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SHOCK AND VIBRATION BULLETIN

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FOREWORD

The fifth symposium gave added impetus to the overall Shock and Vibration program. Its progress is affirmed by the contents of this Bulletin - the prepared papers, and scientific discussions.

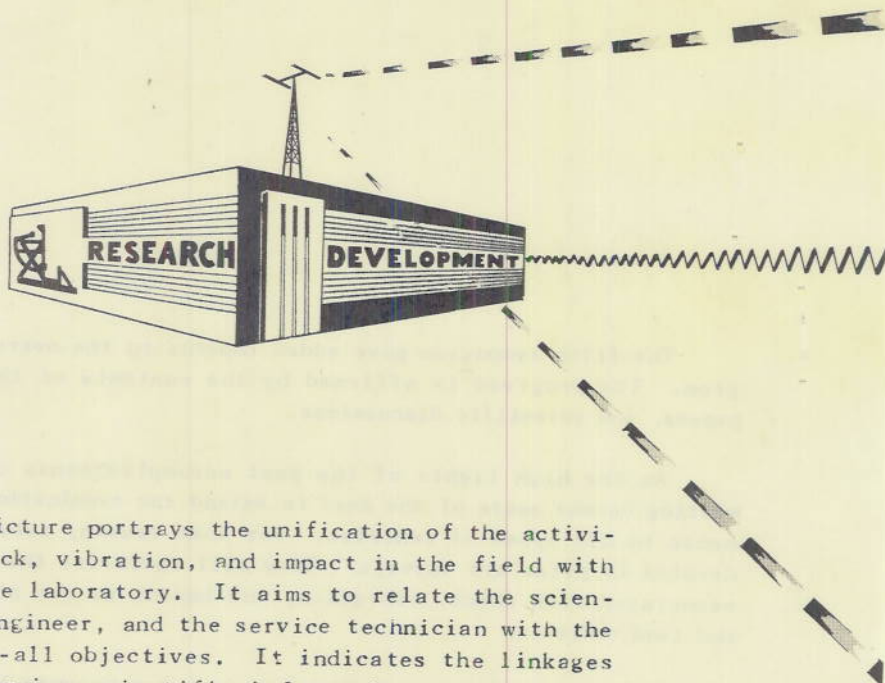
As the high lights of the past accomplishments on ships were reviewed, the meeting became aware of the need to extend the examination of previous field measurements to *all* types of vehicles. For that reason, several future symposia will be devoted to prior art surveys. They will summarize the past methods and techniques associated with shock, vibration, and impact in the fields of ordnance, aircraft, and land vehicles.

When all these are assembled into one panoramic background, it should become an effective guide to future measurements and field experimentation. Then full scale tests on any vehicle may be undertaken with confidence and enlightened enthusiasm.

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This picture portrays the unification of the activities in shock, vibration, and impact in the field with those in the laboratory. It aims to relate the scientist, the engineer, and the service technician with the common over-all objectives. It indicates the linkages for transforming scientific information received from the sources of disturbance and from the operational forces, into useful techniques by means of research and development.

To safeguard our mechanized forces the "Technologist" is employing every skill at his command. His ingenuity prevents devices from becoming inoperative as a result of sudden jars. He isolates and protects men and machines from the disturbing effects. However, his usefulness and "know-how" depend entirely on the ceaseless efforts of the laboratory, the source of his bloodstream.

The sketch also conveys a word of caution. Unless there is constant communication of scientific information, supplemented by an interchange of advancing knowledge, research and development fail to serve effectively the general welfare.

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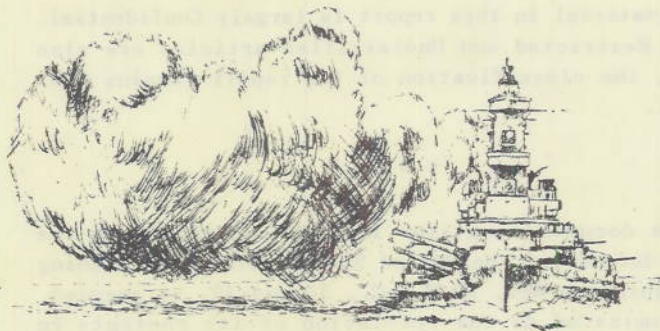
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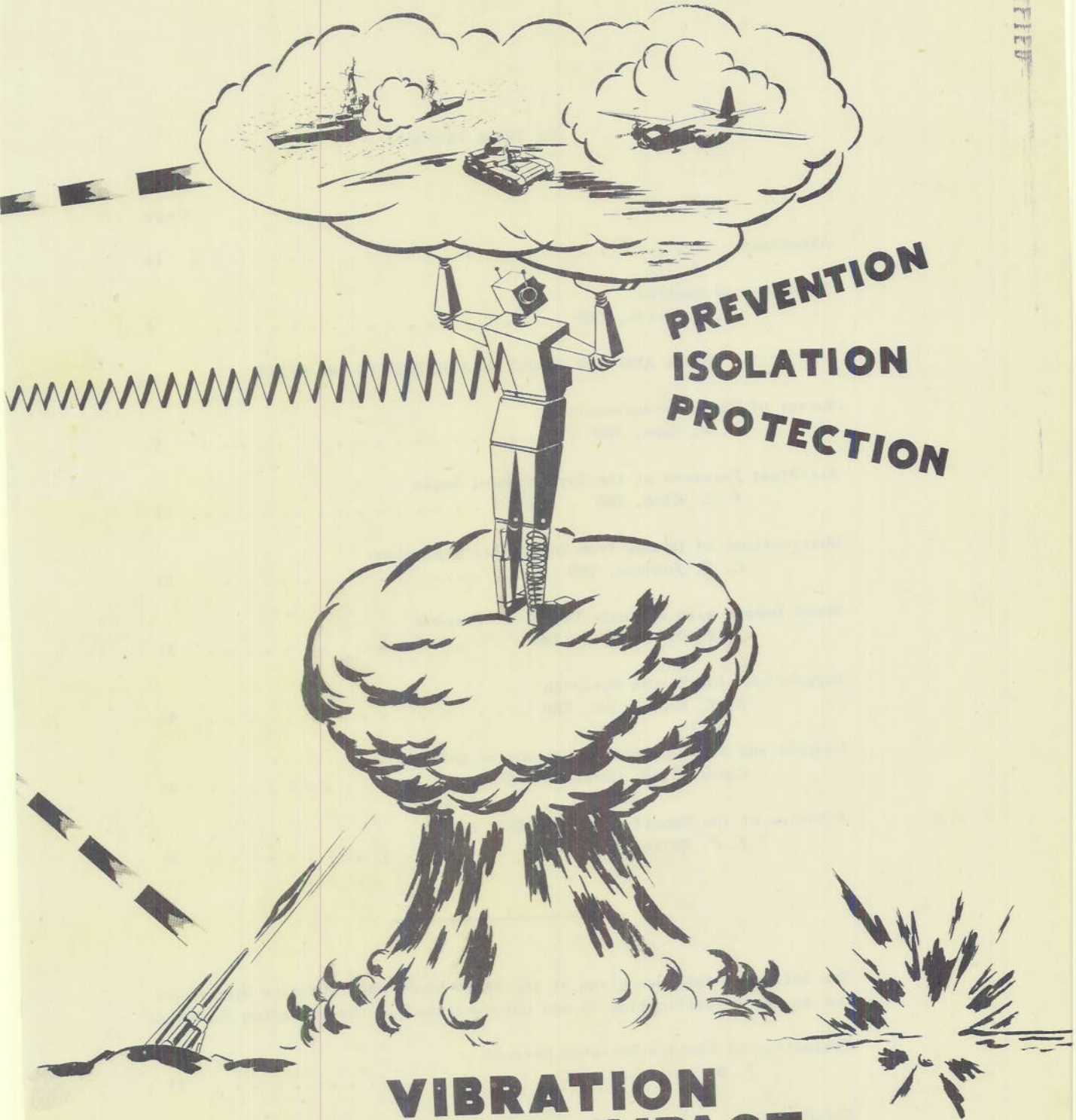
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**PREVENTION
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**VIBRATION
SHOCK IMPACT**

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IN THIS ISSUE

	Page
Attendance	ix
Introductory Remarks	
<i>W. J. Sette, TMB</i>	1
SHOCK AND AIR-BLAST MEASUREMENTS ON SHIPS	
Survey of Shock Measurements	
<i>F. F. Vane, TMB</i>	3
Air-Blast Research at the Taylor Model Basin	
<i>H. L. Rich, TMB</i>	11
Observations of Damage from Underwater Explosions	
<i>C. T. Johnson, TMB</i>	21
Shock Damage with a Single Degree of Freedom	
<i>J. W. Wrench, Jr., TMB</i>	31
Suggestions for Future Research	
<i>R. T. McGoldrick, TMB</i>	41
Contact and Near-Contact Explosions on Models	
<i>Comdr. C. H. Gerlach, BuShips</i>	49
A Review of the Report on the CAMERON Trials	
<i>J. P. Walsh, NRL</i>	59

The following talk was given at the Third Shock and Vibration Symposium. Due to its classification it was not published in the preceding Bulletin.

Evaluation of Inertia Operated Devices	
<i>J. H. Armstrong, NOL</i>	77
SAVIBULL	87

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THE FIFTH SYMPOSIUM
David Taylor Model Basin
25 June 1947

INTRODUCTORY REMARKS

W. J. Sette, TMB

At this symposium papers will be presented on shock and related subjects by members of the Staff of the Structural Mechanics Division of the David Taylor Model Basin. For these papers we have drawn on material obtained from what we call our blast and underwater explosion programs, as well as on material from the shock program. I mention this because it helps bring out that at the Taylor Model Basin emphasis in the past has been on structures and the response of structures to static and dynamic loads. These fields have been given our attention for years. In spite of that I must in all fairness admit that we still do not know all about structures; nor do we know all about shock. It seems that the more we learn about the subject, the more clearly we realize how much remains to be done.

However, progress on shock research has been made even though the gaps in our knowledge are so formidable. We complain about the shortcomings of the available test instruments, but a few years ago there were fewer and poorer types of instruments. Likewise, we deplore the lack of field data. But here again a few years back the data were more scarce and less reliable. Equipment that must withstand service shock has in many cases been made more rugged through the joint efforts of many navy agencies and industrial firms.

We will present some of the information that has been obtained in recent

years at the Model Basin and elsewhere. The topics were selected with the aim of presenting a bird's-eye picture of the scope of investigations on shock and related subjects.

Mr. Vane will give historical background of field work at TMB and describe briefly a variety of tests on naval vessels which led to some of the existing information on shipboard shock.

Mr. Rich will discuss the pressures associated with gun blast. As most of you know, gun blast is a common cause of shock on naval vessels. These pressures have been a subject of special interest at TMB and we believe a good start has been made in collecting data.

Mr. Johnson will discuss loads and damage associated with underwater explosions. He has drawn, as necessary, on data obtained at other laboratories, especially the Underwater Explosion Research Laboratory at Woods Hole, Massachusetts, under contract with the Bureau of Ordnance.

Dr. Wrench will give an analysis of the motion of a system with a single degree of freedom subjected to shock motion at the base. This we felt might be of interest to you since it approaches one of the ultimate objectives of the shock program: Calculation of the performance of service equipment under shock loads.

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Mr. McGoldrick will conclude this session by presenting an evaluation of the present status of some phases of shock work and suggestions for future research.

We would like to thank Dr. Klein and the Agenda Committee for this opportunity to address you and hope you will all enjoy and profit somewhat from the papers to be presented.

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SHOCK AND AIR-BLAST MEASUREMENTS ON SHIPS

SURVEY OF SHOCK MEASUREMENTS

F. F. Vane, TMB

An outline of shock measurements conducted by TMB on various types of Naval vessels. The instruments used and the locations of these instruments are described. Some data are evaluated and correlated with experiences of operating personnel and with damage reports.

Time is too limited at this meeting to do much more than outline the shock measurements the David Taylor Model Basin has made on a number of Naval vessels. The purposes of the tests, the types of vessels involved, and the nature of the measurements are indicated. A little data is presented to indicate the order of magnitude of the quantities measured. However, the object of this paper is primarily to show the reasons for the particular measurements and to indicate how this information may be used in practical application.

Depth charge firing, bursting bombs, and missiles create shock motions and create impacts which result in damage on naval vessels. Circuit breakers, safety valves, overspeed trips, and other similar items have become inoperative due to the above causes. Hull structures, range finders, chronometers, electrical panels, radio and radar equipment have been damaged.

Forces acting on a vessel together with their causes may be categorized as follows:

Underwater pressure - caused by depth charges and bombs

Air blast - caused by bombs and the firing of the ships' own guns

Mechanical forces - caused by projectiles, gun recoil, torpedoes and bombs.

For many years the interest of the Navy in damage caused by shock motion was small. Electrical equipment on shipboard was less extensive, radar equipment was nonexistent, and many of the controls now on naval vessels were not used. However, through this post World War I period equipment was redesigned to withstand blows ranging from 25 to 250-foot pounds on a shock machine.

The Navy has been interested in what might be considered a shock problem as far back as 1921 when the Bureau of Standards was asked to make measurements of motions and of deflections of turrets on the U.S.S. CALIFORNIA during firing trials.

In the late 1930's the Navy began to worry about the durability of turret rollers and turret roller tracks due to the proposed introduction of high-powered projectile propellant. This interest in the turret tract assembly widened to one of re-evaluation of turret design and of turret foundation design. The quantities of prime interest in this program were deflection, strain, and dynamic load factor. About 1938, the Model Basin began to make static and dynamic tests of turret models principally at the Philadelphia Navy Yard and also made some measurements on shipboard during structural firing trials. Dynamic deflections at turrets were measured on the U.S.S. NASHVILLE (CL43), U.S.S. WICHITA

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(CA45), U.S.S. NORTH CAROLINA (BB55), U.S.S. WASHINGTON (BB56), and the U.S.S. BALTIMORE (CA68).

On the U.S.S. NASHVILLE (CL43) measurements were made at Turret 1 during the firing of the 6-inch main batteries. The maximum relative displacement between turret and barbette was about 0.2 inch.

On the U.S.S. WICHITA (CA45) measurements were made again at Turret 1 in this instance during the firing of the 8-inch main batteries. The maximum relative displacement between turret and barbette was about 0.2 inch.

Comparable results were obtained on the U.S.S. NORTH CAROLINA (BB55) and U.S.S. WASHINGTON (BB56) during the firing of 16-inch main batteries and on the U.S.S. BALTIMORE (CA68) during the firing of 8-inch main batteries.

On the U.S.S. NORTH CAROLINA and U.S.S. WASHINGTON the following measurements were also obtained during gun firing:

1. Maximum strains in stanchions and bulkheads under the forecastle deck - 65,000 psi
2. Main deck deflection forward of Turret 1 - about 0.5 inch
3. Superstructure deck deflection over wardroom - 1.2 inches
4. Maximum blast pressure - 40 psi

On these tests scratch type gages were used to measure deflections, latch key and wire resistance gages to measure strains. Williams gages and prototype TMB diaphragm gages were used to measure blast pressures. Of these, a time record can be obtained only with the wire resistance strain gage and the TMB diaphragm blast gage.

On the series of turret tests, in addition to the information obtained for design of turrets and of foundations, the

results indicated that structural damage and equipment damage in and near turrets due to gun recoil was nonexistent. If fragile equipment is located near the turrets in the future, gun recoil may again become a problem but it is hoped that eventually there will be no fragile equipment and that all equipment could withstand a high order of shock motion.

Concern about gun recoil can be brushed aside rather easily but that does not hold true for air blast. The problem of damage due to air blast caused by the firing of the ship's own guns was a serious problem and necessitated restrictions on train and elevation angles at which guns could be fired. On some classes of ships, where conditions were severe, a certain amount of local stiffening was introduced. On the U.S.S. NORTH CAROLINA and U.S.S. WASHINGTON lagging in the wardroom had to be removed. In many instances doors and door frames had to be redesigned.

The model tests and the shipboard tests were an opportunity for the Model Basin to apply what were then new techniques and an opportunity to develop other techniques. The application of the wire resistance strain gage and the development of the TMB diaphragm blast gage hastened the use of electronics. Without this the Model Basin could have done very little in the study of the shock problem.

Some tests have been made of projectile impact on armor at Dahlgren and on the U.S.S. WYOMING. The data from the tests together with information from damage reports indicate the nature of the forces and motions created by projectile impacts.

During firing trials on the U.S.S. SARATOGA in 1940 measurements were made of air-blast pressures, strains, and deflections. The instruments were located on and near the after elevator since the purpose of the test was to determine the

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effect of firing 8-inch guns across the elevator. Correlation between blast pressures, strains, and deflections were made and alterations in the elevator structure were suggested. On this test maximum Williams gage blast pressures of 21 psi were obtained. The combined deflection and movement of the elevator platform relative to the main deck was about 6-inches downward and 3-inches upward.

In 1943, developments in antisubmarine warfare brought with them demands for data regarding possible damage to the attacking vessels when depth charges and other similar weapons were used in various patterns and at various speeds. The Taylor Model Basin was requested to make measurements on the U.S.S. BELL (DD587) and the U.S.S. HOPPING (DE155). Measurements were made of strains in the main deck stringers with long base strain gages, of accelerations with peak indicating mass-plug and cantilever-reed accelerometers and with crystal accelerometers.

The damage reports and trouble reports that have been coming to the Bureau of Ships in 1943 caused the people in the pertinent codes to reevaluate their specifications. Most of the reports received by the Bureau of Ships were on failures or maloperation of electrical equipment such as switchboards and wiring racks, failure of doors to close after fun firing or depth charge firing, and on tripping of auxiliary turbine safety valves. The Bureau of Ordnance was much worried about the action of director range finders during the firing of the ship's own guns. On the basis of these reports the Bureau of Ships decided that a considerable amount of investigation would be necessary before they could rationally respecify and redesign for the purpose of diminishing shock damage.

In August 1943, the Taylor Model Basin was directed to embark upon a general investigation of shock. The Basin was

directed to make full scale field tests from time to time, to develop instruments and to determine the general nature of shock phenomena.

Up to this time personnel and equipment from other projects were utilized for whatever tests arose. The general shock directive afforded opportunity to think of the overall problem and to think in terms of fundamental principles rather than make measurements with whatever was available for the trouble-shooting assignments. To this day work on the project has been plagued by lack of personnel, by overriding purchase priorities, and by design and shop priorities at the Basin.

The widespread introduction of radar in modern naval vessels, particularly, the installation of radar control equipment in exposed parts of the superstructure, has created new problems in shock protection. The first shipboard gun firing test under the new directive was the measurement of displacement, velocity, and acceleration in the after main director of the U.S.S. BOSTON (CA69). Much radar equipment was supported by the director cylindrical side plating exposed to gun blast. Peak indicating mass-plug and cantilever-reed accelerometers, crystal accelerometers, British type velocity meters, peak indicating inertia displacement gages, pallographs, and Williams blast pressure gages were installed on the director side plating, on the upper track casting, and on the director foundation.

Some of the results obtained were:

1. Maximum blast pressure - 5 psi
2. Maximum director foundation motion - about 0.2 inch
3. Maximum director plating acceleration - 150 g.
4. Maximum director plating velocity 5 inches per second

The test yielded some useful information for design of mounts for equipment

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in the director and for indicating the motions to which rangefinders are subjected due to the firing of the ship's own guns. The director is separated from the director foundation by rollers with clearances so that the values obtained are not the same as for representative superstructure.

Structural gun firing on the U.S.S. CANBERRA (CA70) afforded the first opportunity to plan measurements for determining relationships from which design criteria might be derived. Two stations, one in the flag cabin and one in the flag stateroom were selected for instrument locations. Here blast pressures would be quite large and interference to the blast wave impinging directly on the side plating would be at a minimum. One disadvantage of these stations were their locations at main deck level. The side plating was not only subjected to the direct blast wave but to the wave reflected from the main deck and indirectly to the wave impinging on the overhead. With the available number of recording instruments these selected locations were believed to give the most information.

Instruments similar to those used on the U.S.S. BOSTON were installed on panels of the side plating in the staff officer's cabin and stateroom.

Typical values obtained were:

1. Maximum blast pressure - 10 psi
2. Maximum velocity - about 6-feet per second
3. Maximum acceleration - about 370 g

No damage occurred and no equipment became inoperable during gun firing. Some electric light bulbs were broken and a little paint flaked off.

This test resulted in some data from which to try to derive design criteria.

In discussing the results of the U.S.S. CANBERRA test with Bureau repre-

sentatives, it became evident that the determination of natural frequencies of the hull and those of local structure would be useful in two ways. First, any shock mount must be designed so it does not vibrate objectionably at ordinary operating speeds of the vessel. Second, the local structural motions are transient motions becoming very quickly free vibrations whose effects under special circumstances can be more harmful than those of the transient motions. Many data were available in the Model Basin files on natural frequencies of hulls, directors, and propulsion machinery components but few were available on natural frequencies of superstructure, decks, side plating, and bulkheads particularly in areas where radar and radio equipment were installed. Therefore extensive frequency measurements were made on the U.S.S. MIAMI (CL89) since much of the local structure was comparable to that of a number types of vessels. On subsequent tests, frequencies were measured whenever time was available in addition to those always obtainable from displacement velocity, or acceleration records.

On the firing trials of the U.S.S. SUMNER (DD692) the Bureau of Ships' particular objective was the determination of the motions of turbo-generator sets, of locations of radar fire control equipment, and of bases of main propulsion turbines and reduction gears. Again the number of instruments was inadequate and the best compromise was measurement of the motions of the main deck, of a turbo-generator, and of the hull. Measurements were made during the firing of single depth charges at various depths and distances and during the firing of patterns. During gun firing trials instruments were available for measuring motions on the side plating of the after deck house. On one of these shots the muzzle of a 5-inch gun was only 5 feet from the instrument locations.

