into consideration.

4. Study of the seasonal cycle and daily changes in structure of as many regions as is practical.

5. Study of the influence of wind and evaporation so that in conjunction with daily weather maps a method can be devised to estimate the effective range in areas towards which the fleet is maneuvering.

6. Development of an instrument for directly and rapidly measuring the change in velocity of sound with depth.

Outline of the Proposed Investigation

1. Field Work

a. The "Atlantis" will be employed in this work on approximately a half time basis. She will make cruises to secure data on the seasonal and diurnal changes in the basic structure of the surface layer in the various primary water-masses of the western North Atlantic. She will also begin a detailed study of wind currents, both as they come into the sonic problem and as they have a navigational importance. These results will as soon as possible be applied to the critical areas of the Pacific.

b. In addition, the oceanographic observations which can be made from naval vessels engaged in sound experiments (such as the "Sammes") will be supervised by one of the men trained at the Woods Hole Oceanographic Institution. A copy of these observations will immediately be made available to the Navy Department to aid in the interpretation of the sound ranging data.

c. As soon as a trained personnel is available and as soon as the observational technique has been sufficiently standardized, pairs of observers will be sent off on Naval, Coast Guard, commercial and scientific vessels to explore the oceans from the standpoint of sound as thoroughly as time permits.

d. If the results are sufficiently promising, it is planned that rapid surveys of certain critical areas will be made for the purpose of constructing detailed temperature charts of the superficial layers. It seems probable that some of the Coast Guard vessels could be used for such work.

2. Instrumental Development

At the outset of the investigation the basic instruments will be the bathythermograph and the pressure operated sea sampler. Both of these need further refinement. However, it is also clear that the development of an instrument capable of directly measuring the changes in sound velocity with depth would be most desirable. The principles of such a device have already been worked out and construction can start as soon as funds are available. Further instrumental developments will no doubt be suggested as the investigation proceeds and as a better knowledge is gained of the Navy's requirements.

If the preliminary investigations are successful, it is expected that before long 8 technicians will be needed for the field work and 4-6 clerical assistants for the routine laboratory analysis. Some of these people will be supplied by various cooperating agencies.

Cooperation

Besides the cooperation of the Naval Research Laboratory various agencies have already agreed to contribute assistance:

a. Submarine Signal Company
Technical advice and design of instruments.

b. Woods Hole Oceanographic Institution
Salary of three investigators, laboratory facilities and the use of the "Atlantis" on a part time basis.

c. Scripps Institution of Oceanography
Laboratory facilities and possibly part of the salary of one or more qualified men.

d. Oceanographic Laboratory, University of Washington
Laboratory facilities and possibly part of the salary of one or more qualified men.

In addition, it is expected that it can be arranged with the U.S. Coast Guard to assign to this work a considerable proportion of the oceanographic personnel of the International Ice Patrol Service.

Budget

It will require at least two years to carry through the proposed oceanographic investigation and related instrumental development. The best estimate which can now be given as to the cost of this work, over and above that contributed by cooperating institutions, is $100,000. It is proposed that this money be paid to the Woods Hole Oceanographic Institution on a quarterly basis in 8 installments, but the actual investigation will be continued until the funds are exhausted, unless the National Defense Research Committee advises that it be discontinued.

3. Laboratory Work

a. Within the next few months a manual will be prepared for use at the naval sound schools. This will admittedly be a stop-gap, but the existing oceanographic knowledge and the technical reports on operation of sound equipment now on file at the Navy Department will be summarized. This hand-book will be written in simple language so that it can be used in the training of enlisted men for sound duty.

b. The existing oceanographic data will also be analyzed more technically and as the work progresses reports will be submitted to the Navy Department for distribution to the interested agencies.

c. In the same way, the new observations to be collected by the "Atlantis" and other cooperating vessels will likewise be analyzed and from time to time reported to the interested naval people for criticism.

Personnel

The scientists and technicians engaged in this program will be selected by the Director of the Woods Hole Oceanographic Institution. However, as the work proceeds he will consult with the proposed sub-committee on submarine detecting of the National Defense Research Committee. In short he will be responsible for the personnel which secures and analyzes the observations, but will look for guidance and criticism on the course of the investigation from such outside qualified scientists and naval authorities as may be designated.

The trained investigators already arranged for can be listed as follows:

Physical oceanographers:
C. O'D. Iselin
R. B. Montgomery
M. C. Ewing

Oceanographical and instrumental technicians:
A. C. Vine
A. H. Woodcock
J. L. Worzel

In addition, it is expected that Dr. Fleming or Dr. Revelle of the Scripps Institution of Oceanography and Dr. Church of the Oceanographic Laboratory of the University of Wash-

ington can be persuaded to join the investigation. Additional technicians will be trained as needed. However, only the 4 or 5 senior men will be completely informed as to the practical objectives of the program.