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Typical values obtained were:

For depth firing -

1. Maximum velocity of the hull - about 8-ft/sec.

2. Maximum acceleration of the hull - about 1400 g.

For gun firing -

1. Maximum velocity of after deck house side plating - about 13 ft. per sec.

2. Maximum acceleration of after deck house side plating - about 600 g.

Miscellaneous minor damage was incurred, such as: throwing of relays and switches on some electrical equipment; damage to an improperly dogged door; breaking of the bracket of a range finder compass; and buckling of the hull in the after part of the ship.

When vessels are subjected to depth charge firing, or, are damaged in action due to contact and noncontact explosions, or, are laboring in heavy seas, they develop violent whipping action at natural hull frequencies. This whipping action has damaged some vessels severely. On this Mr. McGoldrick will have more to say.

The values of shock motions on the turbo-generator obtained on the U.S.S. SUMNER (DD692) were unsatisfactory; therefore measurements were made on the U.S.S. LEARY (DD664). Maximum accelerations of 175 g and maximum velocities of 2 ft/sec. were measured.

In the spring of 1944, the Bureau of Ships desired measurements made on the U.S.S. DRAGONET (SS293) particularly on the hull, on the control cubicle, and on the foundation of a heavy item of machinery. The Naval Research Laboratory and the Taylor Model Basin both participated in these tests. First a series of nine (9) charges were fired at different distances abeam of the submerged submarine. Next a series of six charges were fired 75-feet from the hull at the mid-length

and the quarter-lengths on the starboard and port sides.

Acceleration-time, velocity-time, displacement-time and maximum relative displacements were obtained. Pressure-time records of the water outside the hull were obtained on a few of the shots.

Appreciable damage to electrical and mechanical equipment, including failure of numerous ballast-tank vents was associated with velocities of about 10-ft per second and accelerations of about 3000 g. This damage was incurred on shots 75-feet from the hull.

It was found that maximum velocity and maximum acceleration produced by depth charge explosions are approximately inversely proportional to the range, provided the charge locations are all at the same level and on the same bearing.

Application of results obtained on the U.S.S. DRAGONET to other types of naval vessels is not feasible because a submarine has a unique construction. Data obtained on hulls and particularly on superstructure housings of classes such as battleships, cruisers, destroyers, and destroyer escorts are similar because plates and stiffeners of these components are arranged in about the same way and respond in like fashion to the same types of loadings in these classes of vessels.

In July, 1944, gun firing trials on the U.S.S. MISSOURI (BB63) again afforded the Model Basin carte blanche in locating instruments. A section was desired where a large expanse of side plating was substantially flat. It was expected that on the U.S.S. MISSOURI, the blast wave impinging on the side plating at the instrument locations would be relatively free from secondary effects. It was desired also that the plating selected be fairly close to both 16-inch and 5-inch guns. The side plating of the senior staff officer's cabin and stateroom on the second super-

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structure deck best satisfied these conditions.

At the two locations instruments were installed on panels and adjacent stiffeners. Acceleration-time, and velocity-time records were obtained at both locations. In the stateroom strain-time and blast pressure-time records were obtained.

Typical values were:

1. Maximum velocity about 6-ft. per second.
2. Maximum acceleration about 800 g.
3. Maximum blast pressure 11 psi.

Damage was minor: the planking of a whaleboat amidships was sprung, the lens of a 26-inch searchlight next to the stack, and some electric light bulbs were broken.

There is still much to be done in developing instruments for shock investigations. Peak indicating accelerometers used on these tests were very rough indicators. Refinements are still needed in crystal accelerometer circuits to make them more stable and rugged. The British type of velocity meter needs a rigorous analysis to see how long it continues to represent velocity without excessive distortion. A good shock displacement gage is needed. If, equipment is to be improved to be operable as long as a vessel floats, and if ship structure is to become more resistant to damage, then investigational instruments must be developed that are rugged, have greater range and are simple. They should be built in sufficient quantities to allow adequate investigations to be made.

In spite of the scarcity of data available, enough records have been obtained to establish the characteristics of loadings imparted to ship structures, the characteristic structural motions, and transmission times through air and the structures.

The shipboard data, the analysis of simple structures, and the use of modern computing devices lead the way to rational shock protection. The motions, masses, and frequency characteristics of supporting structures, and the masses and frequency characteristics of equipment and elements of equipment should give information for the specification of equipment protection and for design of tougher ship structure. This information could be reduced to a few general approximate rules and to families of curves as a convenience to the designer. Further shipboard tests will be necessary to round out the data. From time to time additional analysis and tests will be needed for special structures. For most equipment a rationally designed shock test will still be the quickest way to make sure all components will perform satisfactorily.

The Model Basin takes this opportunity to thank the ships' officers on these trials for the wholehearted cooperation that enabled the Model Basin to obtain records successfully. It wishes too, to thank the many individuals who have contributed ideas and suggestions, particularly representatives of NRL and Code 660 of the Bureau of Ships.

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AIR-BLAST RESEARCH AT THE TAYLOR MODEL BASIN

H. L. Rich, TMB

Air blast measurements at TMB during the past several years, particularly on gun blasts, are surveyed. Data are presented on the magnitudes and durations of the pressure from various sizes of guns and on the effect of structures in modifying the characteristics of the blast.

The destructive effects on personnel and equipment of air blast from guns has been of concern to the armed services for many years. This concern is evidenced in the fact that today regulations for some classes of vessels limit the arcs and train and elevation of large caliber guns to prevent blast damage to personnel and shock damage to equipment. The extensive development of rockets and bombs, during the last war, has added the effect of air-blast leading from these two sources to the problems of the designer of service equipment and structures. The concurrent development of sensitive navigational and ordnance instruments has made the need for protection of equipment from air-blast effects more acute.

Destructive effects of air blasts are of two types. One type is the localized damage produced directly by the pressure pulse. Typical cases of this are the destruction of searchlight lenses, damage to ears of personnel, distortion of bulkheads and decks in the vicinity of guns, and the shredding of wing surfaces of airplanes near rockets. The second type of damage is that produced indirectly by the transmission of energy from the air blast through the ship's or plane's structure to equipment remote from the guns. It is this type of damage which is of primary concern to this group.

The design of structures to withstand the effects of air blast has been the

subject of research at the Taylor Model Basin since 1940. At that time, an investigation of the capacity of the flight deck and the airplane elevators of the U.S.S. SARATOGA to resist gun blast pressures produced by the firing of the ship's main battery, was undertaken. In the preparation for this test, it was soon realized that no adequate data on gun-blast pressures, nor suitable instruments for measuring it existed. The only gage available was the Williams' gage, a single-value-reading instrument used for determining the safe distance for personnel from guns. Although the readings from this gage were reasonably consistent, the gage did not read peak pressure. The purely empirical result obtained by its use was that a pressure of seven pounds per square inch, read on the gage, set the limit within which blast from a particular type of gun was dangerous to personnel. The data obtained by use of the gage had been almost entirely restricted to the establishment of seven-pound isobars for various guns. Although these data did not afford any direct indication of actual pressure in the blast field, they nevertheless constituted the only information available on the magnitude of the gun-blast load, and had been extensively used in connection with questions of damage to structures. In view of many uncertainties in the readings, because only a single parameter could be obtained, and the instrument could not be used in the vicinity of structures, a

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new gage was designed for the test. This instrument recorded electrically in permanent form the shape of the blast pressure curve as a function of time. In this and other early tests, a few of these electric gages were used to measure the entire pressure time history. A much larger number of Williams' gages were used in conjunction with them to measure the distribution of pressure at various positions. As the electric gage was further developed, it supplanted the Williams' gage at TMB.

The complicated pressure-time records and structural responses recorded on various early shipboard trials demonstrated the need for a systematic study of gun blast, particularly the effects on structures in the pressure field as well as the response of the structures to the blast loading. As a result of this need, an investigation was undertaken at the TMB Blast Range of the gun blast pressure produced in a free field as well as on simple structures. The structures used were oriented in various positions in the blast field to simulate shipboard structures and load pressures were measured with gages set flush in their surfaces. Efforts were made to determine the relative effect of angle of incidence of the blast load as well as the effect of structural pockets on the loads. One of the purposes of these tests was to compare the data obtained on the structures with the free space data and to attempt to determine a method of conversion between the two sets of data. This procedure, if successful, would lead by analysis of the free space data to some of the simple blast load criteria needed by design engineers. In these tests which were conducted with the cooperation of the Bureau of Standards at the TMB Blast Range, a 3 inch 50 caliber naval gun was used. Later, at the request of the Bureau of Aeronautics, similar tests were conducted with a 20 mm aircraft machine gun.

The first need in the investigation of gun blast was for a time recording instrument capable of recording the rapid transient shock pressure developed. None had existed prior to 1941 in this country, but the development of wire strain gages and electronic equipment, particularly the cathode ray oscillograph, furnished tools which had not been previously available, and a new instrument incorporating these tools was developed for the U.S.S. SATEATOCA trials. This gage, which is shown in Figure 1, has undergone considerable development since its use in that project, and a more recent model is shown here. The gage incorporates a thin circular 'Downmetal' diaphragm with a thick integral rim as the pressure sensitive element. A spirally wound wire resistance or metaelectric strain gage is cemented to the inside of the diaphragm. The compartment behind the diaphragm, containing the strain gage, is sealed at one atmosphere pressure. A positive pressure deflects the diaphragm inward, the tangential strain produced in the diaphragm is transmitted to the resistance wire and an increase in resistance results. The change in resistance of the metaelectric strain element which is one arm of a bridge circuit causes variations in voltage which are amplified and recorded on a cathode ray oscillograph.

With this instrument rapid transient pressures having durations of less than 150 milliseconds can be measured. However, this gage was also used for early measurement of rocket pressures although the duration of the pressure was found to be greater than 150 milliseconds. For these measurements a carrier system was employed with the gage to measure the low frequency components of the pressure and a second gage was used directly to record the high frequencies. In order to record the complete pressure-time curve produced by the firing of a rocket, the development of a new blast pressure instrument was

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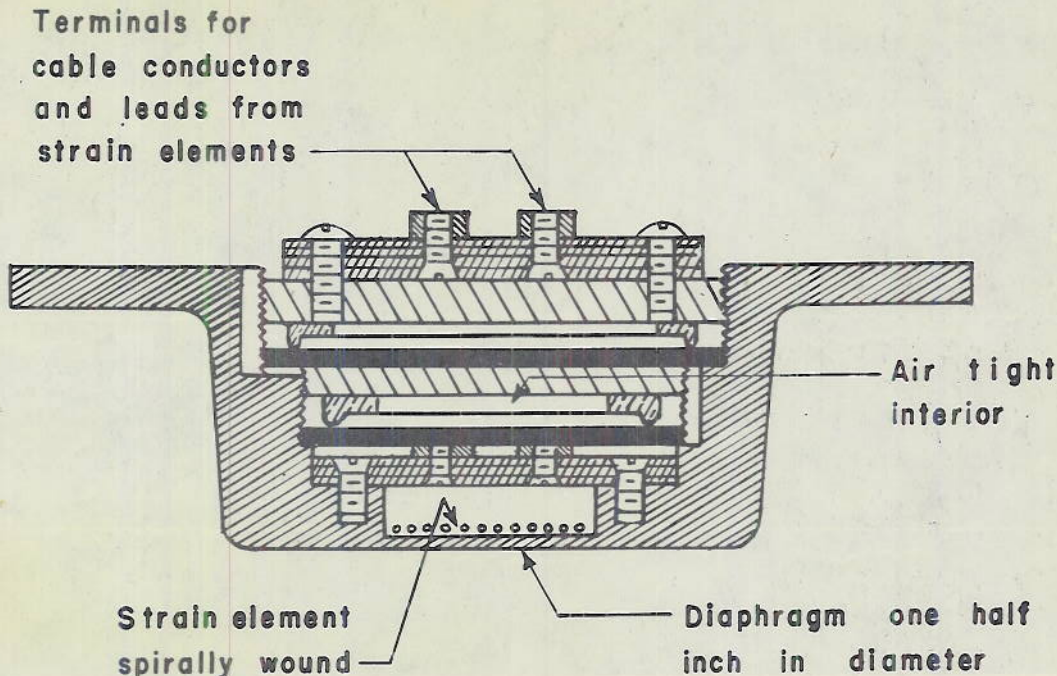


Figure 1. Cross-Sectional View of TMB Diaphragm Blast Gage

undertaken at the Basin. With this new instrument, frequency components from zero to 20,000 cycles per second may be measured, and in addition it is expected that the equipment will be suited for mobile use in small airplanes. The new gage is of the capacity type, and is used in conjunction with a one-half megacycle carrier system.

Typical pressure records on a time base made at the Taylor Model Basin Blast Range with a 3 inch 50 caliber gun are shown in Figure 2. The records from two gages at different distances from the gun are shown.

The gun blast pressure at the left side of each record is characterized by an impulsive rise in pressure followed by an exponential decay. This positive phase is followed by a rarefaction or negative pressure phase. For this gun the duration of the positive pressure is approximately one millisecond.

From the distance on the record between the arrival of the pressure pulse

at the two locations the time of transit of the pressure wave may be computed. From the time and distance, the average velocity of the wave and its average pressure is computed independently as a check on the actual gage readings.

As the first step in the study of gun blast at the Model Basin Blast Range, a survey was made of the free-field pressure from a 3 inch 50 caliber naval gun.

For these measurements each gage was oriented edge on to the blast wave which travelled parallel with the gage face. The resulting contours of constant pressure around the gun are shown in Figure 3. These curves may be roughly approximated by a series of progressively larger circles whose center moves out along the line of fire. The resulting pressures are therefore a maximum at a position in front of the gun and much lower at positions behind the muzzle. In preparing this survey, a natural question arose as to whether gun blast pressure distributions may be scaled dimensionally

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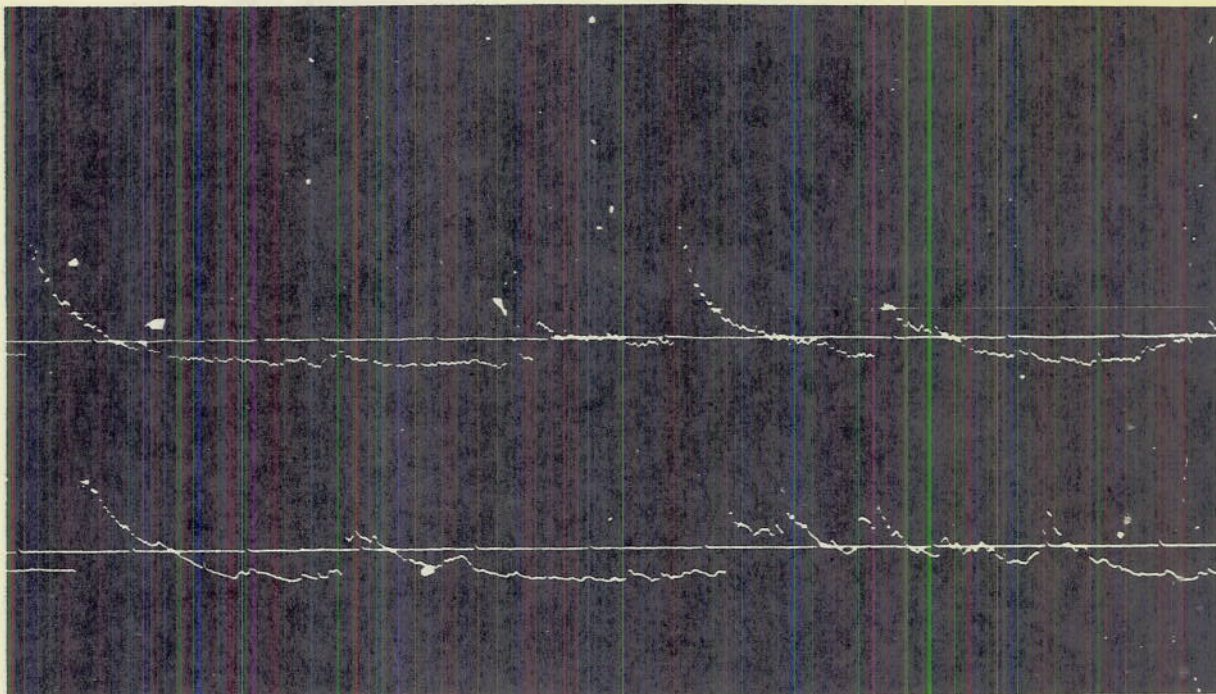


Figure 2. Typical Gun Blast Pressure Records From 3-Inch/50-Caliber Gun

from one gun to another. If this were possible, peak pressure contours determined experimentally from one gun would be sufficient for deducing the pressures for other guns. Assuming geometrically similar guns and ammunition, and the same propellant, the theory of similitude states that at the same relative position in calibers from different guns the peak pressures are equal. The distance in calibers is a nondimensional unit defined here as the actual distance divided by the bore diameter. In this figure the isobaric curves are plotted as a function of these units.

To find the pressure at a particular point in the blast field of the gun, divide both the distance of that point along the line of fire from the muzzle, and the distance from the point at right angles to the line of fire, by the diameter of the bore of the gun. The dimensions are now in calibers and the pressure is then read directly from the curves. An experimental check of the scaling was made at the Naval Proving Ground at

Dahlgren. Pressure-time measurements were made on 3, 5, 6, 8, 14, and 16 inch guns. These measurements show that a mean deviation of 25 percent exists when the pressure is read from this chart for guns

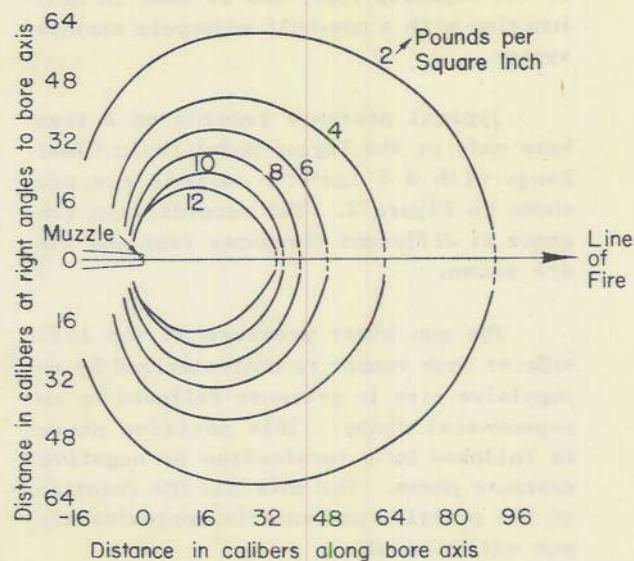


Figure 3. Free-Field Isobars Around a Gun

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other than the 3 inch 50 caliber. This may be partly due to the fact that the length of the barrel was neglected as a factor in the scaling. However, for most practical problems approximations of this order of magnitude are quite satisfactory. A comparison of a similar set of contours plotted from observations of pressure from a 20 mm machine gun with these show that in general the pressures for the 20 mm gun are lower at corresponding positions by about 35 percent. This may be due to the greater caliber length of the 20 mm gun.

In Figure 4 the positive impulse contours from the 3 inch 50 caliber gun are plotted on nondimensional distance coordinates. These data are obtained by integrating the area of the positive pressure under each pressure-time curve. The theory of similitude indicates that at the same relative position in calibers from different guns, the positive duration of the pressure and the impulse varies as the ratio of the bore diameters. Consequently, a plot of isoimpulse contours will be the same for all guns if the impulse divided by the bore diameter is plotted as it is here against distance in calibers. The experimental check on these curves made on other sizes of guns at Dahlgren show that for the positive impulse measurements the mean deviation from these curves for larger guns is 13 percent. For the 20 mm machine gun the deviation is somewhat larger, the impulse being smaller than expected from these curves.

A complicating factor which frequently appears during the measurement of gun blast pressures is the flash pressure. This pressure is the result of after burning of unburned particles of the propellant which are expelled from the gun. The flash pressure occurs at random and is generally localized. It is seen on the two typical gun blast records on Figure 2. On the upper record the flash pressure at the right is greater than the gun blast pressure, while on the lower record, at a

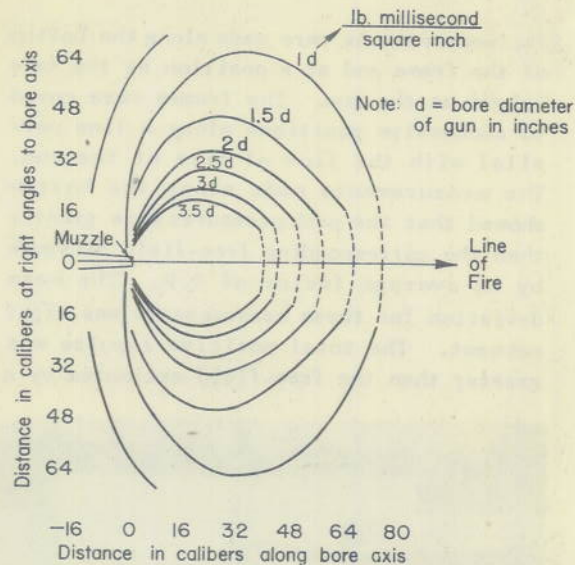


Figure 4. Free-Field Isoimpulse Contours Around a Gun

greater distance from the muzzle, it is smaller. On these two records, we also see the pressure produced at the gage by the pulses reflected from the ground. Both the gun blast pressure and the flash pressure are reflected.

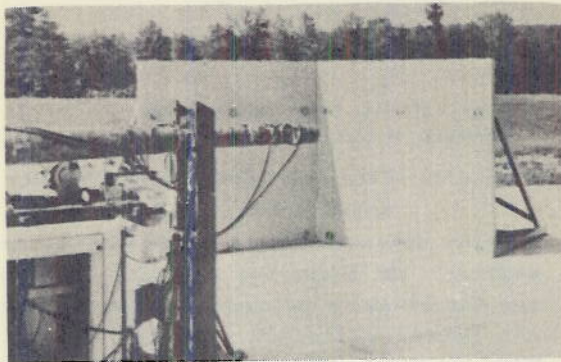
In conducting investigations of blast pressure acting on large flat surfaces, several types of frames were used. In Figure 5, two types of test frames for measurements from the three inch gun are shown. The blast gages are inserted in each frame and adjusted so that their sensitive surfaces are flush with the panel. Simultaneous pressure-time records are taken, the signals being recorded in the instrument house behind the gun. Figures 5a and 5c show arrangements for pocket tests simulating similar arrangements of bulkheads and decks. Under these conditions, the incident pressure pulse is reflected from several surfaces, including the ground in Figure 5a with a resulting multiplication in pressure. A considerable collection of data have been obtained and are being analyzed.

For the reflection tests using two six-foot by six-foot frames shown in Figure

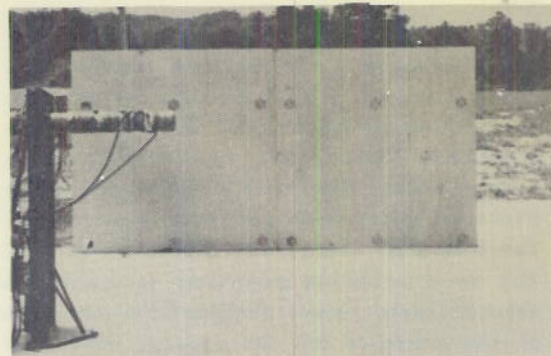
5b, measurements were made along the bottom of the frame and at a position at the same height as the gun. The frames were moved to successive positions along a line parallel with the line of fire of the gun. The measurements made along the bottom showed that the peak pressures were greater than the corresponding free-field pressure by an average factor of 4.9. The mean deviation for these measurements was eight percent. The total positive impulse was greater than the free-field estimates by a

factor of six, with a mean deviation of 14 percent. The records indicate that the gages were in the Mach region, which together with effects due to flash and reflection gives a satisfactory explanation for the abnormal increases.

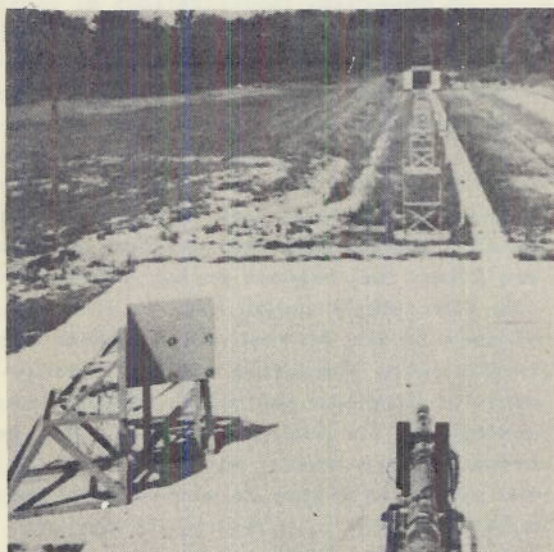
A summary of the data for the upper gages in the six-foot frames and for other reflection tests in which only the effect of a single reflection was evident yielded the following information: For angles of



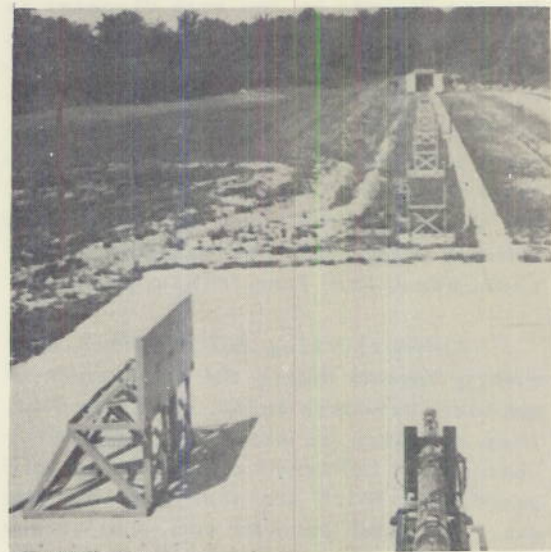
a - Pocket Test of 6'x6' Frame



b - Reflection Test of 6'x6' Frame



c - Pocket Test of 3'x3' Frame



d - Reflection Test of 3'x3' Frame

Figure 5. Typical Test Arrangements for Blast Measurement, 3-Inch Gun

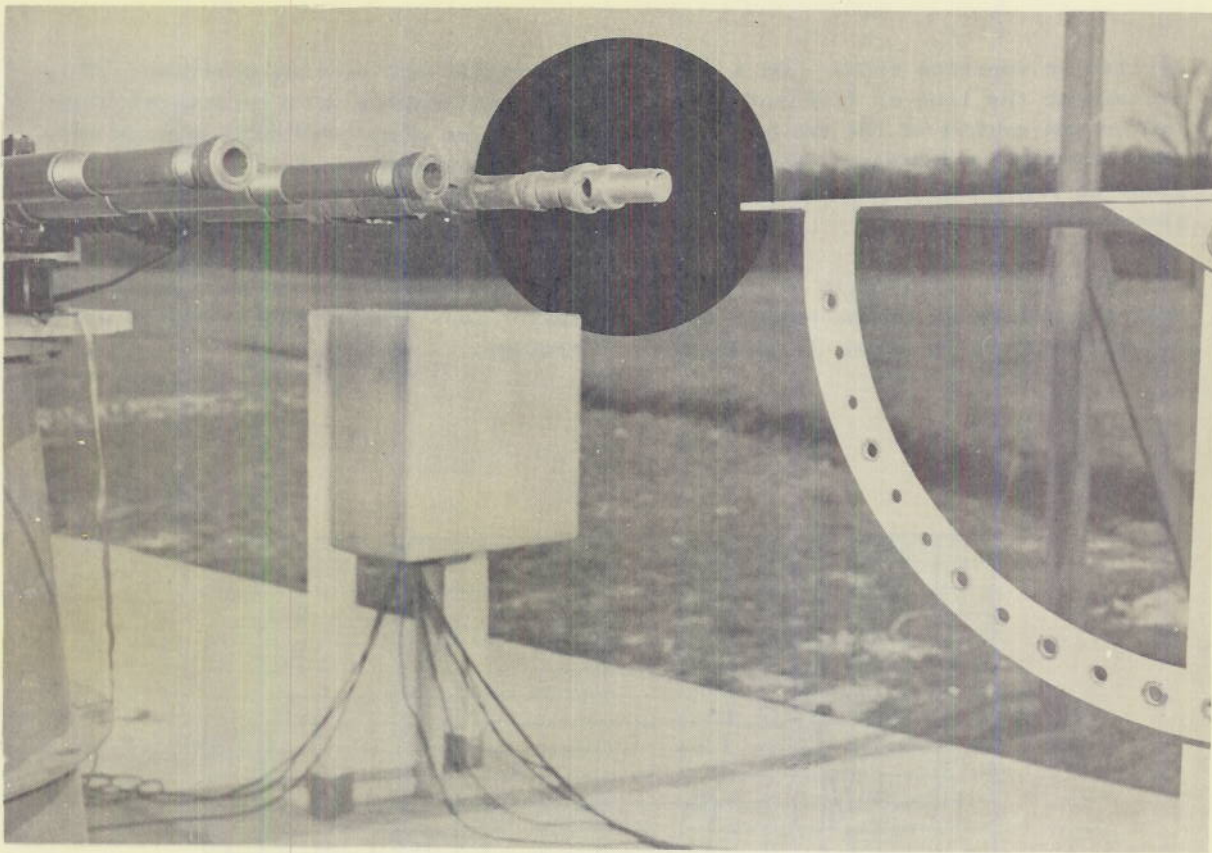


Figure 6. Simple Blast Deflector Installed on 20MM Gun

incidence of the blast wave between 0 degrees, normal incidence, and 75 degrees, approaching the glancing incidence, the ratio of the pressure measured on the structure to the corresponding free-field pressure varied from 1.5 to 3. The increase in pressure at the reflecting surface is the result of several factors. Some of the gage positions were in the Mach region and the increase in pressure at a reflecting surface is a function of the magnitude of the incident pressure. For example, for free-field pressures of one or two pounds per square inch, the pressure on the structure is doubled, while for a free-field pressure of 30 pounds per square inch the pressure on a structure normal to the wave front is more than tripled.

At the present time plans are being made for correlated blast pressure and

structural motion studies of test structures in the blast pressure field of a 5 inch 38 caliber gun at the Taylor Model Basin Blast Range. These tests will be an extension of a few similar measurements made during the structural firing trials on the U.S.S. MISSOURI.

In closing, I would like to present a novel method of coping with the gun blast problems, which is worthy of attention. This method involves the use of blast tubes or deflectors. In these devices, the gas pressure behind the shell in the barrel is vented in directions where minimum damage may be produced.

A very simple form of blast tube (Figure 6) was tried in conjunction with the 20 mm gun blast program at the Basin. The deflector is in effect an extension of the barrel of the gun and has vent holes

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drilled in opposite sides. On a plane containing the line of fire and a line joining the centers of the two holes, the blast pressure is increased; while on the plane at right angles to the first, the pressure is reduced.

In Figure 7 the ratio of pressure near the deflector to the normal free-field pressure is shown in both the

protective and venting position. This method of coping with structural blast problems on planes and ships shows promise of limited usefulness.

A considerable body of additional information concerning blast pressures on structures will be embodied in several Taylor Model Basin reports now in preparation.

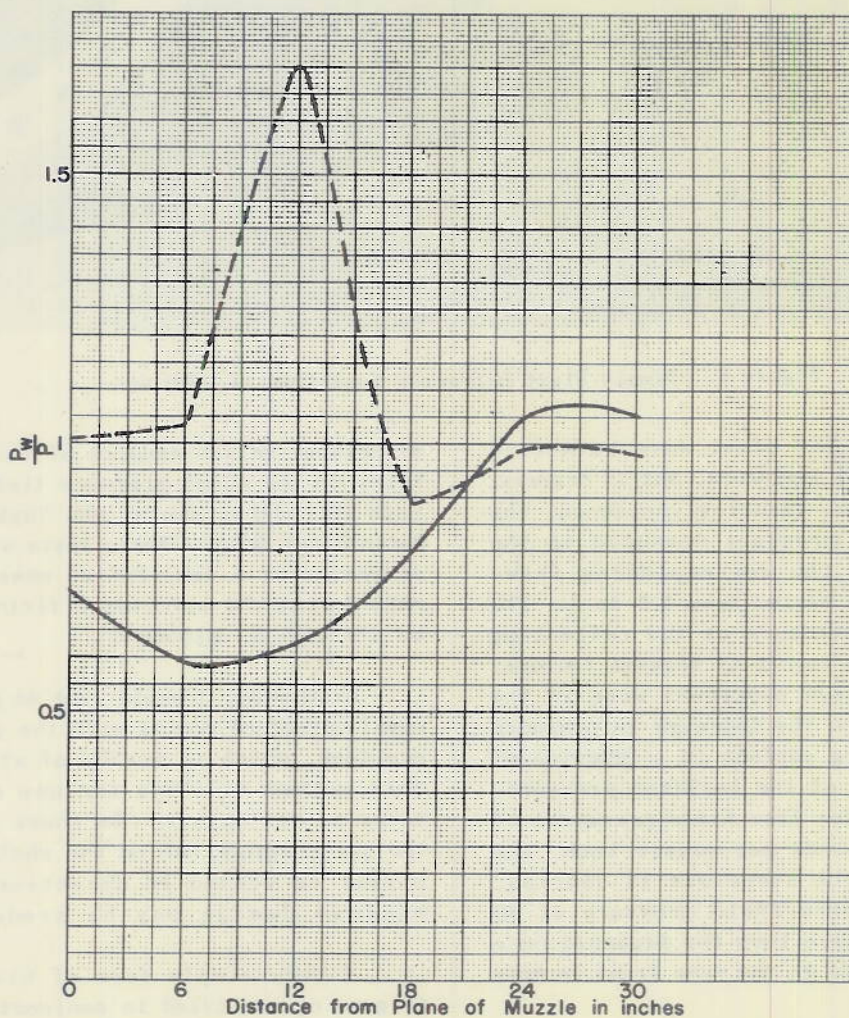


Figure 7. Effect on Gun Blast Pressure Distribution of Simple Blast Deflector

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DISCUSSION

MR. GOLDBERG, BUORD, asked what the effect the ground had on the gun blast measurements.

MR. H. L. RICH, TMB, replied that for the free-field measurements the height of the muzzle and of each gage from the ground was kept at five feet. At this height, reflections of the gun blast wave from the ground did not arrive at any gage position until after the complete positive pressure pulse had been passed.

For the measurement of pressure on structures, the ground was made use of as an additional reflecting surface. In some cases, where only the effect of a single reflector was desired, the structure in which the gages were set was placed horizontally on the ground instead of vertically (See Figure 5).

COMDR. D. W. MALIM, British Admiralty Delegation.

The statement was made by Mr. Rich that the personnel blast curve was assumed to be seven pounds per square inch measured by a Williams gage.

In England, the personnel blast curves for various gun calibers have been drawn up by means of a human "guinea pig" because the Williams gage was found to give not only an exaggerated measure of peak pressure but also because its percentage of "inaccuracy" varied widely with the size of gun under test. Years of experience led this human "guinea pig", an ex-naval officer, to state categorically that the maximum air blast pressure to which personnel can be exposed and continue to perform their fighting function is two and one-half pounds per square inch. Isobars at this pressure level have therefore been drawn up for all guns in the Naval Service, the higher pressure curves necessary for structural considera-

tions are being worked out by an empirical formula.

Although two and one-half pounds per square inch has come to be accepted as the personnel limit, the evidence that this was indeed the true value of the pressure was scanty, with the result that the "guinea pig's" increasing years, combined with the scepticism of youth and improved recording techniques led to the development of a piezoelectric recorder. Trials with this recorder showed that the two and one-half pounds per square inch curves deduced from human reactions approximated closely to the piezoelectric curve. However, they deviated consistently on certain azimuthal bearings from the muzzle, for reasons which have not been explained.

German work on the effect of air blast on personnel seconded by the opinion of physiologists in England indicate that peak pressure alone is not the only harmful factor to personnel in air blast. Investigation into this is clearly an urgent requirement in view of the advent of rocket missiles. The whole problem is now to be investigated in England by a combined team of physicists and doctors.

It is understood that the variables inherent in air blast which must be considered include:

- (1) Peak pressure of the wave or waves.
- (2) Velocity of the waves in air.
- (3) Rate of build up and decay of the waves.
- (4) The "mass" effect of the waves.

Presented with such data from guns and rockets of varying sizes it is then necessary for the medical profession to evaluate each item in terms of its relative harmfulness to personnel and to produce a family of curves relating each item with its potential destructiveness.

It would seem then essential for the United States and United Kingdom to try and employ agreed standard methods of measurement. This will involve a survey of existing techniques and the probable development of new and improved methods of instrumentation. Co-operation in obtaining the mass of data and its interpretation would also seem highly desirable.

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OBSERVATIONS OF DAMAGE FROM UNDERWATER EXPLOSIONS

C. T. Johnson, TMB

Experimental data concerning damage to simple structures attacked by underwater explosions are discussed. Under certain conditions damage caused by the pulsation of the gas globe may exceed that caused by the initial shock wave. A description is given of the variation in magnitude of the pressure pulses accompanying the gas globe pulsation from charges fired at different depths beneath the surface, in open water.

When an explosive charge is detonated under water, a volume of highly compressed gaseous explosion products is formed and a shock wave of pressure is emitted. About one-fourth of the energy of detonation of the explosive is transmitted in the shock wave, another fourth may be absorbed in the water, and the remaining half of the energy is in the gas globe, from which it is eventually lost in several ways. The gas globe will experience a series of expansions and recompressions, emitting a pulse of pressure each time its size reaches a minimum. In general, the gas globe will also move bodily while pulsating.¹

Figure 1 shows the variation with time of the diameter of the gas globe from a small charge as measured from high speed photographs.² Because of carbon streaks left in the water as the gas globe collapsed, the minima could not be measured accurately. The solid curve is the result of the measurements, but the dashed curve is probably more like the true course of events. The lengths of the periods are not equal, but decrease progressively. The amplitude of the oscillations decreases also, the maxima becoming

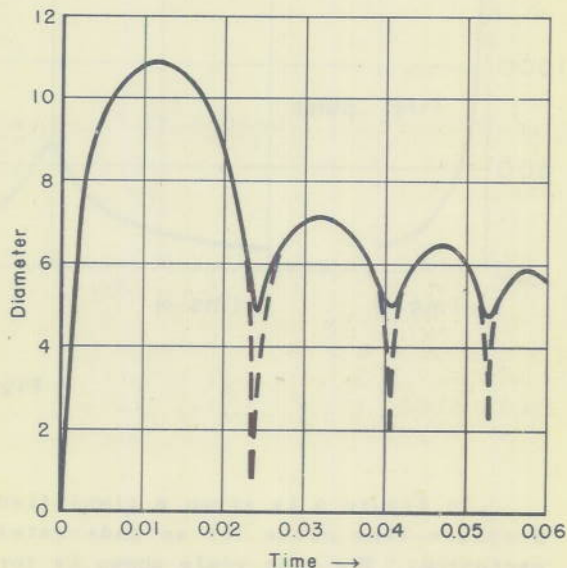


Diagram showing variation of gas globe diameter with time.

Figure 1

smaller and the minima larger. These effects accompany the loss of energy which the gas globe undergoes, such as in the pulses of pressure emitted each time the globe reaches a minimum.

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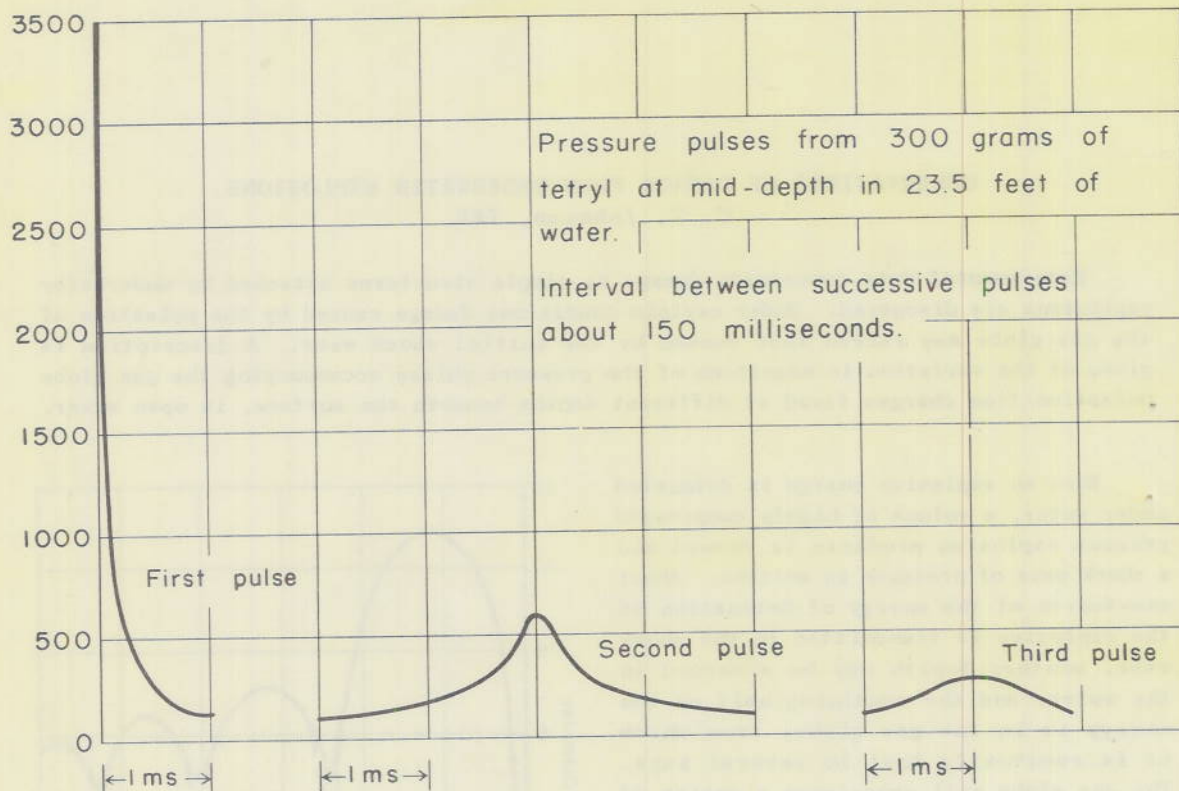


Figure 2

In Figure 2 is given a simplified pressure-time curve for an underwater explosion. The time scale shown is for a 300-gm charge, in which the interval between the successive pulses is about 150 milliseconds. Notice that the shock wave's pressure is high and the duration is short, and that the second pulse, although of pressure amplitude only about one-tenth that of the shock wave, has a much longer duration, with the result that its impulse is approximately equal to that in the shock wave.