BREAKDOWN OF EXPECTED EXPENSES OVER A PERIOD OF TWO YEARS

1. *Field Work*		
a. "Atlantis" The Woods Hole Oceanographic Institution will continue to pay her normal operating cost, approximately $38,000 per year. However, under the proposed program there will be an increase of roughly 15%, due to additional time at sea ...		$ 12,000
b. "Anton Dohrn" This smaller vessel will be used for at least two months each summer		4,000
c. Traveling The traveling expenses of senior investigators between Woods Hole, Washington and California, and the cost of sending the technicians to join cooperating vessels will not be inconsiderable		3,000
2. *Instrumental Development and Winches*		
2 Bathythermographs and 4 multiple sea samplers with auxiliary equipment		5,000
Sound Velocity Meter		10,000
3 Special high speed, portable winches		4,500
3. *Laboratory Rental*		
During the winter months especially, the Woods Hole Oceanographic Institution will be put to additional expense for heat, light, power and minor laboratory supplies		3,000
4. *Salinity Determinations*		
A very large number of water samples must be analyzed		4,000
5. *Personnel*		
Dr. Ewing	$9,000	
Mr. Vine	5,000	
Mr. Woodcock	4,000	
Mr. Worzel	4,000	
Dr. Fleming, ½ time	3,500	
Dr. Church, ½ time	3,000	
4 additional field technicians	16,000	
2 laboratory assistants	7,000	
Stenographer	3,000	
		54,500
Total		$100,000

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36. *Development of a Flotation Device* (Final Report), K. A. Chittick, OSRD 44, OEMsr-33, Report D3/1248, RCA, Sept. 19, 1941. Div. 6-123-M1
37. *Underwater Sound Direction and Range System, USDAR*, OSRD 5315, NDRC 6.1-sr1347-2331, Service Project NS-297, RCA, June 30, 1945. Div. 6-633.23-M3
38. *Completion Report Covering Period June 1941 to April 1, 1946* (Final Technical Report), OEMsr-30, UCDWR, April 1946. Div. 6-116-M1
39. *Summary of Cavitation Tests on a Systematic Series of Rounded Torpedo Heads* (Final Report), Hunter Rouse, John S. McNown and En-Yun Hsu, OSRD 5253, NDRC 6.1-sr1353-2330, State University of Iowa, May 31, 1945. Div. 6-810.23-M8
40. *Project Report and Instruction Book for Model XQHA Sonar Equipment* (Serial 106), OSRD 4946, OEMsr-1288 and NXsr-46933, Task No. 2, NDRC 6.1-1288-2117, BuShips and Sangamo Electric Company, April 1945. Div. 6-632.221-M3
41. *Project* [NO] *-149, Mark 21 Torpedo, Final Technical Report under Contract OEMsr-1051*, OSRD 5015, NDRC 6.1-sr1051-2121, Westinghouse Electric and Manufacturing Company, Feb. 28, 1945. Div. 6-911.2-M1
42. *Mark 22 Torpedo, Final Report of Project* [NO] *-157*, NDRC 6.1-sr1053-2125, Westinghouse Electric and Manufacturing Company, May 23, 1945. Div. 6-912.2-M1
43. *Torpedoes for High-Speed Aircraft* (Final Report), OEMsr-1342, NDRC 6.1-sr1342-2334, Research Project 176, Newark College of Engineering, 1945. Div. 6-115-M1
44. *Final Technical Report under Contract OEMsr-1419*, OSRD 6560, NDRC 6.1-sr1419-2394, Leeds and Northrup Company, Nov. 30, 1945. Div. 6-125-M1
45. *Research and Development of Aerial-Type Torpedo* (Final Report and Supplement), OSRD 6456, NDRC 6.1-sr1105-2390, American Can Company, Dec. 31, 1945. Div. 6-124-M1
46. *Counter-Rotating Motor for Torpedo Drive* (Final Technical Report on Contract OEMsr-1370), Gerhard Mauric, OSRD 6659, NDRC 6.1-sr1370-2397, Electrical Engineering and Manufacturing Corporation, Apr. 15, 1946. Div. 6-933-M1
47. *Sound Ranges under the Sea*, Thomas H. Osgood, OSRD 660, NDRC C4-sr20-100, CUDWR, June 5, 1942. Div. 6-500-M1
48. *Reverberation in Echo Ranging, Part I, General Principles*, Thomas H. Osgood, OSRD 807, NDRC C4-sr20-149, CUDWR, July 28, 1942. Div. 6-520-M1
49. *The Magnetic Airborne Detector*, Thomas H. Osgood and R. R. Palmer, OSRD 1124, NDRC 6.1-sr20-664, CUDWR, Dec. 19, 1942. Div. 6-423-M3
50. *Probability Studies for Patterns of Antisubmarine Contact Charges Launched from Surface Craft*, H. R. Davidson, Conyers Herring, and Leonard I. Schiff, OSRD 1368, NDRC 6.1-sr20-834, CUDWR, Apr. 5, 1943. Div. 6-112-M3
51. *Reverberation in Echo Ranging, Part II, Reverberation Found in Practice*, Thomas H. Osgood, OSRD 1422, NDRC 6.1-sr20-840, Service Project NS-140, CUDWR, Apr. 14, 1943. Div. 6-520-M3
52. *A Theoretical Study of Factors Influencing the Effectiveness of Attacks Against Deep Submarines*, Conyers Herring, OSRD 3885, NDRC 6.1-sr1131-1153, Service Project NA-121, CUDWR, Dec. 13, 1943. Div. 6-112.3-M1
53. *Probability Studies on the Effectiveness of Antisubmarine Attacks by Surface Craft*, E. Ward Emery, OSRD 3916, NDRC 6.1-sr1131-1426, CUDWR, June 2, 1944. Div. 6-112.3-M2
54. *A Theoretical Study of the Effectiveness of a 20-Knot Acoustic Torpedo and of Possible Modifications Having Lower Speeds with or without an Automatic Speed-Changing Mechanism*, Conyers Herring and E. Ward Emery, NDRC 6.1-sr1131-1882, CUDWR, Nov. 22, 1944. Div. 6-912.4-M1
55. *A Torpedo Survey on Project N-121*, NDRC 6.1-sr1131-1892, Special Studies, CUDWR, Dec. 22, 1945. Div. 6-900-M3
56. *Survey of Underwater Sound, Report No. 1, In-*