For a 300-pound depth charge, the interval between the pulses is about two-thirds of a second, approximating the natural frequency of vertical flexural vibration of some ships. The amplitude of the initial pulse at a distance of 50

feet from a 300-pound charge is about 2100 pounds per square inch.

At this point it is probably well to define a few terms which are used in discussions of gas globe phenomena. The intervals of time between successive minima in the size of the globe are spoken of as the periods of pulsation. Thus we have first, second, and succeeding periods. There are different ways of designating the various pressure pulses; I shall adopt the convention that the initial shock wave is the "first pulse"; the pulse occurring at the first recompression is the "second pulse" and so on. The third and later pulses are like the second, only weaker, and phenomena of the second pulse may occur on a smaller scale with the later pulses.

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The pressure pulses which are emitted at the instant of detonation and at each subsequent minimum in the size of the gas globe travel outward in the water with continually decreasing amplitude, delivering energy to any structures they meet. The initial shock wave has been the subject of much study^{3,4,5,6,7,8}, but the secondary pulses were, until lately, rather overlooked as factors to be considered so far as damage to ship structures goes. Within the past six years, however, photographic cameras and techniques have been developed which make it possible to obtain photographic records of the progress of damage to simple structures attacked by underwater explosions. These records have shown that the amount of damage from the pressure pulses accompanying the gas globe oscillation may, under certain conditions, be considerable.

Before considering damage tests, however, let us turn our attention to the gas globe and the second pulse of pressure at different depths in open water. The behavior of the gas globe can perhaps be most easily explained by referring to ex-

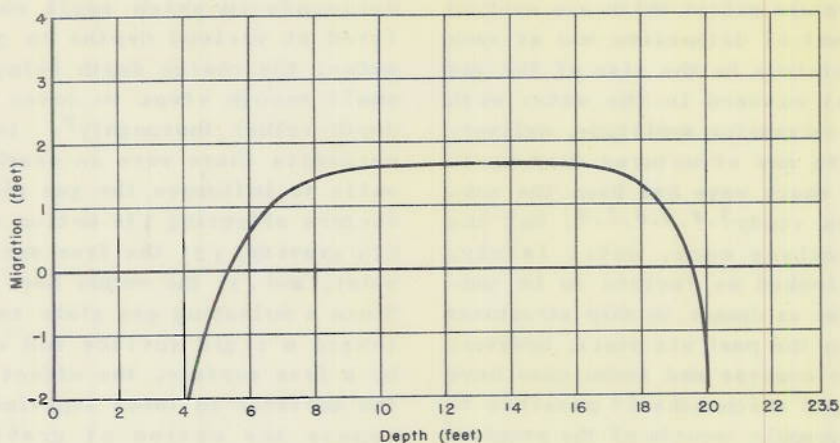
periments in which small charges were fired at various depths in 23½ feet of water, the charge depth being varied in small enough steps to cover the entire depth rather thoroughly⁹. In these experiments there were no nearby vertical walls to influence the gas globe, so the factors affecting its motion were three: (1) gravity, (2) the free surface of the water, and (3) the rather hard sea bottom. Since a pulsating gas globe tends to move toward a rigid surface and is repelled by a free surface, the effect of each of the surfaces in these experiments was to oppose the action of gravity on the globe¹. Measurements were made of the migrations of the gas globe and of the pressure-time-curves from the globe-oscillation pulses.

Figure 3 shows the amount of migration during the first period for a charge equivalent to about 300 grams of TNT. We see that over a range of depths around mid-depth, the gas globe rises somewhat during the first period, whereas near the surface or near the bottom the gas globe migrates downward. This is explained by

3. H. W. Hilliar, "Experiments on the Pressure Wave Thrown out by Submarine Explosions". Research Experiment 142/19, 1919, Confidential.
4. "Summary of Piezo Gauge Results on Large Charges: Peak Pressures, Momenta, and Pressure-Time Curves", pp. 3-13, UE-16, Interim Report of Division 8 of NDRC, Nov. 15, 1943 to Dec. 15, 1943, Confidential.
5. John G. Kirkwood and Stuart R. Brinkley, Jr., "Theory of the Propagation of Shock Waves from Explosive Sources in Air and Water". NDRC Report No. A-318, OSRD No. 4814, March 1945.
6. J. S. Coles, E. A. Christian, J. P. Slifco, C. R. Niffenegger, and M. A. Rogers, "Shock Wave Parameters from Spherical HBX and TNT Charges Detonated Under Water". NAVORD Confidential Report 103-46, 6 December 1946.
7. A. B. Arons and P. F. Smith, "The Measurement of Small-Charge Shock-Wave Parameters with UERL Type B Underwater Gauges". NAVORD Confidential Report 104-46, 24 December 1946.
8. A. B. Arons, A. Borden, and B. Stiller, "Measurement of Bubble Pulse Phenomena: II. Small Charges". NDRC Report No. A-470, OSRD No. 6578, Confidential, March 15, 1946.
9. M. Shiffman and B. Friedman, "Studies on the Gas Bubble Resulting from Underwater Explosions. On the Best Location of a Mine near the Sea Bed". AMP Report 37.1R, AMG-NYU No. 49, May 1944.

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Displacement of bubble center from initial charge level at the first minimum vs. depth; about 300 grams of TNT.

Figure 3

the fact that near mid-depth the water surface and the bottom are rather remote and so the buoying effect of gravity predominates and the gas globe rises. Near the water surface the repulsion of the bubble by the free surface overcomes the gravity effect and near the bottom the attraction of the bottom overcomes it, in both of which cases the globe migrates downward. Separating the three regions are two depths at which the various effects are balanced, so that the gas globe does not migrate at all during the first period. Since migration of the globe entails a loss of energy to the water, the second pulse of pressure shows a maximum of amplitude at each of the two depths where the gas globe migration during the first period is zero⁹.

The sharpness of the effects of migration is observable only for small charges. According to theory, there should be no upper rest position for charges over one pound¹. Although this has not been tested experimentally for

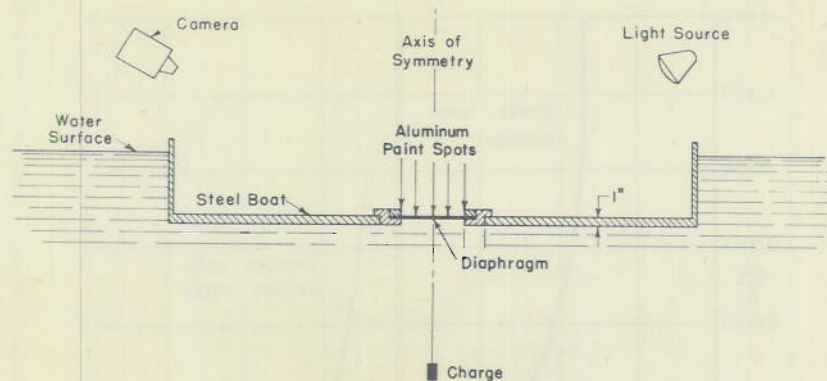
1-pound charges, it is known that for 300-pound charges there is no upper rest position¹⁰. Near the bottom, the non-rigidity of ocean bottoms when attacked by large charges prohibits any sharply defined lower rest point, but the data so far obtained by the Woods Hole group indicate that there may be a range of distances in which the migration is nearly zero. Furthermore, gas-globe effects do not scale as other effects do¹, so that small scale experiments must be considered as giving only qualitative indications of what happens on full scale.

Let us turn our attention from open water experiments, and consider a few damage experiments, keeping in mind the fact that they are necessarily more qualitative than quantitative.

In a set of experiments performed at the David Taylor Model Basin, small charges of tetryl were fired at a series of distances beneath a thin circular steel diaphragm mounted horizontally at

10. C. P. Slichter, W. G. Schneider, and R. H. Cole, "Measurement of Bubble Pulse Phenomena: I. Mark 6 Depth Charges, TNT Loaded". NDRC Confidential Report No. A-364, OSRD Report No. 6242, 16 September 1946.

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SCHEMATIC DIAGRAM OF UNDERWATER EXPLOSION APPARATUS ARRANGED FOR STREAK PHOTOGRAPHY

Figure 4

the center of a flat-bottomed steel boat^{11,12,13}, as shown in Figure 4.

The upper surface of the diaphragm was painted black with a row of aluminum paint spots across a diameter. Light from a spotlight was reflected from the spots into a camera which recorded their motion as the diaphragm deflected.

Although these experiments are not very similar to mine or torpedo attacks on ships, they are instructive in showing what effects can occur. Knowing what effects are possible, experiments can be designed to determine to just what extent they actually do occur on full scale.

In these experiments, the charge was located beneath the center of the diaphragm at distances of from 5 to 32 inches. For charge distances greater than 18 inches the diaphragms were deformed, but not

ruptured. Although rupture occurred whenever the charge distance was 18 inches or less, the shock wave itself was not sufficient to cause rupture until the charge distance was reduced from 18 inches to only 5 inches. For all the shots at distances of 6 to 18 inches, it was the second pulse that finally caused the break-through. If the charge was between 20 and 24 inches distant, even the third pulse caused measurable damage, but it was never observed to cause rupture.

In Figure 5 is shown the ratio of the increase in area of the diaphragm to the original area plotted against charge distance. The increase in area of the diaphragm caused by the shock wave was measured and was found to be proportional to the solid angle subtended by the diaphragm at the charge. The damage done by the second pulse could also be measured in some instances. This damage, however, was

11. G. E. Hudson and C. T. Johnson, "Analysis of Damage to 10-inch Circular Steel Diaphragms from Underwater Explosions of Tetryl". TMB Confidential Report 552, in preparation.
12. G. E. Hudson, "Early and Ultimate Damage due to Underwater Explosions against 10-inch Diaphragms". TMB Report 509, August 1943.
13. G. E. Hudson, "Progress Report on Underwater Explosion Research - Bureau of Ships Symbol E139 - Part 13 - Time-Displacement Studies of Diaphragms Deformed by Explosive Loading". TMB Report R-248, May 1944.

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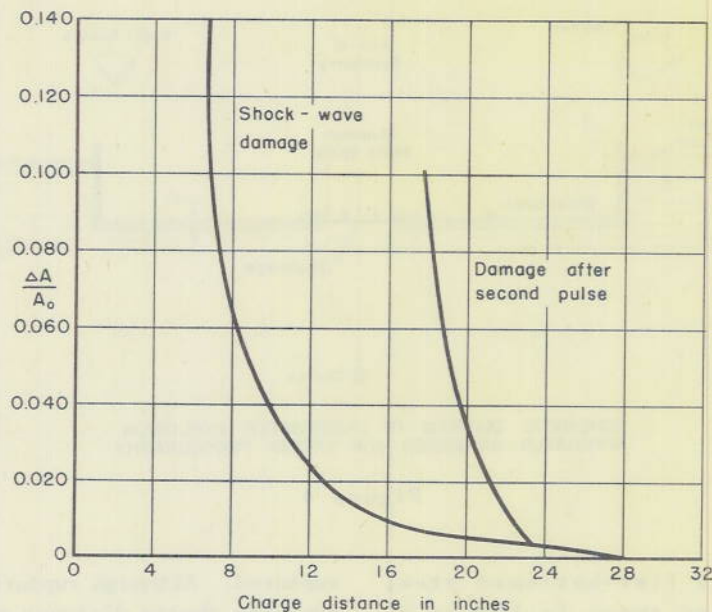


Figure 5

found to be negligible at charge distances greater than 24 inches. With decreasing charge distances, the second pulse damage increased very rapidly, becoming large enough to rupture the diaphragm when the charge distance was 18 inches.

The explanation for the abrupt change in the amount of damage from the second pulse is probably to be found in the effect of the boat on the migration of the gas globe. The boat used in these tests would probably appear as a rigid surface to the gas globe, which would therefore tend to move toward it. For small charges, at least, the amount of migration of a gas globe toward a rigid surface varies rapidly with the distance, however, being greatest when the charge is slightly more than one maximum gas-globe radius from the surface². The maximum radius of the gas globe in these tests was about 18 inches. Consequently, it can be supposed that at charge distances greater than about 24

inches the gas globe migrates very little during its first oscillation, so that when the second pulse is emitted the gas globe is at almost the same distance from the diaphragm that the charge was initially. For distances somewhat smaller, the second pulse is emitted by a gas globe which has migrated so that it is much closer to the diaphragm than was the charge, with a consequent increase in the pulse's damaging power.

This same boat has also been used more recently in some model-scale shock tests in which small charges set off in water gave shock excitation to equipment mounted on the boat.

These tests are described in TMB Report R-342 by H. L. Rich and S. Fifer¹⁴. In another series of experiments, carried out by the Underwater Explosives Research Laboratory of the Woods Hole Oceanographic Institution, a series of watertight

14. H. L. Rich and S. Fifer, "Reproduction in Models of Explosive Shock in Ships". TMB Confidential Report R-342, in preparation.

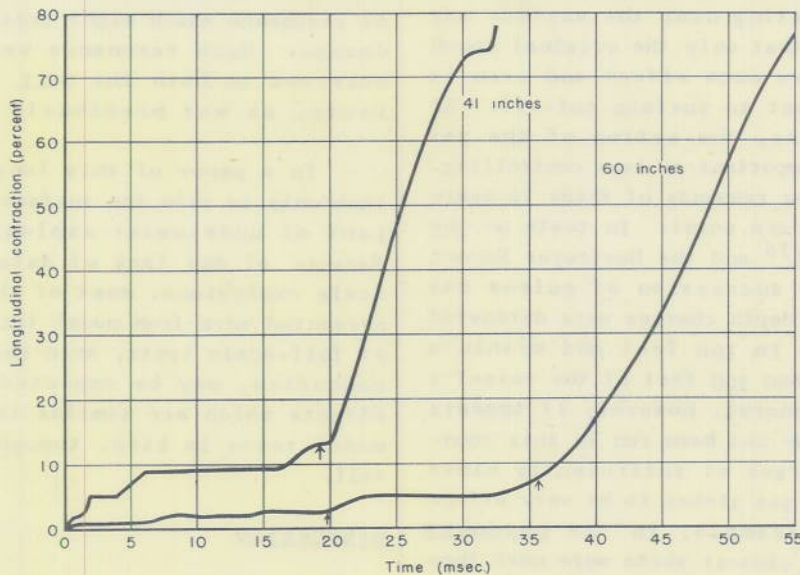
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cylinders, scale models of a portion of a submarine's pressure hull, were attacked by charges exploded near them in water at depths as great as 700 feet¹⁵. Moving-picture records were made of the progress of damage to the cylinders. Except for shots fairly near the water surface, damage caused shortening of the cylinders and the progress of the shortening could be measured on the films. When this shortening is plotted against time, it is apparent that there is often a period of stability when no shortening takes place, after the shock-wave damage is done.

that the second pulse "tipped the scales" and precipitated the failure.

Figure 6 shows two of the damage-vs-time curves for the cylinders. The left-hand curve shows final collapse caused by the second pulse, the arrival of which is marked by the arrow. The right-hand curve shows a second stable period after the second pulse; collapse did not occur until after the arrival of the third pulse.

The foregoing has considered only small-scale experiments. Tests made by



Longitudinal contraction vs. time at about 480 feet depth.

Figure 6

Later, at a time coinciding with the arrival of the gas globe's recompression pulse, the damage is increased, in some cases many-fold over the amount of shock-wave damage. In these tests, the gas globe migration was usually small, and the second pulse was able to increase the damage so greatly only because the shock wave had damaged the targets to a point such

the Woods Hole group using 290-pound depth charges show that the gas-globe phenomena observed on small scale are also observed in modified form on full scale¹¹. Gas globe motion in model tests does not scale as do other quantities; on full scale the gas globe migration is quite large and rapid, imparting a large amount of momentum to the water. However, the general

15. J. C. Decius and G. Gever, "Damage to Thin-Steel Cylindrical Shells by Under-water Explosions II". NAVORD Confidential Report No. 106-46, 21 November 1946.

nature of the phenomena should be similar to those occurring on model scale. It will be of interest, therefore, to consider the implications of the model scale results with regard to what may be expected on full scale from underwater explosions.

It appears from the foregoing that a ship subjected to attack from a near miss may experience a sequence of pressure pulses -- the shock wave, followed after some time separation by loads due to the gas globe. What happens in practice will depend on the depth of the charge. A charge detonating near the surface may blow out, so that only the original shock wave will have much effect and even it will be subject to surface cut-off. At greater depths, the action of the gas globe may be important or even controlling. Data giving the response of ships to near-by explosions are scant. In tests on the Destroyer BELL¹⁶ and the Destroyer Escort HOPPING¹⁷, a succession of pulses was observed when depth charges were detonated at depths up to 100 feet and within a little more than 100 feet of the vessel's stern. In general, however, it appears that tests have not been run in this country with charges at sufficiently close distances for gas globes to be very effective. For example, in the DRAGONET tests¹⁸, the closest shots were more than three gas-globe radii distant from the ship. Data are needed relating the response of a ship to loads for charges at fairly short distances. For most shock studies, on the other hand, the distance should not be so short that major structural damage occurs. Judging from model tests, the range of charge distances over which the damage changes from superficial to major may be rather small.

If a charge were to be detonated some distance beneath a ship and the gas globe were to rise to the ship's bottom just at the globe's instant of recompression, the mass motion of the water might be great enough to cause damage to the ship. Apart from the water's motion, however, a gas globe which at its first recompression is near a ship's bottom will certainly do considerable damage. The periods of oscillation of a full scale charge are of the order of two-thirds of a second. This is comparable with the period of a ship in vertical flexural vibration, so that there is the possibility of resonance which might greatly increase damage. Such resonance was, in fact, observed in both the BELL and HOPPING tests, as was previously mentioned.

In a paper of this length there is time only to skim the surface of the subject of underwater explosion damage. Because of the lack of data from full-scale explosions, most of the data here presented were from model tests. Results of full-scale tests, when such tests are conducted, may be expected to exhibit effects which are similar to those from model tests in kind, though not in detail.

DISCUSSION

Mr. N. H. Jasper of the Taylor Model Basin asked, "Why does the gas globe move toward a rigid surface and away from a free surface?"

Answer

Consider the case of a gas globe near a rigid wall. When the pressure in the gas globe is greater than the hydrostatic

16. H. R. Thomas and J. S. Parkinson, "Depth Charge Structural Firing Tests on the Destroyer BELL (DD 587)". TMB Confidential Report R-156, July 1943.

17. H. R. Thomas and J. S. Parkinson, "Structural Firing Tests with Depth Charges on the Destroyer Escort HOPPING (DE 155)". TMB Confidential Report R-185, November 1943.

18. H. L. Rich, "Shock Measurements during Depth-Charge Tests on the USS DRAGONET (SS-293)". TMB Confidential Report R-283, April 1945.

head at that depth, the pressure in the water is increased, the increase in pressure being greatest between the gas globe and the wall because the water flow which would lessen the pressure there is most obstructed. This inequality of pressure tends to cause the globe to move away from the wall. When the pressure in the gas globe is less than the hydrostatic pressure, the pressure in the water is decreased, and the decrease is greatest between the globe and the wall because the inflow to relieve the pressure decrease is least. Consequently, the gas globe is pushed toward the wall during this phase of the globe's cycle. The action during the low-pressure phase predominates both because that phase is of longer duration and because the pressure difference has a greater effect on a large globe than on a small one. After

the first short phase of motion away from the wall, the distribution of momentum in the water will always be such that the globe will move toward the wall, the momentum increasing during each low-pressure phase and losing only a little during each compression phase.

In the case of a free surface, pressure-relieving flow can occur at that surface very easily, so that instead of the pressure variation being greatest there, as in the case of the rigid wall, the variation is least between the globe and the surface. Therefore, during the expansion phase -- the predominant one -- the pressure decrease is greatest on the side of the globe away from the free surface, with the result that the gas globe moves away from the surface.

SHOCK DAMAGE TO A SYSTEM WITH A SINGLE DEGREE OF FREEDOM

J. W. Wrench, Jr., TMB

The response of a system with a single degree of freedom under representative shock loads is presented graphically. Factors entering into the failure of simple systems under such loading are discussed. Correlation of theoretical and experimental results is made in the case of one such system.

In the following discussion we shall be concerned with the examination of the response of a system with a single degree of freedom to representative shock loads. The factors contributing to the failure of simple elastic systems under such loading will be considered, and in a particular case, correlation of theoretical and experimental results will be made. The analysis will be based largely on material abstracted from the first two references in the bibliography.

We shall consider the mass-plug accelerometer as a representative system possessing a single degree of freedom. This type of accelerometer and the equivalent mass-spring system are shown schematically in Figure 1. The theory of opera-

tion assumes that when the instrument is subjected to acceleration in the direction of its longitudinal axis, the mass exerts a force on the plug proportional to the acceleration. Hence, breakage of the plug at the neck indicates the lower limit of the acceleration. Consequently, the acceleration to be measured must be bracketed by two or more gages to yield an estimate of its magnitude.

Mr. Drewry M. Smith of the Taylor Model Basin Staff, author of TMB Report R-267 entitled "Experimental and Theoretical Investigations of the Mass-Plug Accelerometer" has described the results of a series of tests involving accelerometers mounted on the hull of a 20-foot wooden model of a destroyer-escort. This

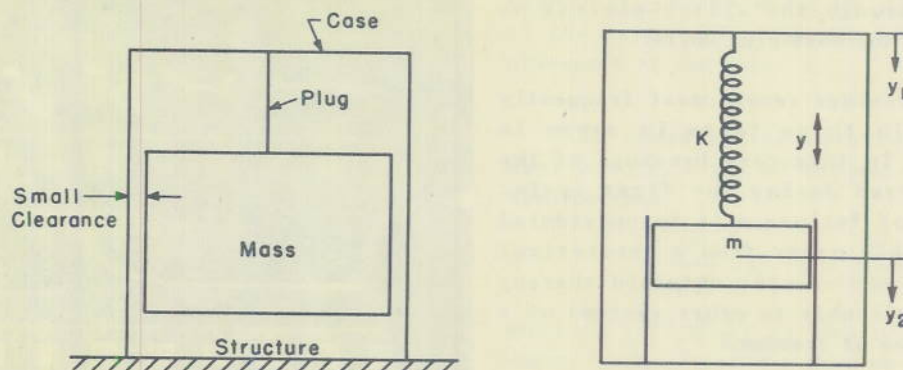


Figure 1. Schematic Diagram of Mass-Plug Accelerometer and the Equivalent Mass-Spring System

which is in turn dependent on the magnitude of the explosion; (2) the statically determined breaking acceleration; (3) the shape of the driving motion; and (4) the

acceleration on the first cycle, which can be obtained from an acceleration record made at the critical distance, and ω is the circular frequency of this

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The solution of the differential equation of motion conforming to the condition that the initial relative displacement and velocity both vanish is:

$$y = \frac{a_0}{\omega_0^2 - \omega^2} (\sin \omega t - \frac{\omega}{\omega_0} \sin \omega_0 t), \text{ if } \omega_0 \neq \omega \quad (4a)$$

$$y = \frac{a_0}{2\omega_0^2} (\omega_0 t \cos \omega_0 t - \sin \omega_0 t), \text{ if } \omega_0 = \omega \quad (4b)$$

Computed curves of y against t for both wood and steel mountings at the respective critical distances are given in Figure 7. The point of maximum elongation is the theoretical breaking point for the critical distance, and the time in-

terval from zero to this maximum is the theoretical time for fracture. Comparison of theoretical and experimentally observed breaking times is shown on the slide. The discrepancy in the case of wood mounting is about 25%, and in the case of steel about 12%. From the maximum elongation of the plugs we may infer the force that caused rupture. The close agreement (to within 1%) of the computed relative acceleration and the design value shows that the values of the tension and elongation of the neck at failure under dynamic loading equal those found for static loading. In contrast, the peak applied acceleration at failure may vary widely. This is borne out by the experimental data, and may be

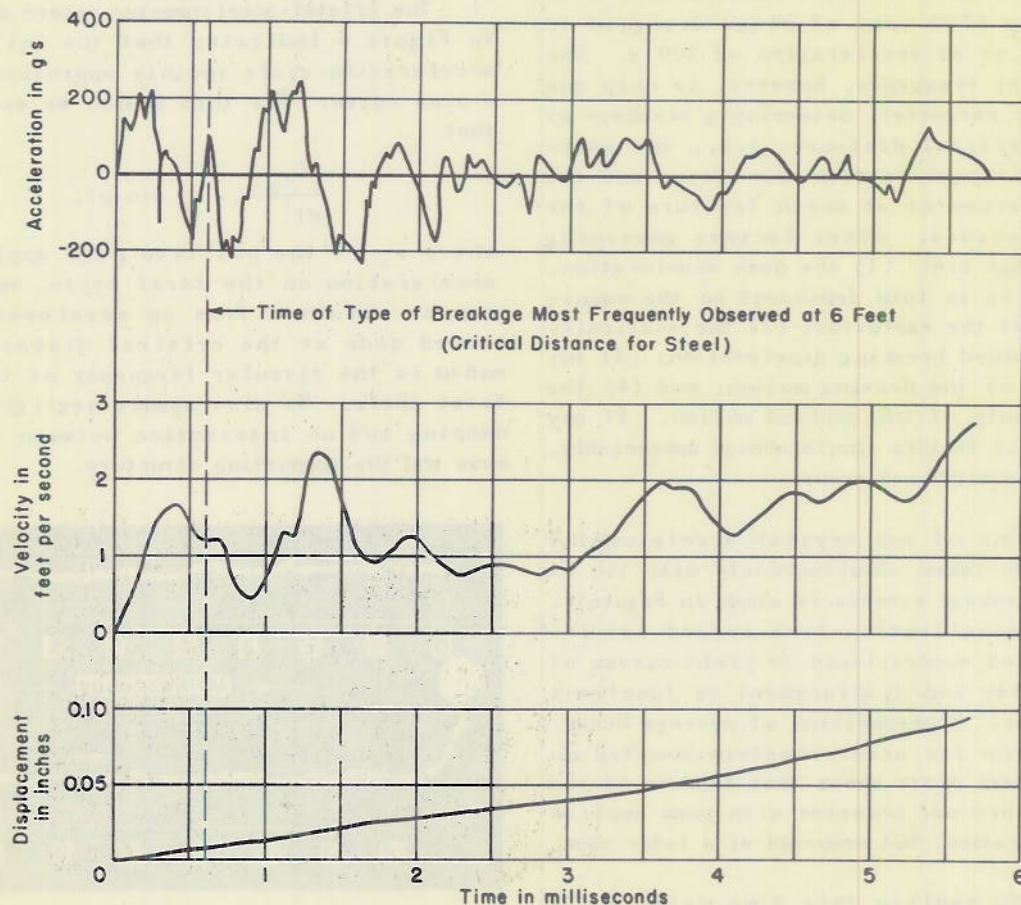


Figure 6. Records Obtained with the Accelerometer Mounted on Steel Plate

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demonstrated theoretically by calculating the first maximum displacement from Equation (4a). We deduce the relation:

$$\frac{a_o}{a} = \frac{\omega_o - \omega}{\omega_o} \csc \frac{2\pi\omega}{\omega_o + \omega},$$

or

$$\frac{a_o}{a} = \frac{\frac{\omega_o}{\omega} - 1}{\frac{\omega_o}{\omega}} \csc \frac{2\pi}{\frac{\omega_o}{\omega} + 1}, \quad (5)$$

where $a = (y_{\max} \omega_o^2)$ is the statically determined breaking acceleration and, we recall, a_o is the peak applied acceleration. Figure 8 consists of a graph of this relation between a_o/a and ω_o/ω for the range $\omega_o/\omega = 0.1$ to $\omega_o/\omega = 10$.

From this it will be noted that the ratio of peak applied acceleration at failure to the design acceleration varies widely, depending on the ratio of the resonant frequency to the applied frequency.

We may well inquire into the implication of this analysis with regard to equipment that must withstand shock. Presumably the analysis may be applied to any equipment that can be approximated by a system with a single degree of freedom, such as the mass-plug accelerometer.

It follows that in the case of such equipment the resonant frequency of the system and the applied frequency must both be considered in estimating the ability of the equipment to withstand the

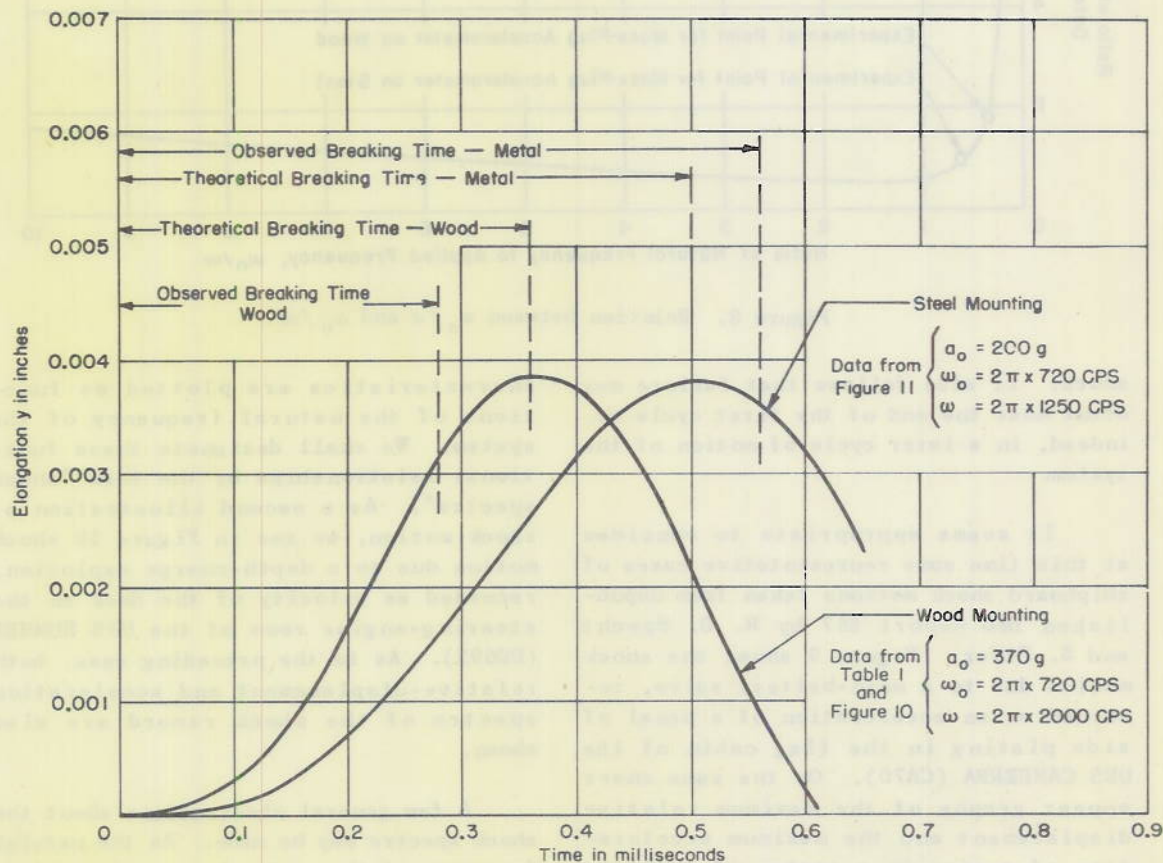


Figure 7. Elongation of the Neck of the Plug Plotted against Time

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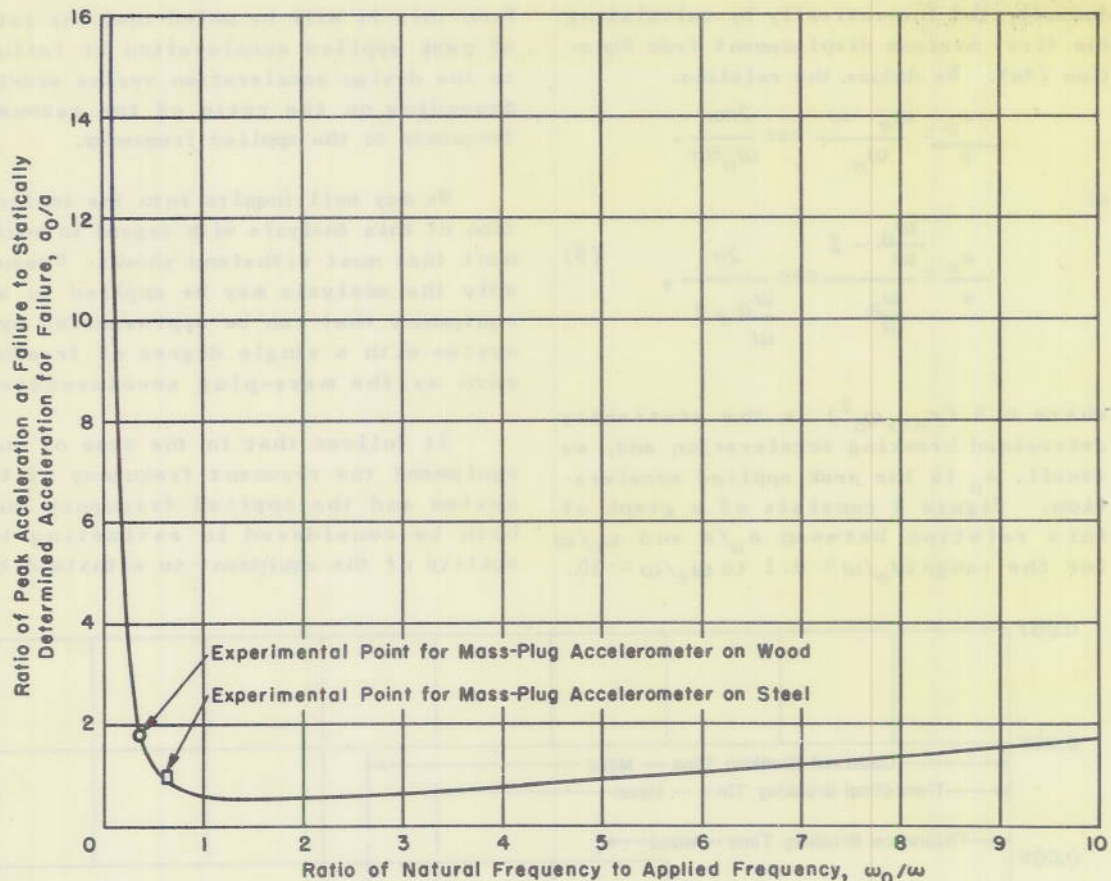


Figure 8. Relation between a_0/a and ω_0/ω

shock. It also follows that failure may occur near the end of the first cycle or, indeed, in a later cycle of motion of the system.

It seems appropriate to consider at this time some representative cases of shipboard shock motions taken from unpublished TMB Report 567 by R. D. Specht and S. Fifer. Figure 9 shows the shock motion due to a main-battery salvo, recorded as an acceleration of a panel of side plating in the flag cabin of the USS CANBERRA (CA70). On the same chart appear graphs of the maximum relative displacement and the maximum acceleration of a mass in a system of a single degree of freedom acted upon by the observed shock motion. These response

characteristics are plotted as functions of the natural frequency of the system. We shall designate these functional relationships by the term "shock spectra". As a second illustration of shock motion, we see in Figure 10 shock motion due to a depth-charge explosion, recorded as velocity of the deck in the steering-engine room of the USS SUMNER (DD692). As in the preceding case, both relative-displacement and acceleration spectra of the shock record are also shown.

A few general observations about the shock spectra may be made. As the natural frequency of the system becomes very high, the relative displacement approaches zero, while the absolute acceleration of

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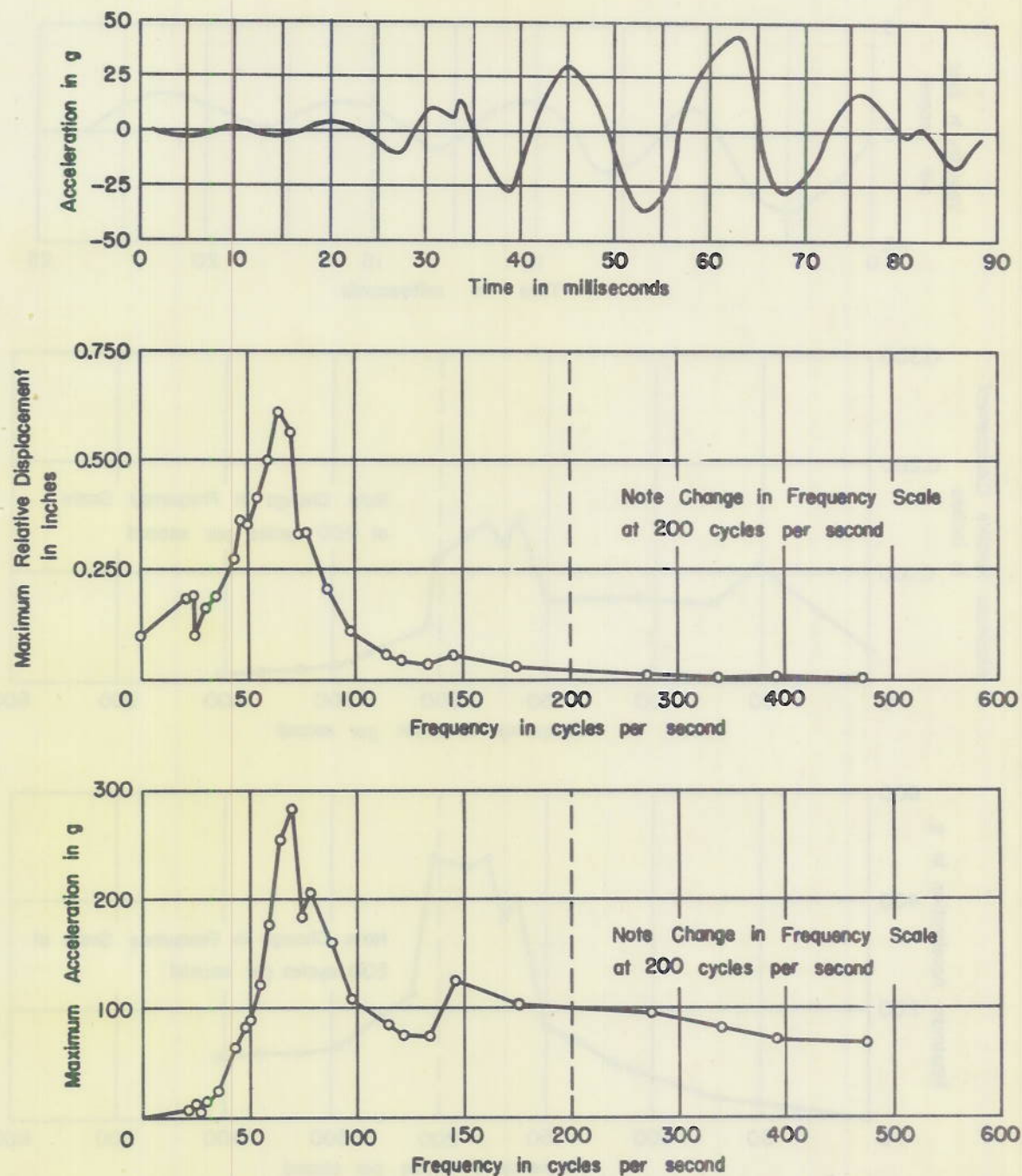


Figure 9. Shock motion due to Main-Battery Salvo, recorded as Acceleration of Panel of Side Plating in Flag Cabin of USS CANBERRA (CA70)

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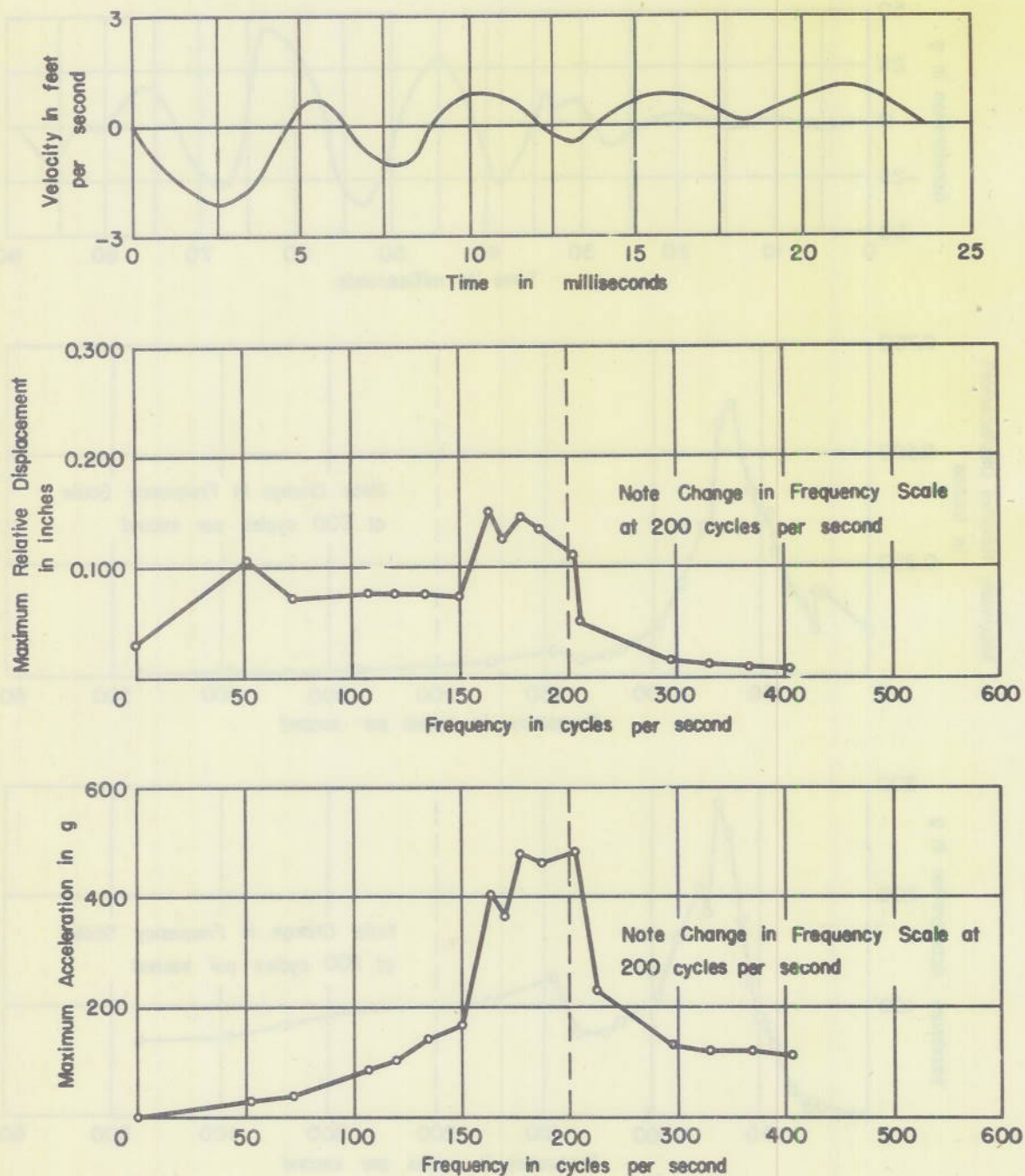


Figure 10. Shock motion due to Depth-Charge Explosion, recorded as Velocity in Steering-Engine Room of USS SUMNER (DD692)

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the mass tends toward the maximum acceleration of the support of the spring-mass system. At very low frequencies the acceleration is near zero, while the relative displacement is approximately the same as the maximum absolute displacement of the support.