troduction, Vern O. Knudsen, R. S. Alford, and J. W. Emling, 6.1-NDRC-729, Division 6, Feb. 26, 1943. Div. 6-580-M1

57. *Survey of Underwater Sound, Report No. 2, Sounds from Submarines*, Vern O. Knudsen, R. S. Alford and J. W. Emling, OSRD 3247, 6.1-NDRC-1306, Dec. 31, 1943. Div. 6-580.1-M2
58. *Sonar Scanning Systems*, Roy C. Hopgood, OSRD 3220, 6.1-NDRC-1307, January 1944. Div. 6-600-M1
59. *Survey of Underwater Sound, Report No. 3, Ambient Noise*, Vern O. Knudsen, R. S. Alford and J. W. Emling, OSRD 4333, 6.1-NDRC-1848, Sept. 26, 1944. Div. 6-580.33-M2
60. *Concluding Summary Report of the Selection and Training Committee Division Six, NDRC*, Gaylord P. Harnwell, Dec. 15, 1944. Div. 6-300-M1
61. *Survey of Underwater Sound, Report No. 4, Sounds from Surface Ships*, M. T. Dow, J. W. Emling and Vern O. Knudsen, OSRD 5424, 6.1-NDRC-2124, June 15, 1945. Div. 6-580.2-M7
62. *Design of the Mark 25 Torpedo* [Parts I and II], (Final Technical Report), OSRD 6672 and 6673, 6.1-sr1131-2393, Service Project NO-176, Dec. 31, 1945. Div. 6-800-M6
63. *Bibliography and Brief Review of Published Material on the Physical Principles of Submarine Detection*, Millard F. Manning, Conyers Herring, and David Keppell, OSRD 237, NDRC C4-sr20-018, CUDWR, September 1941. Div. 6-112-M2
64. *Method of Harbor Protection Against Non-Magnetic Submarine*, L. B. Slichter and L. Batchelder, CUDWR. Div. 6-112-M4

OSRD APPOINTEES

DIVISION 6

Division Personnel

Until December 1942 work proceeded under direction of Section C-4 of Division C, NDRC. During this period Dr. F. B. Jewett was Chairman of Division C and Dr. John T. Tate Vice-Chairman, Division C, and Chairman Section C-4. In December 1942 Section C-4 became Division 6, with Dr. Tate Chief of Division and Dr. Colpitts Chief of Section 6.1, the only section established. The Members of Section C-4 were reappointed as Members of Division 6 with exception of Drs. Carl D. Anderson, E. O. Lawrence and Max Mason. The following persons served as Members of Division 6 for all or a portion of the period December 1942 to about December 1945, when their appointments were terminated.

E. H. COLPITTS
W. D. COOLIDGE
P. D. FOOTE
G. P. HARNWELL
V. O. KNUDSEN
P. M. MORSE
G. B. PEGRAM
T. E. SHEA
L. B. SLICHTER

The following persons served as Technical Aides to Section C-4 and Division 6 for longer or shorter periods:

ELMER HUTCHISSON, *Head Technical Aide*
L. G. STRAUB, *Head Technical Aide*
RICHARD H. BOLT, *Chief Technical Aide*
L. F. MOREHOUSE, *Senior Technical Aide*
A. G. ANDERSON, *Technical Aide*
A. W. BARRUS, *Technical Aide*
R. C. HOPGOOD, *Technical Aide*
DAVID KEPPEL, *Technical Aide*
DOROTHY M. LASKY, *Technical Aide*
O. A. WANTUCH, *Technical Aide*

During period 1941-46 the Office Administrative Assistant was first Miss Fern Sullivan and later Mr. Joseph P. Lee.

The following persons were appointed as Consultants to Division 6:

R. D. FAY
T. C. FRY
T. K. GLENNAN
D. G. C. HARE
W. V. HOUSTON
F. V. HUNT
V. O. KNUDSEN
D. P. MITCHELL
H. NYQUIST
T. C. POULTER
R. S. SHANKLAND
H. W. SVERDRUP
M. S. VITELES
E. G. WEVER
S. S. WILKS
E. M. WISE

CONTRACT NUMBERS, CONTRACTORS, AND SUBJECT OF CONTRACTS

Contract Number	*Name and Address of Contractor*	*Subject*
NDCrc-40	Woods Hole Oceanographic Institution Woods Hole, Massachusetts	Studies and experimental investigations in connection with the structure of the superficial layer of the ocean and its effect on the transmission of sonic and supersonic vibrations. Studies and investigations in connection with the oceanographic factors influencing the transmission of sound in sea water.
OEMsr-20	The Trustees of Columbia University in the City of New York New York, New York	Studies and experimental investigations in connection with and for the development of equipment and methods pertaining to submarine warfare.
OEMsr-30	The Regents of the University of California Berkeley, California	Maintain and operate certain laboratories and conduct studies and experimental investigations in connection with submarine and sub-surface warfare.
OEMsr-34	General Electric Company Schenectady, New York	Development of equipment and methods for detection of submarines by magnetic effects.
OEMsr-40	Western Electric Company, Inc. 120 Broadway, New York, N. Y.	Experimental studies and investigations of the development of equipment and methods for detection of submarines by magnetic effects.
OEMsr-42	General Electric Company Schenectady, New York	Studies and experimental investigations in connection with the development of magnetic barnacles and non-magnetic streamlined darts or stingers.
OEMsr-43	General Electric Company Schenectady, New York	Studies and experimental investigations in connection with the detection of submarines by light pulsing.
OEMsr-44	General Electric Company Schenectady, New York	Studies and experimental investigations in connection with short range submarine location utilizing short non-directional impulses.
OEMsr-58	Harvard University Cambridge, Massachusetts	Studies and investigations in connection with the measurement of underwater noise from ships, and investigations of the transmission thereof through the medium.
OEMsr-27	Gulf Research and Development Company Pittsburgh, Pennsylvania	Studies and experimental investigations in connection with the development of equipment and methods applicable to the detection of submarines by magnetic effects, including magnetic airborne detection.
OEMsr-31	Woods Hole Oceanographic Institution Woods Hole, Massachusetts	Studies and experimental investigations in connection with the structure of the superficial layer of the ocean and its effects on the transmission of sonic and supersonic vibrations.

CONTRACT NUMBERS, CONTRACTORS, AND SUBJECT OF CONTRACTS *(Continued)*

Contract Number	*Name and Address of Contractor*	*Subject*
OEMsr-33	RCA Manufacturing Co., Inc. Camden, New Jersey	Studies and experimental investigations in connection with the design and development of radio sonic buoys (capable of being dropped overboard from a ship).
OEMsr-54	Western Electric Company, Inc. 120 Broadway, New York, New York	Studies and experimental investigations in connection with the construction and testing of a supersonic prism as applied to methods of underwater ranging.
OEMsr-212	Western Electric Company, Inc. 120 Broadway, New York, New York	Studies and experimental investigations in connection with the development, construcion, and calibration of hydrophonic standard receivers and projectors, and establish and operate field stations necessary for the maintenance of a calibration system.
OEMsr-315	Goodyear Aircraft Corp. Akron, Ohio	Studies and experimental investigations looking toward the development of streamlined aerial housings for magnetic detection equipment, including windtunnel and aircraft tests.
OEMsr-124	California Institute of Technology Pasadena, California	Studies and experimental investigations in connection with jet propulsion of underwater detection devices and projectiles.
OEMsr-352	Western Electric Company, Inc. 120 Broadway, New York, New York	An exploratory development program to determine whether a magnetic tape compensator may be used to indicate the direction of incoming underwater sounds in submarine detection.
OEMsr-287	President and Fellows of Harvard College Cambridge, Massachusetts	Studies and experimental investigations in connection with (i) the development of equipment and devices relating to subsurface warfare.
OEMsr-207	California Institute of Technology Pasadena, California	Construction and operation of a high-speed water tunnel, and use of such water tunnel in research and experimental investigations involving underwater projectiles and detection equipment.
OEMsr-323	General Electric Company Schenectady, New York	Studies, experimental investigations, and development work in connection with submarine and subsurface warfare.
OEMsr-329	California Institute of Technology Pasadena, California	Studies and experimental investigations in connection with the descent of underwater projectiles when falling freely and when initially propelled.
OEMsr-346	Western Electric Company, Inc. 120 Broadway, New York, New York	Studies and experimental investigations in connection with submarine and subsurface warfare.