The shock spectra reveal whether resonance occurs (frequency range between 0 and ∞) between a predominant component in the shock motion and a particular system with a single degree of freedom.

The analysis of shock motions requires a consideration of the total response -- that is, the transient and the steady-state motions of the system subjected to the shock motions. In steady-state problems, where the transient is neglected, the resonance curve gives the maximum displacement of a system with a single degree of freedom as a function of its frequency and the frequency of the driving force, which is usually taken to be periodic. In shock problems, however, the transient cannot be neglected, since the maximum response of the system may occur in the very early part of the record where the transient is still an important component of the total response. For these problems the shock-motion spectra, such as were shown in Figures 9 and 10, play the same role that the resonance curves play in steady-state problems.

The preceding discussion has dealt exclusively with simple elastic systems possessing a single degree of freedom. Although all physical structures possess many degrees of freedom, it frequently occurs that one of these is so predominant that it determines the behavior of the system for all practical purposes. Likewise, the amount of damping commonly encountered in structures is so small that it may be neglected for most purposes in calculating the response of the system. Consequently, the simplifications contained in the fundamental assumptions as

to the nature of the system just discussed are justifiable in many practical cases.

* * *

DISCUSSION

MR. J. P. WALSH, NRL asked whether the effect of particle velocity had been considered in the analysis of the failure of the plugs in the mass-plug accelerometers.

Answer: The values of Young's modulus, mass density, and the ultimate tensile strength of the type of bakelite used in the fabrication of the plugs yield a critical particle velocity of fifty-five feet per second. The maximum applied velocity at breakage of the 200 g plugs was observed to be about 1.5 feet per second. Consequently, the failure of the plug cannot be ascribed to particle velocity, but rather to tension in the neck of the plug under the action of the mass suspended therefrom.

The relatively good agreement between the rated acceleration of the plug and the computed relative acceleration at the time of breakage lends credence to the present method of analysis wherein wave effects are ignored.

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SUGGESTIONS FOR FUTURE RESEARCH

R. T. McGoldrick, TMB

The subject matter of this paper is somewhat more limited than might be inferred from its title. The shock research program of the Bureau of Ships alone covers a very extensive territory, and other bureaus represented in these symposia also have programs of their own. A great deal of thought has gone into the formulation of these programs and to suggest ideas that are entirely new at this stage of the game would be a formidable undertaking. What the David Taylor Model Basin is offering in this paper, therefore, is a sort of running comment on those phases of the Bureau of Ship's program which are most familiar to the people at Carderock, with some suggestions as to where the most emphasis should be placed in obtaining the objectives of the program. Our point of view is that unless what is found out about shock is translated into design practice the objective of the program has not been attained. The Agenda Committee is aware that the Bureau of Ordnance is more interested in producing shock than in rendering it ineffective, and it is expected that the other side of the picture will be presented at a future date. The phase of the program under consideration in this paper, however, is the shipboard program which is mainly a defensive one.

Most of the work being done on shock at the Taylor Model Basin is classified under the general project C-197, the title of which is "The Determination of Shock on Shipboard and its Duplication in the Laboratory." Project C-197 was established by a Bureau of Ships letter dated 4 August 1943 to the Director, David Taylor Model Basin, and at the

present time the two sections under the Structural Mechanics Division of the Taylor Model Basin most concerned with this project are the High-Speed Dynamics Section and the Vibration Section.

The Bureau of Ships' publication "Mechanical Shock on Naval Vessels," prepared by W. P. Welch, gives a very good summary of the shipboard shock picture at the close of World War II. As pointed out in that publication and in other papers presented here today, considerable progress has been made in the development of instrumentation for measuring shock on board ship. Also, considerable information has been accumulated as to the nature of the motions associated with shock. While much remains to be done in the further development of instrumentation and in the accumulation of further data in the field, it is essential that concurrently there be carried on a systematic study and analysis of the large amount of data already on hand. There is need for correlating the magnitudes of shocks observed at various locations on ships with the observed blast or water pressures, and the fact that there is as yet no accepted unit of shock emphasizes the need for making such correlations.

Since our aim is to translate the information obtained in the field into the language of the designer, we need to find out as much as possible about the designer's problems. Unfortunately there is a great diversity of interests among the people concerned with shock problems, and the report of a laboratory agency is apt

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42

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to be written from only one particular point of view. A report describing an extensive shock investigation on a naval vessel may take upwards of 100 printed pages and include dozens of tables and reproductions of instrument records. In many cases, the person referring to the report wants only one specific item of information, perhaps only the magnitude of the shock to be anticipated at one specific location on one particular class of vessel. All that he may find in the report with regard to this item is a velocity-time record or an acceleration-time record which may be very difficult to interpret. There is thus really a job for a statistician and, of course, one of the purposes in designating the Naval Research Laboratory as an information center for shock and vibration was to help resolve this difficulty. If the designer is in a position to make direct use of the instrument data obtained in the field he should be able to obtain the information promptly, and where direct use cannot be made of such data he must make his needs known to the report writer so that the analysis will be made from a practical point of view.

With regard to shock instrument development the conflict between the objectives of obtaining the maximum of information from the field tests and of making the instrument as simple as possible to operate in the field still exists. For the present there is need for development along both lines; that is, both time-base and peak-indicating instruments must be perfected and the range must be extended, so that more information can be obtained about shocks of sufficient magnitude to cause structural damage. At the Taylor Model Basin, drawings have recently been completed for the pilot model of a new multi-frequency reed gage which will have a spring-actuated sliding target so that the course of the movement of the reeds can be observed without fulfilling the rigid requirements of the usual time-base instrument which re-

quires a wiring installation. This represents a compromise between the two points of view in instrument design just mentioned, and also takes into account the fact that the initial motions accompanying a shock are not always the most important. It is hoped that this new reed gage will be tried out in the near future.

The desirability of further shock measurements in the field under controlled conditions was generally agreed upon in the conferences preceding the establishment of the Shock and Vibration Symposia. It is especially important to measure the shocks resulting from series of changes spaced at gradually decreasing distances from the ship, and to continue this process up to the point of structural damage even though the instrumentation may have to be simplified in the later stages. Recent economy moves have delayed the postwar field program, but tests on two vessels of the attack transport class are anticipated at the present time.

The Taylor Model Basin has some suggestions to offer with regard to the problem of analyzing shock records. In TMB Report 567 (now in preparation) entitled "Response of Systems with a Single Degree of Freedom to Shipboard Shock Motions", by R. Specht and S. Fifer, it is shown that even in cases involving very complicated shock motions the peak relative deflections and peak accelerations sustained by shock mounted assemblies having one degree of freedom can be computed by means of the differential analyzer or the Biot pendulum. For this purpose, the acceleration-time record of the shock motion must be on hand. The use of such methods points out one possible way of evading the difficulty of defining a unit of shock. Since the method reveals what the peak acceleration and relative deflection of the shock mounted assembly will be for any given natural frequency of the shock mounted system, it furnishes at once the basic data needed for designing a mount to

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resist the particular type of shock in question. Of course, it must not be assumed from the attention given to shock mounts in the research program that all equipment installed in a ship must be shock mounted. Studies of the shock motions may reveal that under the worst conditions to be anticipated the equipment can be so specified that it will resist the shock even with a rigid mounting.

Here the specification writer wants to know whether specifying equipment to resist a constant acceleration of a certain number of g 's will insure adequate strength against shock, and the laboratory should aim to answer this question.

In addition to the differential analyzer and the Biot pendulum, another useful aid in the analysis of shock motions which so far has received only limited attention is the electrical analogy. This analogy has been used at the Taylor Model Basin with a fair measure of success in steady-state vibration problems and we know that elsewhere, particularly at Westinghouse, it has been applied successfully to transient problems. When we realize the complexity of the mathematical analysis of systems of only two degrees of freedom, we can appreciate the saving in time that may be provided by such schemes as the electrical analogy, and application of it to the shock problem is now on our agenda at Carderock.

The problem of modifying existing shock machines more nearly to simulate shipboard conditions was frequently discussed in the previous conferences and is a knotty one. The Taylor Model Basin does not have any shock machines on hand, but we have considered this problem, and it seems fairly clear that floating steel models subjected to underwater explosions come nearer to producing motions such as encountered on board ship than the hammer-and-anvil type of machine can be expected to do. The fact remains, however, that the hammer-and-anvil type of shock machine has

become widely established. If, instead of mounting the equipment to be tested directly on the table of the shock machine, it is mounted on a member of many degrees of freedom which is then attached to the table, a motion nearer to the desired motion may be expected, but the shock is apt to be considerably attenuated by this procedure. It would then be necessary to increase the weight or drop of the hammer to make up for the attenuation. Unfortunately, in offering this suggestion we are not as yet able to furnish experimental justification for the recommendation.

At this point it is well to recall the fact that the Bureau of Ships' shock research program is by no means limited to the protection of equipment installed on ships, but extends to the establishment of proper specifications for the structural design of the vessel itself to insure its ability to resist such shocks as may be encountered in service. This means taking into account not only shocks due to the detonation of explosives, but shocks due to the action of the sea and to a number of other causes. There are, moreover, both general and local structural design problems, and the laboratories must keep both points of view in mind. During the war, the local problems were handled largely on a "trouble-shooting" basis. If damage occurred during a structural firing test, or from enemy action, it was fixed up on return to the yard, and frequently other vessels of the class were modified accordingly. When, however, new designs are underway in peacetime, it is essential to anticipate such contingencies as far as possible. Structural designers seem to have a preference for thinking in terms of the equivalent static load criterion which will insure against failure under dynamic load. Hence the laboratories studying shock can be of great assistance to the designer if they can furnish the so-called dynamic load factors so that he can treat his problem like one in statics.

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In many cases, model experiments in this field can be of assistance to the structural designer, but there are two very dangerous fallacies to guard against in resorting to dynamic model testing. One is the disregarding of the laws of similitude involved. The other is the failure to include sufficient of the surrounding ship structure in the model to insure the correct boundary conditions. It is also well to remember that the production of scale models of steel structures involves difficult shop techniques which may be a decisive factor in excluding their use. Crude models are frequently helpful in making qualitative checks of new theories, however, even where it is known that the conditions of similitude cannot be entirely fulfilled. For example, in the underwater explosion research program at the Taylor Model Basin, series of diaphragms separated by various energy absorbing materials were tested as described in TMB Report 491, and, prior to the tests at Bikini, very small sheet brass models of certain of the target vessels were tested in the "little Bikini" pond at Carderock. An example of possible model experimentation at the present time would be the study of various blast-deflection devices as mentioned in the paper by Mr. Rich.

The usefulness of mathematical studies in the setting up of structural design specifications involving shock is not to be overlooked, academic as they may seem at first. In this connection it might be fruitful to mention the contract which the Office of Naval Research has established with the University of Michigan to carry out experimental and theoretical research in the dynamics of ship structures. The Taylor Model Basin is performing the liaison function in connection with this contract. When, a year or so ago, the question arose as to whether dangerous stresses could be built up in the hull of a ship if a shock disturbance from an ocean wave striking the bow should be reinforced by the reflection of a

similar shock disturbance from the stern, it was found that present theories of flexural vibration of ships gave no answer to the question of how such shock disturbances are propagated. Flexural vibrations of beams are not considered from the point of view of wave propagation, and, in fact, the differential equation for flexural motion of a beam does not have a wave function as a solution.

Professor Ormondroyde and his colleagues at Michigan are working on the general solution of the problem of the response of a uniform bar to an arbitrary load. This problem therefore includes both the case of steady-state excitation and the case of transient or shock excitation. The method will be made available to naval personnel shortly, and the Taylor Model Basin expects to test out its application to ships. Even though the ship is far removed from the uniform bar, it is anticipated that the response of the latter to various types of shock loads will indicate important clues as to what happens in the case of the ship. Briefly, it is expected that the Michigan method will show how the complex motion of a free-free beam under shock load can be resolved into a series of normal functions. This is one reason for trying to determine the natural frequencies and normal modes of vibration of vessels incident to a series of systematic shock tests. If, in the case of a field test, it could be forecast from the known amount of explosive to be detonated and its position relative to the ship what transient load would be applied to the ship, and if the motion of the ship under this loading could be calculated mathematically, much progress would be indicated in our understanding of shipboard shock. If, then, data were on hand as to the forces produced by ocean waves, it would be possible by the same theory to set up design criteria for shock effects in a seaway to supplement the present strength calculations which are based only on the hogging and sagging moments due to trochoidal waves.

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It is not to be expected, of course, that such a study as that just mentioned will reveal more than the large flexural motions of the hull in its first two or three normal modes. These are, however, the most important as far as the structure as a whole is concerned. These are the motions which may be expected to break the ships "back". When it comes to the failure of equipment in the ship, the high-frequency vibrations of the local structures are in many cases of more importance. The possibility of predicting mathematically the behavior of the ship at high frequencies is far less promising, and here it will probably be necessary to rely upon statistical data obtained in the field tests for some time to come.

The Taylor Model Basin's suggestions, therefore, in running a systematic series of shock tests on naval vessels, are as follows:

(1) whenever feasible, to determine in advance, by means of a vibration generator, the natural frequencies and normal modes of vibration of the entire hull for vertical flexural, transverse flexural, and torsional modes of vibration;

(2) to determine in advance of the tests, by recording free vibrations after impact, the natural frequencies of as many "local" structures on the ship as possible;

(3) during the tests to record the shock motions at as many stations on the ship as possible, using both the time-base and peak-reading instruments (and it is assumed that such measurements will be carried up to the point of structural damage);

(4) wherever possible, to record blast or water pressures in the vicinity of the hull on a time base;

(5) by analysis of the blast or water pressure measurements to estimate the resultant transient force acting on the hull, wherever this is feasible;

(6) by analysis of the records from the time-base instruments to try to break

down the flexural motions of the hull into a series of normal functions;

(7) to compare the structural response of the hull in flexure with the theoretical response to the transient force as computed by the method at the University of Michigan; and

(8) from the recorded flexural motions in the different normal modes to estimate the peak bending stresses developed in the hull and to compare these values with any values that may have been obtained experimentally.

Although in general in these Symposia we consider the rather severe shocks to which a vessel is subjected infrequently, it is well to recall that much smaller shocks repeated frequently may eventually lead to serious damage. We still hear of Liberty Ships breaking in two, and one theory that has not yet been disproved is that such failures are due to fatigue from repeated shock or vibration stresses. Other sections at the Model Basin are more concerned with such problems than the two sections represented at this Symposium, but where shock mounts have to be installed at locations on a ship where steady vibration exists the question of fatigue cannot be ignored.

The final suggestion offered is that consideration be given to the publishing of a shock manual which would summarize the important formulas so far deduced in this field for ready reference but contain a minimum of material in the text. It would probably be necessary to make at least part of such a manual confidential, since it should contain formulas by which some estimate could be made of the loads to be expected from the detonation of various quantities of explosives at various distances. Such a manual might have four main sections as follows:

(1) formulas for estimating shock loads produced on ship structures at fixed distances relative to various sources;

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(2) formulas for estimating the shock motions to be expected when various transient loads act on ship structures;

(3) formulas for designing protective mounts for various types of equipment to be installed at locations at which various shock motions may be anticipated; and

(4) formulas for designing various structures that must withstand shock motions when rigidly mounted in the ship.

DISCUSSION

MR. HOPPMANN, NY NAVAL SHIPYARD, asked whether Mr. McGoldrick could say some more about the problem being solved at the University of Michigan. Mr. McGoldrick replied that the problem is to find the response of a uniform bar having a uniformly distributed elastic support and uniformly distributed damping to a force which is an arbitrary function of time and distance. The differential equation is solved by a double Laplace transformation, that is, a transformation with respect to time and a transformation with respect to axial distance along the bar. It is based in general on the operational calculus as outlined in the book on that subject by Prof. Churchill. Because of the general nature of the problem, it should find wide application. For instance, it includes the case of steady-state vibration under a simple harmonic driving force acting at one point of the bar -- a condition which is approximated in ship vibration where the driving force acts in the plane of the propeller.

DR. TRENT, NRL, asked what sort of functions the Michigan method was limited to. Mr. McGoldrick replied that any function of time or distance was covered in the treatment. Thus, the force could be a step function or a pulse with respect to time, and could be applied at a point or be distributed along the bar.

J. G. WATSON, R.N.

In his suggestion for future research, Mr. McGoldrick envisages the development of the shock-test machine of the hammer-and-anvil type for inflicting the test blow in more than one direction at a time to represent the three-dimensional case to be expected in practice.

It appears to me that further study and development of the shock test machine is necessary in order to reproduce more accurately the conditions obtaining in equipment and fittings (I personally am concerned with electrical equipment) in a hull which is subjected to underwater explosions.

Electrical equipment which can, and does, withstand the Admiralty Shock Test "B"--i.e., a vertical blow of 2000 foot pounds, and side and end blows of 1000 foot pounds each--failed during the CAMERON trials at accelerations of 70 - 90 g associated with velocities of 7 - 10 feet per second and displacements of 0.6 - 0.8 inches, and it is important that this equipment should withstand shocks up to the point where the damage to the hull exceeds controllable flooding. As a result of the CAMERON trials, the limit of shock in a destroyer hull requires resistance to 134 g with maximum velocity of 14.2 feet per second.

In Great Britain, tests have been carried out on the target plate of the shock machine which is the same as the one used in the United States, and blows required for shock test "B" indicated above produced very similar conditions for the three blows, each containing a high-frequency component of 1000 g at 1000 - 2000 cps, a medium-frequency component of 200 g at 100 - 200 cps, and a low-frequency component of 2 - 3 g at 5 - 8 cps, and displacements of 2 - 3 inches.

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An attempt to modify the shock administered by the shock-test machine has been made in the case of the machine developed to give an upward blow, in a study of shock resistance of submarine batteries. In this case, a 2000-foot-pound blow was transmitted through helical springs in a spring box between the striking plate and the mounting plate. The springs were compressed to a static loading of 65 tons before the blow, and in this case the characteristics of the blow were more nearly those measured on a dummy submarine cell during actual tests in firing charges near a submerged submarine hull.

I do suggest that an important item for future research is a modification of the shock-test machines to reproduce the characteristics of the shock found in

full-scale tests such as the CAMERON and AMEUSCADE trials.

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CONTACT AND NEAR CONTACT EXPLOSIONS ON MODELS

Commander C. H. Gerlach USN, BuShips

A brief description of the work carried out and under way by the Bureau of Ships Underwater Explosion Research Group is given. The facilities and instrumental techniques commonly used by this group are discussed.

In the business of shock investigations, the role of underwater explosions as an instigator of shock phenomena is a prominent one. The section of the Bureau of Ships which I represent is concerned with underwater explosions, and I believe that Dr. Klein's purpose in asking me to present this paper was to give a general picture of the sort of work our section does, since your work and our work share a mutual interest, and at times our interests and technical problems converge.

Our principal objective in underwater explosions is structural protection. The degree of shock protection required of ship equipment and components is regulated on practical grounds, for some attacks at least, by the extent to which the ship maintains its structural integrity. We share a common interest in the technical problem of the events which are set up in the ship boundary that receives the external disturbance. We use many of the same tools.

In order to understand more fully where our group stands in the subject of underwater explosions, it is necessary to review briefly the history of the group.

The former Bureau of Construction and Repair has always recognized the importance of considering underwater protection as an element in the design of naval vessels. It had followed and participated in underwater explosion work in the late 19th century. In 1908 it embarked upon the

experimental study of structural damage from underwater explosions, when the old monitor FLORIDA was attacked by a charge of 200 pounds of guncotton. The problem confronting the shipbuilder then (and it remained up until the relatively recent past the dominant and indeed almost the exclusive problem) was protection against mobile torpedoes which detonated upon impact with the ship, and hence was confined to explosions initiated at the side of the vessel. Obviously, protection as such could be entertained as a possibility only in the large ships - the battleships, and later the battle cruisers, aircraft carriers and more recently, the large cruisers (CB). These were the backbone of naval power, and the premium on such protection warranted its elaborate recognition in the design of these vessels. As late as 1936, the problem remained that of side protection, and even well after that date, as our war experience has indicated, the threat of side attack was properly the major consideration of underwater explosion protection.

The history of the underwater explosion work connected with ship design is predominantly, then, one of study of side protection. In the meantime, minefields as we know them today have raised the problem of underbottom attack. The study of this problem was colored by the fact that distance (to the explosion) entered as a factor of protection in itself, and by the fact that the shipbuilder is very stringently limited in his freedom

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and choice concerning bottom protection. Only a very little experimental work has been done on the bottom protection problem.

The side protection problem was kept active after 1908. As a result of events leading up to World War I, this work was undertaken on a systematic and extensive basis about 1916. It was prosecuted intensively until around the middle 1920's, when it suffered a relapse, due to considerations of national temperament, military budgets probably much like those prevailing today, and with the disarmament action more restrictive.

There was one mode of procedure available - that of trial and error. That which was judged to be a promising protective system was tested, the steps progressing according to what was seen before. The tools and concepts were limited. Those that were available were engineering in nature, rather than scientific. There were the contributions of Abbott, and the work of Hilliar was just beginning. It could fairly be said that he founded the applied science in this connection. The hydrodynamics of the explosion were not understood and the events of the explosion were pictorialized principally by the expansion of the hot gases at high pressure into the protective system. Generally speaking, the aim of protection was to provide a void space into which the gases could expand and lose pressure, to resist further inward penetration by a combination of bulkheads and a liquid mass, and finally to provide a bulkhead farther inboard which was intended to remain watertight, but not necessarily undeformed.

The first problem of 1916 was to determine if the problem was susceptible to attack on model scale, and if so, having built a scale model, to determine what value of charge weight would reproduce the damage to the prototype from a given explosion. It was determined that similar damage could be produced in the model,

but not by a geometrically similar charge to the same scale. The tools available were merely those of the eye and a ruler for measuring damage, and a type of pellet deformation gauge to measure the explosion. From this work there evolved the so-called 2.45 law - i.e., to reproduce prototype damage in model scale, the ratio of charge weights was to be (scale factor) 2.45 rather than (scale factor) 3. With the tools available, great accuracy of such a determination was not to be expected. The measurement of this sort of damage still depends principally upon the eye and ruler. They are insufficient for the ultimate purpose.

More importantly, there evolved from this work a good protection system, of multiple bulkheads spaced in transverse dimension, with liquid (fuel oil) carried in certain of the layers as formed. This may not appear to be a startling achievement, for we all take the multiple-bulkhead-torpedo-protection form for granted. We may also take the view that such a multiple-bulkhead system was a natural and obvious solution to the problem. We may more objectively assess the merits of this work if we remember that all of the capital ships at Pearl Harbor, and of all of our capital ships of this war until the appearance of the NORTH CAROLINA and WASHINGTON had torpedo protection systems of vintage 1915-1920. Torpedo explosive charges had increased by 25 to 60 percent in the meanwhile. The performance of these structural protection systems was very creditable without any allowance for the overload they were experiencing.

About 1938-1939, the complexion of the experimental work began to change. During the war years, the major effort of the Bureau of Ships group was concerned with side protection, since the possibilities of effective application of the fruits of the work in ships that were to see service in the war were greatest in this phase of protection. In the experiences of our

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Navy, the side attack was also the principal underwater attack.

The underbottom problem was touched upon in some small scale experiments. They appear to show that in attacking the same structure in, or quite close to contact, the resultant damage is essentially the same whether from underbottom or from the side. Certainly, the difference is contained within the experimental error of those tests. It is recognized, however, that the migration of the bubble will have its influence for charges farther removed from the target. In terms of damage, this problem remains for study.

From 1938 to 1939, electronics technology had reached the point where the possibility of making detailed studies of the processes of explosive loading and target response thereto began to be opened to the experimenter. It was easily apparent that any great advance in protection would require an understanding of the cause and effect relationships of the basic phenomena, and a thorough understanding of the time history of the behavior of the target as a mechanical system. We must eventually be able to write equations of force, time, and distance. The first glance is enough to show that this task would be tremendously complicated, the processes at times insuperably unwieldy, and in some phases that the science which must be brought to bear is not far enough advanced to handle the problem.

The start was made. For the problem of structural response, the simplest form in which the problem could be cast is that of an air backed plate having a single axis of symmetry, known edge fixity with parallel investigations by hydrostatic loading and by attack with non-contact explosions from above or at the side. When the case of explosive loading could be handled with satisfactory inclusiveness, and with satisfactory accuracy, the target would take a more complicated form.

We have reached a point where we feel we should attempt a more complicated target. We have chosen a rectangular panel, rather than a target having single axis of symmetry, as the next most simple target. Stated inclusively, but generally, the aim of such studies for our purposes is to determine how the phenomena of the explosion delivers energy to the target or does work against it, to (a) determine the bodily motions of the target, (b) determine the laws according to which the material flows, and (c) determine the processes of its failure. None of these questions can as yet be answered except in the crudest terms.

The road toward answers to these questions is a long one. The single-minded pursuit of such frontal attack will not produce answers to engineering problems of design and construction at times when the business of the Navy requires answers. We have therefore to carry along work of improvement in the gross details of the present protective forms, and in engineering details of construction.

We have also the larger problem of balance in protection with respect to side attacks and underbottom attacks. For the time being, we must regard either of these attacks as equally likely. The full discussion of this problem is not in order at this point but three consequences are of importance: (1) the urgency of determining the basic facts of explosion damage is further emphasized since a more effective use of weight and space is required to provide structural bottom protection (of capital ships), if that is possible at all; (2) the hazards and prevalence of shock damage to equipment are increased beyond the past experience of our Navy; and (3) the bodily motion of the ship from the underbottom explosion raises the threat to the structural strength of the ship as a whole to a seriousness of a more general nature than formerly.

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It seems clear that one of the essential things to be done is to determine the basic facts of life in this field of endeavor. With the war over, and the disruption of Crossroads about to work itself out, I believe we are free to concentrate principally on this line of attack - to try to examine the phenomena piecemeal and fit them together. The majority of such work will be conducted on a small scale; however, some things require full scale targets as a prerequisite. We hope to be able to follow the studies on whatever scale is most appropriate.

Our interest extends beyond things embracing the actual explosion. I have mentioned that we will need to know the laws according to which material deforms, and the cause and manner of its failure. We have one of the few applied problems of structure which are tied up so prominently in the plastic domain. We are sponsoring jointly with Office of Naval Research a project for plasticity surveys and investigations. I hope this will grow into a sustained, serious effort to bring to engineering problems of plasticity the common understanding and everyday workability which are afforded in elasticity.

Apart from contractual services, the underwater explosion experimental facilities of the Bureau of Ships centers in the Taylor Model Basin and Norfolk Naval Shipyard. With the former you are all familiar. For many years, Norfolk has constructed, and executed the tests against caissons, as the torpedo protection targets are called, as a part of the shipyard work. In recent years this came to be a continuing activity, and a small group, principally of engineering talents, came into being to handle the work. This activity now has the status of a research field unit, and is in the throes of growing into that function. It still lacks research scientists.

The essential core of the unit consists of the underwater explosion barge. This is merely a ruggedly constructed barge, 50 feet wide, 25 feet deep to its deck, 150 feet long. Internally, it is all ballast tanks except for the machinery spaces. The machinery consists of diesel generators for power supplies, and ballast pumps. The barge is not self-propelled. The machinery platforms are spring supported for shock protection.

On deck there is an instrument house, also hung on springs. Models of protection systems as large as half-scale can be attached to the end of the barge, brought to the proper draft, and tested, with the gauge recording apparatus installed in the instrument house on board. There are frameworks in the side of the barge for holding circular diaphragms and rectangular panels, and cranes and rigging to hang targets over the side for testing. It amounts, then, to a floating test location with shock protection of recording apparatus to bring the equivalent of a laboratory into the field.

The quantities we are interested in are those of time, acceleration, velocity, displacement, strain relating to the target, the pressure time function of shock waves, and other hydrodynamic properties of the explosion.

The majority of our wartime work having been concerned with complicated structures and aimed largely at engineering objectives, our instrumentation work has been exploratory, either with respect to the gauges, or with respect to the structure. With respect to structure, we wanted to record the time history of the motion of the separate elements of the structure, and the strain history of the principal elements.

The only practicable tool for strain-time measurements is the metaelectric gauge. In our application we have the practical

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problem of a cemented attachment which shall remain serviceable in the plastic range at relatively large extensions. This problem is not satisfactorily solved. On complicated structures, the kind of records that we have obtained defy analysis. This is probably due equally to gauge and recording problems and to the inherent complexity of the actual strain process. We have been forced to conclude that we need to start over to determine how we can get satisfactory records, make useful analyses of the records on the simplest structure possible, and have some independent means of determining strain. A possibility in the latter connection is the photogrid process supplemented by motion picture photography. The photogrid process consists of applying an emulsion to the target, and developing on it a grid system. This promises to be a useful tool for residual-strain distribution studies, but at present we have not completely surmounted the obstacle of keeping the emulsion on the plates under the accelerations involved in explosive loading. At present the problem of adhesion is particularly acute. This problem is present when panels are ruptured in tests and the edge of the fracture is subjected to the inrush of water.

We have had reasonable success in deflection time measurements on elements rugged enough to permit attachments. One version consists essentially of a slide wire rheostat arrangement. Another consists of measuring the electromagnetic coupling between a fixed coil and a coil mounted on the member to be studied. A variation of the latter, using the same recording system, consists of using a modulated light source, the reflection of the light via a piece of motion picture projection screen on the target, and measuring the intensity of the reflected light (a function of distance) by a photoelectric cell. This will provide a solution for a family of problems which prohibit attachment to the target. Ultimately we will need to seek

a device which will have greater resolution, as to both time and deflection.

Our velocity measuring problems are solved only to the extent that we can use the British type velocity meter. Our paramount need now is for velocity measurements of thin plates immediately following the arrival of a shock wave. We have no proposed solution for this problem worth discussing.

For the time being, we have abandoned acceleration measurements because of the instrumentation difficulties. Assuming that we could obtain a valid record, we are not yet able to handle the complicated nature of such measurements.

High speed photography occupies an important role in our work. Its use is valuable from the standpoint of obtaining a visual record as well as its use in obtaining measurements. Our principal application of this technique has been in caissons where we wanted to see general areas, details of construction, and to make deflection studies. For this purpose, the Edgerton type of equipment with its avoidance of rotating prisms or optical flats, presents the best solution for cramped spaces. The problem of lighting for good photographic quality in such an application is not a simple one, and the associated electronic equipment is somewhat temperamental in field use. However, readable results can be obtained with little more difficulty than those involved in other techniques.

Figures 1, 2, and 3 are typical of the results that have been obtained from the caisson studies. In each case, the structure of the caisson being investigated is shown schematically at the top of the figure. In Figure 1, displacement-time curves are shown for three colinear points located on bulkheads 2, 3, and 4, respectively. The main motions take place consecutively from outboard inward. The motions of the three bulk-

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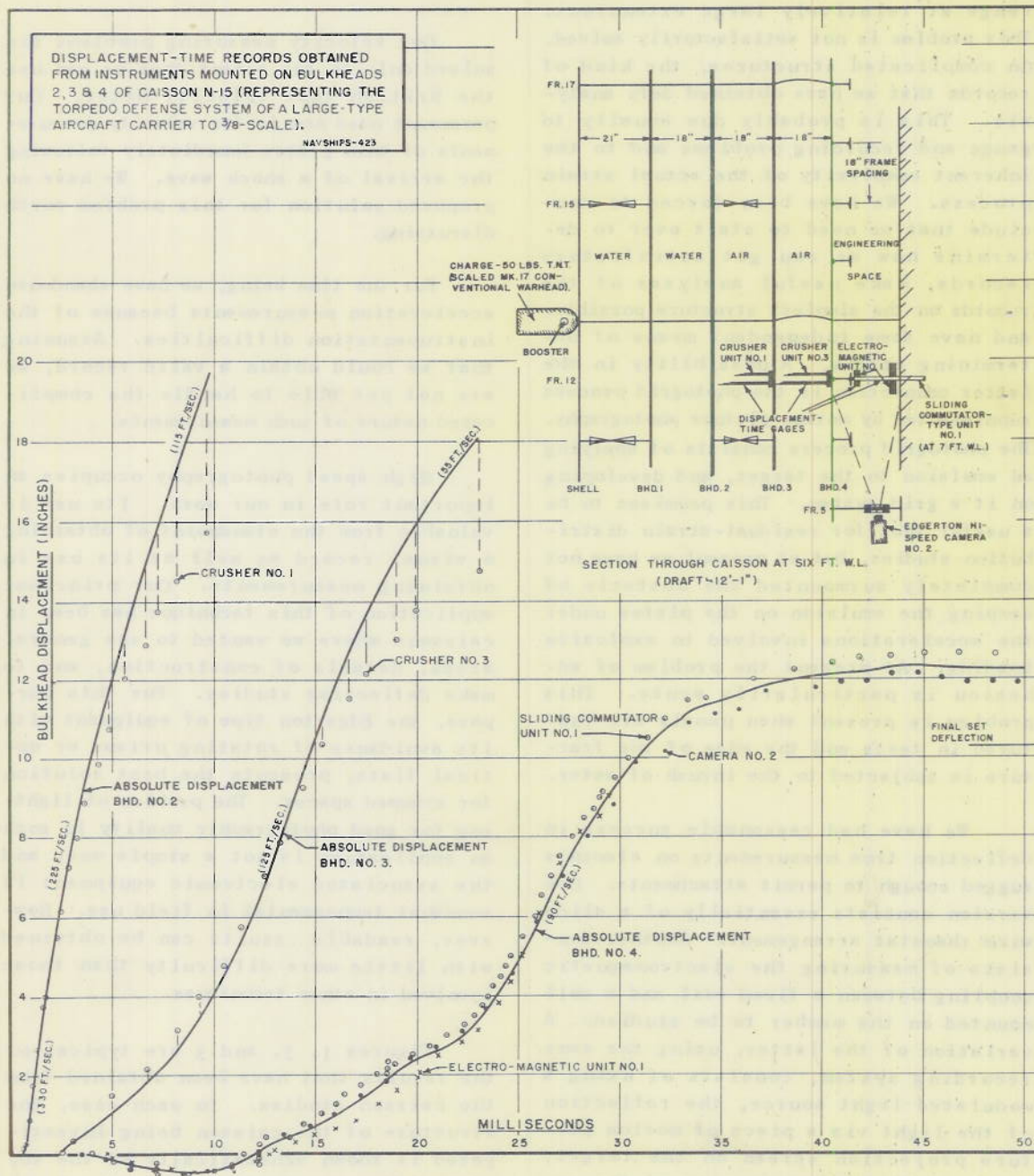


Figure 1

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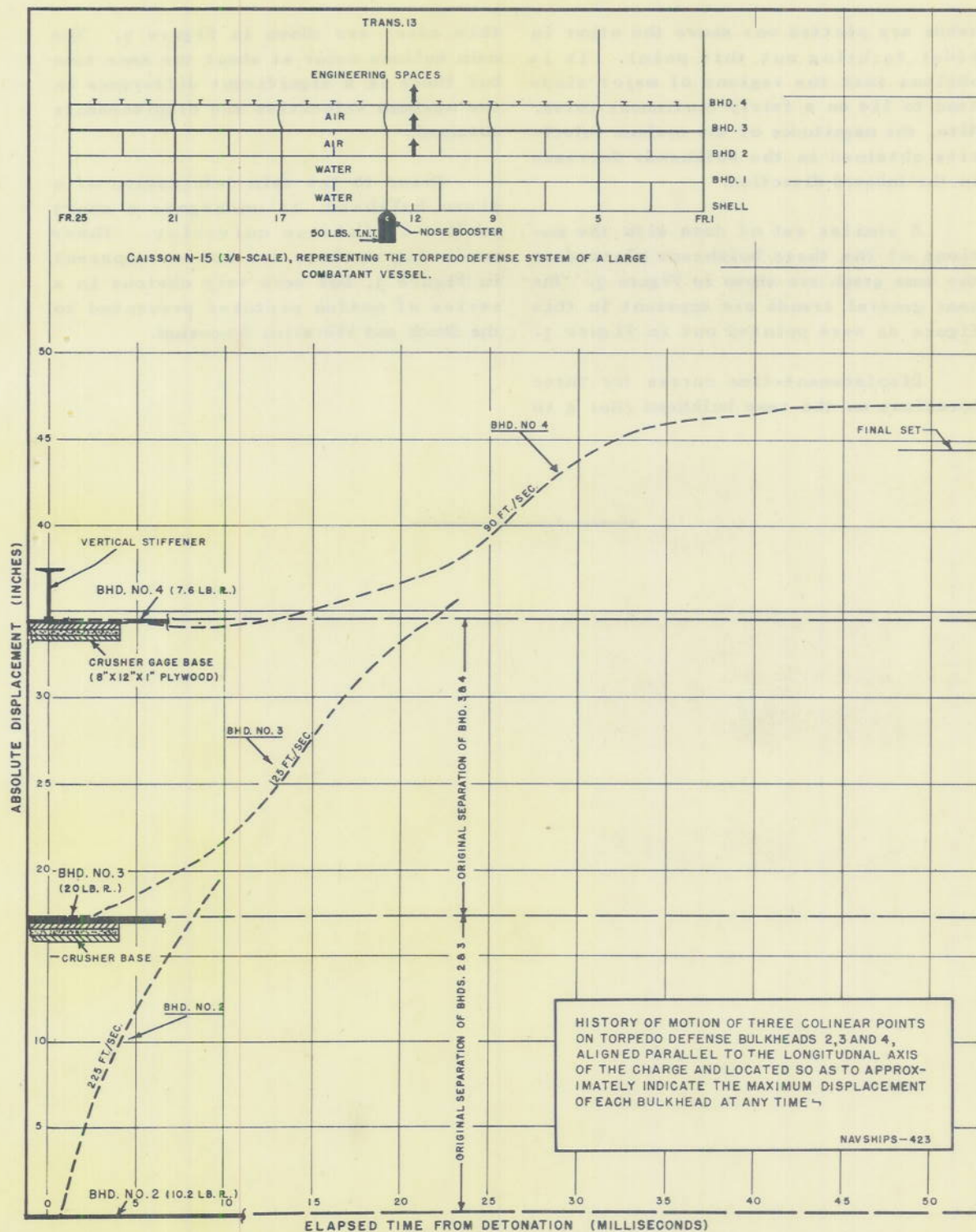


Figure 2

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56

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heads are plotted one above the other in order to bring out this point. It is obvious that the regions of major slope tend to lie on a fairly continuous curve. Also, the magnitudes of the maximum velocities obtained in the bulkheads decrease in the inboard direction.

A similar set of data with the motions of the three bulkheads plotted on the same graph are shown in Figure 2. The same general trends are apparent in this figure as were pointed out in Figure 1.

Displacement-time curves for three locations on the same bulkhead (No. 4 in

this case) are shown in Figure 3. The main motions occur at about the same time but there is a significant difference in the maximum velocities and displacements obtained.

Prior to the main deformation of a given bulkhead, it undergoes a short period of intense quivering. These quivering motions are not so apparent in Figure 3, but were very obvious in a series of motion pictures presented to the Shock and Vibration Symposium.

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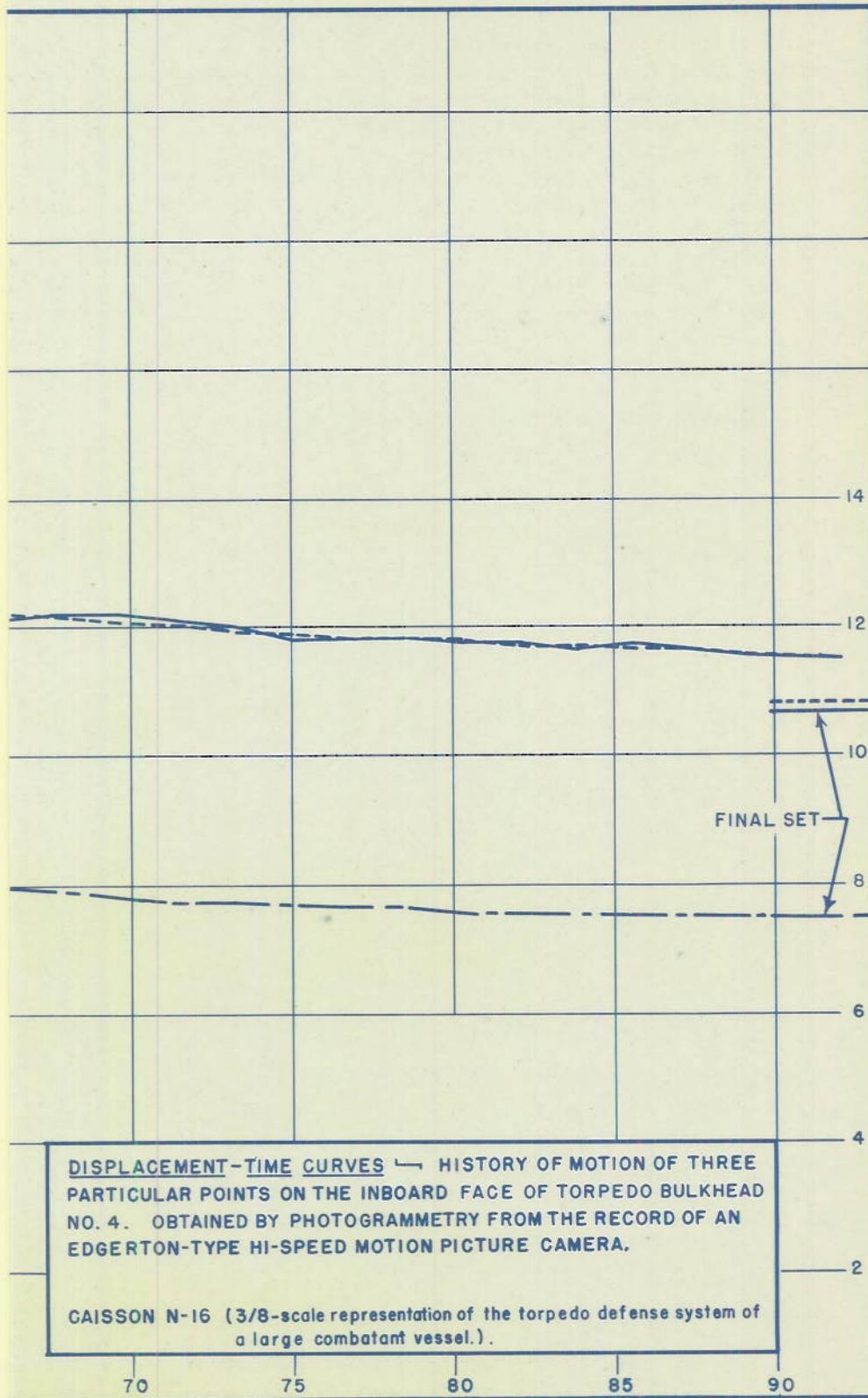