Contract Number	*Name and Address of Contractor*	*Subject*
OEMsr-367	Western Electric Company, Inc. 120 Broadway, New York, New York	Studies and experimental investigations in connection with the detection of submarines by magnetic methods.
OEMsr-692	Western Electric Company, Inc. 120 Broadway, New York, New York	Conduct studies and experimental investigations in connection with the development of listening and detecting systems suitable for surface craft and for submarines.
OEMsr-695	Western Electric Company, Inc. 120 Broadway, New York, New York	Studies and experimental investigations in connection with methods of furnishing harbor protection by means of cables and associated equipment.
OEMsr-783	Western Electric Company, Inc. 120 Broadway, New York, New York	Conduct studies and experimental investigations in connection with, and develop calibration devices and methods in the field of hydrophonics, especially for calibrating stations at Mt. Lakes, New Jersey, and Orlando, Florida, and more particularly, (i) improve devices and testing equipment of types and range previously standardized for said stations, (ii) develop specific additional calibrating equipment and methods as requested; (iii) provide an adequate number of models to equip said calibrating stations, and, (iv) perform such other related work as may be requested.
OEMsr-785	Western Electric Company, Inc. 120 Broadway, New York, New York	Studies and experimental investigations in connection with Project 61.
OEMsr-673	Armour Research Foundation Chicago, Illinois	Conduct studies and experimental investigations in connection with (i) the development and design of a satisfactory fuse for an armor-piercing "Scatter Bomb" and the development of one or more operating models as directed. . . . (ii) such development work on the application of this fuse for use with the vertical bomb as appears to be necessary, and (iii) the design, development, and testing of special types of anti-submarine bombs and of their components and accessories.
OEMsr-967	Western Electric Company, Inc. 120 Broadway, New York, New York	Studies and experimental investigations in connection with the phenomenon of MAD.
OEMsr-1069	Western Electric Company, Inc. 120 Broadway, New York, New York	Conduct studies and experimental investigations in connection with the development of primary batteries having high power output per unit of weight and volume; such mechanical design as to permit, in addition to other incidental uses, their use in bombs or torpedoes launched from an airplane, from a ship's deck, or from a submarine, etc.
OEMsr-1051	Westinghouse Electric Corp. Sharon, Pennsylvania	Studies and experimental investigations in connection with testing Mark 18 samples, and the design, development, construction, and testing of launching samples of an aerial torpedo, acoustically controlled and electrically propelled.

Contract Number	*Name and Address of Contractor*	*Subject*
OEMsr-1053	Westinghouse Electric Corp. Sharon, Pennsylvania	Studies and experimental investigations in connection with testing Mark 19 samples and the design, development, construction and testing of two hand-made samples of an acoustically controlled, electrically propelled submarine torpedo.
OEMsr-1097	Western Electric Company, Inc. 120 Broadway, New York, New York	Conduct studies and experimental investigations in connection with the development, design and construction of pre-production models of the acoustic and electronic arrangements required for Projects NO-149 and NO-157, and such other development, design, and construction work in this connection that may be required.
OEMsr-1046	Massachusetts Institute of Technology Cambridge, Massachusetts	Studies and experimental investigations in connection with (1) underwater sound transmission and boundary impedance measurements; (2) ship sound surveys at high frequencies; (3) development of devices for the control of underwater sounds; and (4) development of intense underwater sound sources for special purposes.
OEMsr-1189	Western Electric Co., Inc. 120 Broadway, New York, New York	Provide the necessary personnel and facilities for manufacturing, stocking, and repairing hydrophonic instruments, equipment and apparatus.
OEMsr-1105	American Can Company 230 Park Avenue, New York, New York	Conduct studies and experimental investigations in connection with (i) the modification and improvement of torpedo design, with the general purpose of (a) enabling torpedoes to be dropped from aircraft without damage at higher speeds than is now possible and (b) improving the operating characteristics of torpedoes designed for high underwater speed; and (ii) the construction of experimental models of torpedoes or parts thereof for test purposes.
OEMsr-1128	The Trustees of Columbia University in the City of New York New York, New York	Conduct studies and experimental investigations in connection with and for the development of equipment and methods involved in submarine and subsurface warfare.
OEMsr-1129	The Trustees of Columbia University in the City of New York New York, New York	Conduct studies and experimental investigations in connection with the development and research work involving the application of magnetic methods to anti-submarine warfare including the development of airborne equipment and methods for training personnel in the use of such magnetic methods, establishing the necessary laboratories and facilities for this purpose.

Contract Number	*Name and Address of Contractor*	*Subject*
OEMsr-1130	The Trustees of Columbia University in the City of New York New York, New York	Conduct studies and experimental investigations in connection with the testing and calibrating of acoustic devices.
OEMsr-1131	The Trustees of Columbia University in the City of New York New York, New York	Conduct studies and investigations in connection with the evaluation of the applicability of data, methods, devices, and systems pertaining to submarine and subsurface warfare.
OEMsr-1198	Massachusetts Institute of Technology Cambridge, Massachusetts	Conduct studies and experimental investigations in connection with (i) torpedo power plants and (ii) the general problem of power-plant design.
OEMsr-1294	Western Electric Co., Inc. 120 Broadway, New York, New York	Conduct studies and experimental investigations in connection with production designs for the extension of Navy Project NO-94.
OEMsr-1224	Armour Research Foundation Chicago, Illinois	Conduct studies and experimental investigations in connection with the development of navigational marker buoy.
OEMsr-1288	Sangamo Electric Company Springfield, Illinois	Conduct studies and experimental investigations in connection with (i) the engineering development of a sonar scanning system for shipboard installation and (ii) the construction of three (3) preliminary models thereof, each model to be complete except for hoist mechanism.
OEMsr-1289	Massachusetts Institute of Technology Cambridge, Massachusetts	Conduct studies and experimental investigations in connection with new and improved fuels for torpedoes, including survey of power supplies for jet-propelled missiles.
OEMsr-1347	Radio Corporation of America, RCA Victor Division Camden, New Jersey	Conduct studies and experimental investigations in connection with the development of small object detectors.
OEMsr-1342	Newark College of Engineering Newark, New Jersey	Conduct studies and experimental investigations in connection with a development and test program for Navy Project NO-176.
OEMsr-1370	Electrical Engineering and Mfg. Corp. Los Angeles, California	Conduct studies and experimental investigations in connection with electric motor development.
OEMsr-1419	Leeds and Northrup Co. 4901 Stenton Avenue, Philadelphia, Pa.	Conduct engineering studies and design work on a controlled mine, including some model shop work; engineering design and construction of a small number of the preproduction models.
OEMsr-1353	The Iowa Institute of Hydraulic Research of the University of Iowa Iowa City, Iowa	Conduct studies, experimental investigations, observations, and tests of pressure distribution about underwater structures of varying form, together with photographic records of the character of the flow, especially with reference to the onset and continuance of the phenomena of cavitation, all at varying speeds and under selected conditions of operation.

The projects listed below were transmitted to the Executive Secretary, NDRC, from the War or Navy Department through either the War Department Liaison Officer for NDRC or the Office of Research and Inventions (formerly the Coordinator of Research and Development), Navy Department.

Service Project Number	*Subject*
NCG-101	Fire hose nozzles.
AC-50	Operations research.
AC-53	Development of a submersible magnetic tow target.
AC-55	Development of a directional radio-sonic buoy.
AC-70	Development of a hydrobomb.
AC-82	Special MAD project for Fifth Air Force.
N-118	Assistance in the submarine training program.
Ext. N-118	Development of a torpedo data computer trainer.
N-121	Torpedo survey.
NA-99	Project Mike—plane carried magnetic sweeping equipment.
NA-107	Towed submarine listening gear for use with lighter-than-air craft.
NA-120	Magnetic detection from aircraft.
Ext. NA-120	Arrangements for measurement of time variations in the magnetic field of the earth.
Ext. NA-120	Construction of a magnetic attack trainer.
Ext. NA-120	Requirements for CM-2/ASQ-2B equipments (39).
Ext. NA-120	Four sets of bulk spares for the CM-2/ASQ-2B equipments.
Ext. NA-120	Request for six AN/ASQ-1A towed birds.
NA-121	Ordnance probability studies.
Ext. NA-121	Antisubmarine search procedure.
Ext. NA-121	Theoretical studies of the optimum patterns to be used in the so-called direct attack against submarines.
NA-123	Development of a recoverable bomb.
NA-143	A preliminary investigation of the possibilities and limitations of using MAD for BTO.
Ext. NA-120	MAD "Bird" for naval airship training and experimental command.
Ext. NA-143	Investigation of the use of MAD for low altitude detection of targets for the purpose of accurately placing shore bombardments in cases where the objectives are protected from observation by camouflage.
NA-174	Investigation of gas generating and high energy compounds.
NO-94	Mark—Mine.
Ext. NO-94	Devices for use by submarines against escort vessels.
NO-96	Fundamental investigation of (a) weapons for attacking submarines, (b) mine detection apparatus, (c) measurement and utilization of acoustic radiation from ships.
NO-100	Underwater photography.
NO-116	Scatter bomb for submarine attack by heavier-than-air craft.
Ext. NO-116	Scatter bombs (request for 200 complete clusters).
Ext. NO-116	Experimental test of AS scatter bomb and fuzes.
NO-121	Retro-rocket bombs for implementing MAD equipment.
NO-125	Oscilloscope course plotter—ASAP.
NO-141	Hydrodynamic characteristics of projectile forms.
Ext. NO-141	Study of British squid projectile type C and the U. S. Mark 11 depth charge.
Ext. NO-141	Request NDRC make a study of the pressure distribution around a model of the torpedo Mark 14 type at a simulated full scale speed of 45 knots at trim.

Service Project Number	*Subject*
Ext. NO-141	Study the hydrodynamic characteristics of the aircraft depth bomb, and Mark 53, Mod. 1, with nose fuze AN-M103 and hydrostatic tail fuze AN-Mark 230.
NO-142	Attack predictors.
Ext. NO-142	Attack director, Mark 3.
Ext. NO-142	Request NDRC construct for BuOrd three sets of plan position from attack predictor scales (PPAP) for use with the attack plotter Mark 1 Mod. 2 to predict the course to steer the ship and the time to drop depth charges.
Ext. NO-142	Construction of simple type of depth charge computer used in conjunction with a bearing recorder.
NO-143	Electric detection (U.E.P.).
NO-147	A/S projector Mark 10—fire control equipment temporary installation.
NO-149	Acoustic control for torpedoes.
Ext. NO-149	Request for appointment of NDRC as consultant on development of special torpedo (NO-149).
NO-157	Acoustically directed 21-inch torpedo for submarines.
Ext. NO-157	Tests of model of German acoustic torpedo.
Ext. NO-157	Consultant services for the adaptation of acoustic gear to 25 preproduction models of the torpedo Mark 18.
NO-163	Cooperation with the Navy in harbor surveys and surveys of ambient underwater noise conditions in various areas.
NO-171	Proximity fuze for the Mark—mine.
NO-175	Projected scatter charges for surface vessels.
NO-176	Torpedoes for high speed aircraft.
NO-177	Jet propelled torpedo for use from aircraft.
NO-181	Echo-ranging control.
NO-195	Depth charge pattern recorder.
Ext. NO-195	Depth charge pattern recorder increased from 12 to a total of 30.
NO-196	Anti-surface vessel ordnance.
NO-200	Development of a sea water primary battery.
Ext. NO-200	Request NDRC supply consulting services to BuOrd on 150- to 300-kw batteries being supplied by Edison General Electric Appliance Company.
Ext. NO-200	Development of special machinery for duplex type sea water battery.
NO-204	Development of contact fuzes.
NO-209	Stabilized roll indicator.
NO-221	Acoustic spectograms of ship sounds.
NO-222	Acoustic reflection fields of submarines.
NO-226	Shipboard submarine attack teacher.
NO-236	Investigation of torpedo fuels.
NS-97	Selection and training program for sound operators.
Ext. NS-97	Study on selection of sound operators attending Fleet Sound Schools.
Ext. NS-97	NDRC sound operators selection and training project.
Ext. NS-97	Production of QFL records and other training recordings displaying effects of FXR gear.
Ext. NS-97	Assembly of an additional "B" unit for the echo recognition trainer.
NS-102	Development of subaqueous microphones for sono-radio buoys and cable connected hydrophones.
NS-106	Expendable sono-radio buoy.
Ext. NS-106	Recordings of underwater explosions as heard over the expendable sono-radio buoy.
Ext. NS-106	Buoy operator trainer for the ERSB.

Service Project Number	*Subject*
NS-113	Listening apparatus for small patrol craft and submarines toroidal magnetostriction hydrophone.
Ext. NS-113	50 Special 5-foot magnetostriction hydrophones.
NS-139	Testing and calibrating facilities.
NS-140	Acoustic properties of the sea bottom.
Ext. NS-140	Range as function of oceanographic factors.
NS-141	Acoustic properties of wakes.
NS-142	Basic improvement of echo-ranging gear.
Ext. NS-142	Request that a bearing deviation indication attachment be provided for attack teacher AirAsDevLant.
Ext. NS-142	7 models of a dynamic demonstrator (for training in the operation of the BDI), consisting in part of an artificial projector and Navy Type OAX monitor.
Ext. NS-142	Study of stabilization of sound projector.
Ext. NS-142	Development of a sturdy design of shipboard hoist equipment for Model OAX (modified) portable testing equipment.
Ext. NS-142	Procurement of 12 units FM sonar equipment.
NS-143	Acoustic marine speedometer.
NS-144	Echo repeater target.
Ext. NS-144	Echo repeater for use in submarine evasion tactics.
Ext. NS-144	Request construction of an echo repeater capable of being towed at pre-determined depths down to 800 ft.
NS-152	Shipboard attack teacher.
Ext. NS-152	Training device, SASAT B Model II.
NS-164	Submarine evasion device.
Ext. NS-164	Electronic noisemakers.
Ext. NS-164	Providing and loading disks for a certain Navy demolition outfit.
Ext. NS-164	Model NAC sound beacon.
Ext. NS-164	Development of a parachute buoyancy control for prosubmarine noisemakers which are heavier than water.
NS-173	Consulting services on SASAT Mark III equipments.
NS-182	Projector requirements and test limits.
NS-195	Consulting service on Model OAS and OAW practice targets.
NS-198	Consultant on contracts with Emerson Radio Phonograph Corporation and Freed Corporation for manufacture of expendible sono-radio buoys.
NS-211	Countermeasures to small depth charges.
NS-212	Noise reduction of submarines.
NS-221	Silent echo sounding equipment.
NS-222	Acoustic treatment of the conning tower.
NS-230	Reduction of interference on magnetic detection loops.
NS-231	Development of navigational marker buoy.
NS-233	Primary listening teacher.
NS-238	Depth charge direction indicator.
NS-240	Consulting service on shipboard antisubmarine attack trainer.
Ext. NS-240	Furnish consultant services to Librascope, Inc., on its development of a modification of the SASAT.
NS-245	Advanced listening teacher.
Ext. NS-245	Development and construction of group listening teacher.
NS-247	Triangular ranging.
Ext. NS-247	Assistance on triangulation-listening ranging system.
NS-248	Underwater voice communication system.
NS-252	Preparation of supplements to sonar instruction books.
NS-253	Time-motion study of operations in the submarine conning tower.
NS-257	Listening adjunct to submarine attack teacher.
NS-287	Periscope bearing indicator.

SERVICE PROJECT NUMBERS *(Continued)*

Service Project Number	*Subject*
NS-293	NAD beacon.
Ext. NS-293	Consulting service on production of several types of model NAD sound beacons.
NS-294	Cavitation research.
NS-297	Detection of small objects by means of underwater acoustic devices.
Ext. NS-297	Request for 10 underwater sound small object locating devices (USDAR).
Ext. NS-297	Working models of the small object locator.
NS-301	Consulting services on underwater sound portable testing equipment.
NS-308	Sonar-surface and submarine bathythermograph instruction program.
NS-316	Consulting services to Bureau of Ships on Model NAC sound beacons at the Sound Equipment Corporation, Hollywood, California, under Navy contract NXsr-60065.
NS-321	25 models of the extended range underwater sound portable testing equipment (7 to 70 kc monitor).
Ext. NS-321	Request for 7 expanded range monitors, 13 to 35 kc.
Ext. NS-321	Procurement of 10 B-19H hydrophones.
NS-324	Sonar group operator trainer (2 units of).
NS-325	BDI modification of the QFD advanced bearing teacher (operational test equipment Model 8) 25 units of for service test from Underwater Sound Laboratory, Harvard, through a subcontractor.
NS-326	Artificial projector for operator training on shipboard monitor equipment Model OAX (10 units of).
Ext. NS-326	Consulting services on development of shipboard sonar monitoring equipment.
NS-329	Development of a device which provides automatic target positioning on dead reckoning tracers from an input of target range and bearing.
NS-330	Consulting services on production of radio transmitting equipments AN/CRT-4.
NS-337	WCA conversion equipments, consulting services on by Columbia University Division of War Research to BuShips (940) on its contracts NXsr-42164 (Task 9) and NXsr-65323 with RCA.
NS-339	Recognition recorder for use in training operators to recognize various ship and torpedo noises (4 models of).
NS-342	Attack teacher for QH type scanning sonar equipment.
NS-355	Consulting service on production of 24-volt seawater battery.
NR-100	Operations research.
OD-99	Determination of the dynamic characteristics of specified bomb and projectile shapes.
OD-135	Development of a high velocity open water channel.
SC-64	Development and construction of expendable radio sonic buoy training device.



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