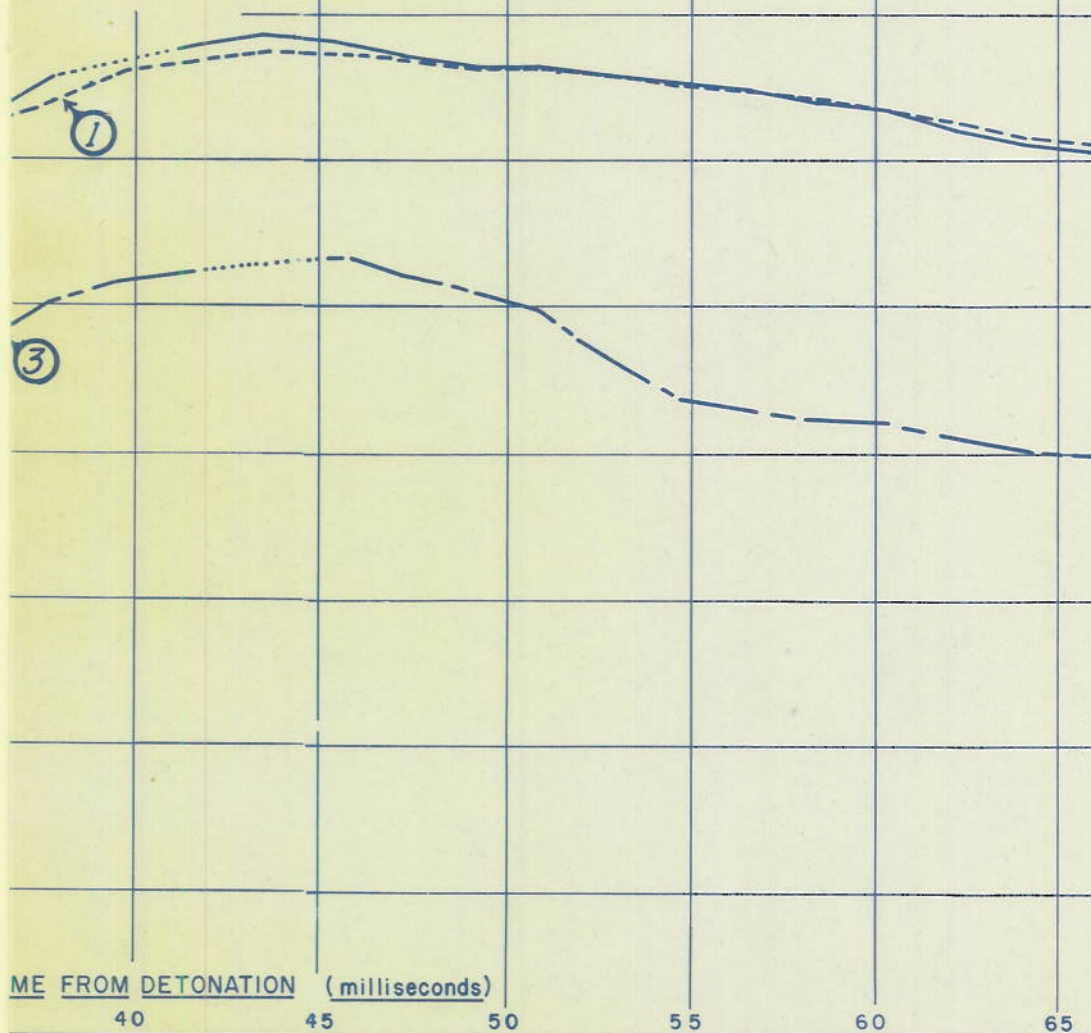
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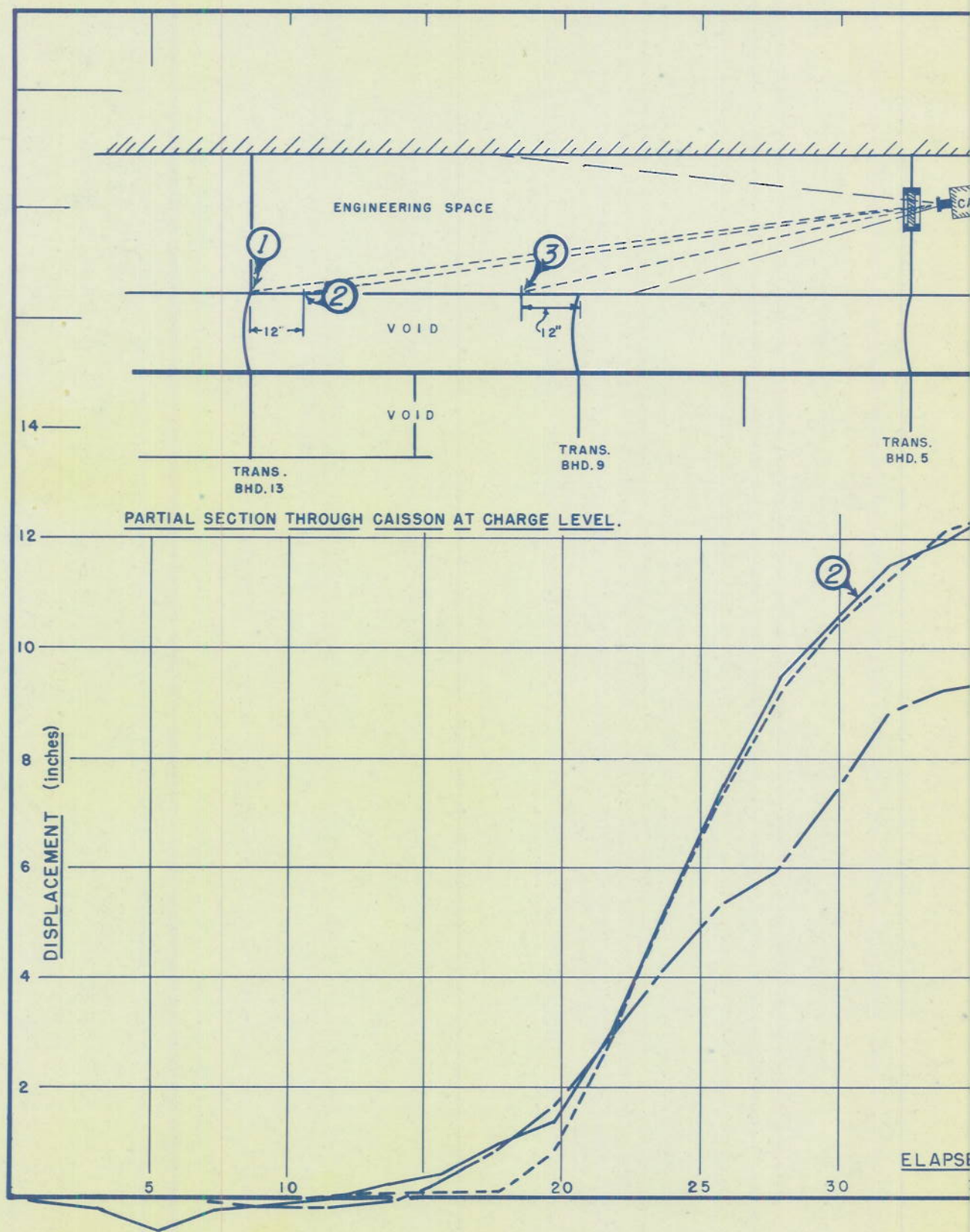
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A REVIEW OF THE REPORT ON THE CAMERON TRIALS

J. P. Walsh, NRL

Trials were conducted on H. M. S. CAMERON, an ex-United States Town Class Destroyer, to determine the nature and severity of shock in ships resulting from noncontact underwater explosions. The trials give information for single hull ships up to the point where plastic deformation of the hull commences. This paper reviews the objectives, the procedures, and a few of the results of these trials.

To review, in a short paper, a highly condensed report such as this Report on the CAMERON trials requires that only a portion of the topics in the report be discussed in the review. Those topics chosen reflect the personal interest of the reviewer. It is probable that another reviewer, having different interests, would have chosen for discussion other topics from the Report. To obviate this probability the "Summary" section of the Report is included in its entirety at the end of the review.

No attempt has been made to distinguish between those parts of this review which have been taken directly from the Report and those that have not.

Perhaps the most important results of these trials are the formulae by which the characteristics of the shock motion in various parts of the ship can be estimated in terms of weight, distance, and orientation of the charge. These formulae also provide a guide for future work in single hull as well as double hull ships. The reader is cautioned that there is no evidence that these results apply to other than the elastic range of single hull ships.

This Report reviewed here, is one to which future reports on work in this field of shock-in-ships will be compared. It sets a high standard.

— INTRODUCTION

Prior to the outbreak of the recent war, the devastating damage within a ship resulting from noncontact underwater explosions had not been fully realized. The advent of the magnetic mine, however, made it apparent that almost all the internal gear in a ship was liable to be damaged by this type of shock.

With the realization of the vulnerability of internal gear, steps were taken to make the gear less liable to such shock damage. The severity of the shock test was increased until service damage was duplicated on the shock machine. Equipment was then designed to pass this test. Steps were taken to strengthen those members of heavy machinery which had failed in service but it was necessary to rely upon a theoretical treatment of the problem to yield rules for the design of new equipment and the protection of existing equipment.

At the end of 1941, it became evident that no further progress could be made on the problem until experiments were conducted to test the validity of the action already taken and to determine the parameters affecting shock damage. Accordingly an interdepartmental committee was formed with the following mission:

1. To investigate the nature and severity of shock in warships resulting

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from noncontact explosions and the transmission of this shock to machinery and apparatus.

2. To control and direct experiments necessary to solve this problem.

3. To make proposals both for existing ships and new construction which will enable the machinery and apparatus to function correctly and suffer no deterioration under a repetition of shocks liable to be experienced at sea, to the point which the ship's structure itself will stand.

The Shock-in-Ships Committee studied the theories which existed at the time and found that the many points of difference could be resolved only by direct full-scale trials. The CAMERON, an ex-United States destroyer, was made available to the Shock Committee. She had been damaged severely by bombing while in dry dock and was considered not fit for sea. The object of the trials was to determine:

1. The effect of varying weight, distance, depth, and bearing of explosive charges.

2. The effect of variations in the target ship of the mass supported per unit area of bottom, and the stiffness of shell plating and of hull framework.

3. The relationship between the displacement, velocity, acceleration and deceleration of simple masses supported on the ship's bottom and of typical machinery items similarly situated.

4. The shock effects received by items mounted on bulkheads and decks.

5. The "whipping" motion set up in the ship as a whole.

6. The protection afforded by the introduction of flexible mountings for internal gear.

7. The factors determining the maximum intensity of shock which can be transmitted by the hull to internal gear before failure in the former permits uncontrollable flooding.

8. *Ad hoc* trials of various types of gear to ascertain any particular sus-

ceptibility to damage by shock.

9. Modifications indicated by any of the foregoing to the present instructions for the protection of internal gear from damage by shock.

10. Modifications indicated by any of the foregoing to the nature and severity of shock given by the Admiralty Shock Test for electrical switch and control gear.

The trials were conducted as three series of tests. Series A and B shots consisted of a number of equidistant shots of variable charge weights ranging from 100 to 1,000 pounds, in addition to 300 pound charges at various depths, bearings and distances.

Series C, was made up of the following shots:

1. A series of 50 pound charges fired in a vertical circle ranging from a shot on the beam 10 feet deep to a shot directly beneath the center line of the ship.

2. 300 pound Amatol charges, 50 feet deep, at 100 and 150 feet horizontal distance abeam and a 1,600 pound Minol charge.

Series D, was planned to answer some of the questions which arose during the prior series of shots, and to extend the data gathered during the previous series. This series consisted of the following shots:

1. Two 50 pound charges, directly astern, to measure whipping. (1D and 2D)

2. Two further of shots in Series A and B. (3D and 4D)

3. 300 pound charges of Amatol, Minol, Torpex, and Gunpowder to measure their relative effects. (5D₁ to 5D₆)

4. 10 and 25 pound charges, at normal incidence, and at 60° to obtain further information on light charges.

5. Two 50 pound charges 60 feet beneath center line of the ships - one amidships, one well forward. (10D and 12D)

6. A 300 pound charge 100 feet from shell plating with angle of incidence of 60° to the ship's bottom. (11D)

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7. Two 25 pound charges 25 feet deep - one just off and one directly beneath the stern. (16D and 17D)

8. A bulk and a line charge of 100 pounds each on the sea bottom directly beneath the ship. (18D and 19D)

9. 180, 300, and 600 pound charges at 100 feet normal to shell plating at the points where the majority of readings were taken. (Shots 13, 14, and 15D)

Figure 1 shows the locations of the shots which were fired abeam of the ship.

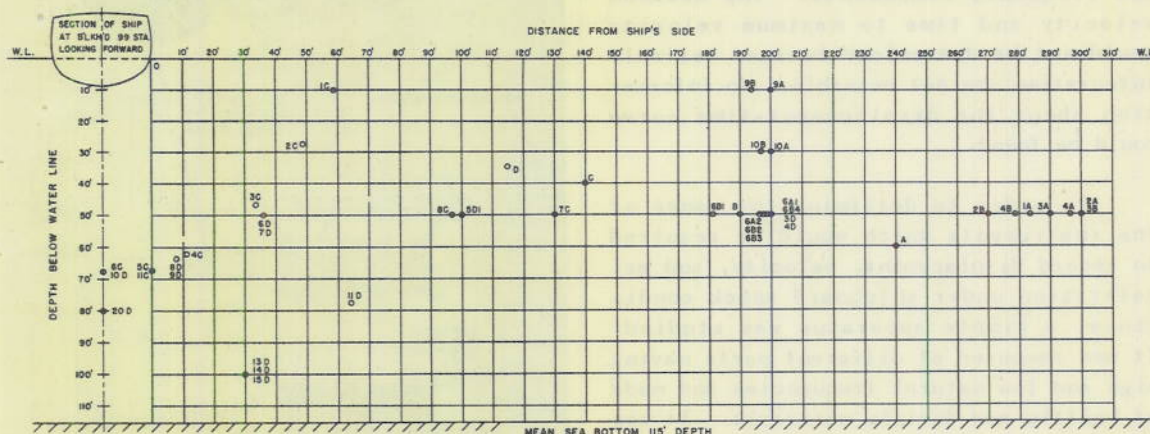


Figure 1. Elevation showing position of beam shots relative to section of ship at 99 station

INSTRUMENTATION

A complete discussion of the instruments, the recording methods, the amplifiers, instrument room layout, etc., is given in the Report, as well as the theory of operation of the instruments used for the trials.

Extensive tests on shock recording instruments were conducted and it was concluded that shock recording in ships can be best carried out using velocity recording instruments, resonance meters (reed gages), maximum and relative displacement indicators and copper crushers.

Since this conclusion is important, particularly in regard to velocity meters,

and since it is one which has been the subject of a great deal of discussion among those responsible for the planning of tests, the main line of reasoning followed to reach these conclusions will be repeated here.

"Shock" is a term used to define certain types of change of motion. In practical cases of shipboard shock due to noncontact explosions, the shock motions are characterized by a velocity change from zero to maximum velocity in a time

of the order of 10 milliseconds or less followed by a damped vibration having a fundamental frequency of about 100 cps plus higher frequency components. These frequencies depend, of course, upon the structure. The high frequency components are of small displacement amplitude. A representative shock motion was chosen and the displacement-time, velocity-time, and acceleration-time records of this motion were considered.

From the slope of the displacement-time curve, approximations could be made of the maximum velocity, the time to maximum velocity, and acceleration at the start of the record. The low frequency component is clear but no trace of the high frequency component is visible.

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From the velocity-time record, the maximum velocity and time to maximum velocity could be accurately determined. The acceleration associated with the velocity change could be found. Both the low and high frequency components were visible and could be accurately measured. The displacement-time curve could be found by integration.

On the acceleration-time record the high frequency component obscured the low frequency components. The maximum velocity and time to maximum velocity could not be determined because reliable integration was not possible. No information about the displacement-time curve could be found.

In order to determine the range of the instruments which would be required to record displacement, velocity, and acceleration under shipboard shock conditions, a simple apparatus was studied. It was composed of different parts having high and low natural frequencies and made of brittle and ductile materials. It was shown that a variation in acceleration between $2.45 g$ and $9 \times 10^3 g$ combined with displacements varying between 1.9 and 7.6×10^{-4} inches was necessary to produce damage. The extremes of each would damage one part but not affect others. The extremes of velocity associated with the extremes of displacement and acceleration were 2.5 feet per second and 20 feet per second. This is a narrow range compared with the ranges of displacement and acceleration. Since the range of velocities is small, the extremes can be represented graphically without the one obscuring the other. This is not the case for displacement or acceleration due to their wider ranges. For these reasons the principal instrument used to obtain time records of the shock motion was the velocity meter.

Description

The velocity meter (see Figure 2) consists of an electromagnet provided with an

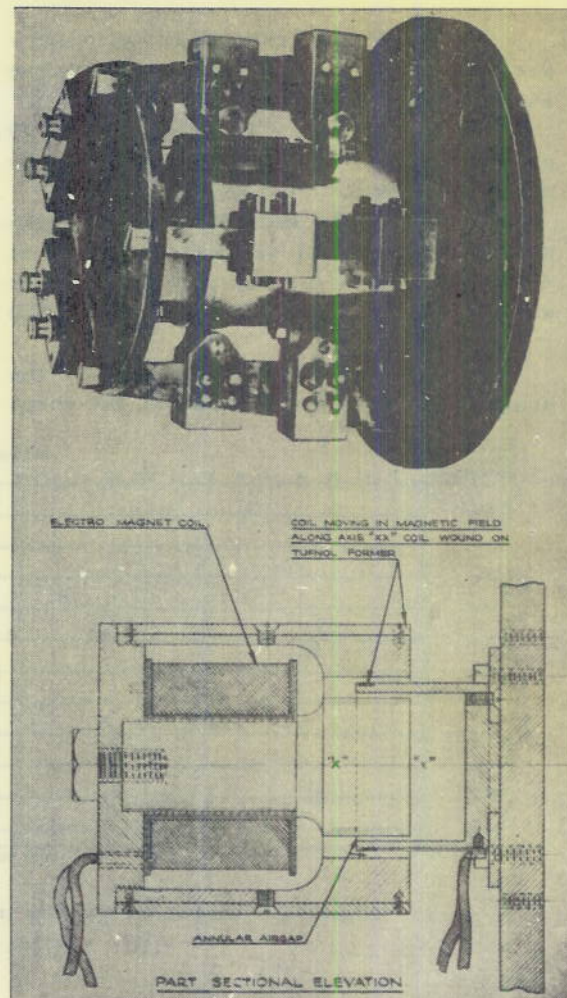


Figure 2. Diagram and photograph of velocity meter

annular air gap. The magnet is constrained to move in a straight line by means of rollers and is located by means of springs. A coil, fixed to the base, is located in the annular air gap of the magnet. When used for recording shock motions, the base of the instrument is bolted to the structure whose motion is being studied. The movement of the coil relative to the magnet produces a voltage in the coil proportional to the relative velocity between the coil and magnet.

The relative displacement indicator indicates the maximum relative displacement in a given direction between two items. The instrument consists of a pin

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free to slide in a block. For example, the block was attached to a shock-mounted apparatus and the pin rested on the deck. Under shock, the pin was forced to move in the block by the motion of the apparatus relative to the deck. The displacement of the pin in the block measured this relative motion. The instrument was also used to measure elastic and plastic dishing of the shell plating.

The resonance meter (reed gage) consists of a frame supporting cantilever steel reeds which have masses attached to the free ends. The maximum displacements of the masses relative to the base of the instrument are recorded by pencils tracing on paper. The instrument allows a calculation to be made of the relative maximum accelerations which items of different natural frequencies receive from an explosion. It also gives a measure of the maximum relative displacement which occurs between items, having corresponding natural frequencies, and their supports. The instrument used had reeds whose fundamental natural frequency ranged from 5 to 100 cps.

The copper crusher unit consists of a copper pellet, about 5 mm in diameter and 7 mm long supporting a 10 pound weight. Under shock, the weight exerts a force on the pellet proportional to the acceleration of the weight. The force causes the pellet to deform. This deformation is measured and compared with a static calibration of the unit. This gives a measure of acceleration to which the unit has been subjected. It is a peak reading accelerometer.

PARAMETERS

In order to determine the characteristics of the shock motion imparted to equipment supported by the ship's bottom, special foundations were designed. These foundations, supporting special castings, were installed so that they were supported by clearly defined areas of the ship's

bottom. Both casting and foundations were instrumentated with velocity meters. Typical items of machinery were also instrumentated.

A theoretical study was made of the mechanics by which the energy of the pressure wave in water, due to an explosion, appears as energy in the ship's structure and in items supported by the ship's structure. This was done in order to correlate the results, to allow an estimate to be made of what might happen under different conditions, and to check the equations derived from the observed results.

When a compressive wave strikes the hull plating of a ship, a tensile wave is reflected accompanied by a movement of the plating. The pressure wave resulting from an explosion in water can be described as a rise to a peak pressure in a time so short that it is usually considered instantaneous. The rise is followed by an exponential decay. When the sum of the compression and the tension at any point in the water exceeds the critical tension which water can sustain, separation takes place. The separation limits the impulse delivered to the ship's plating and allows a layer of water to be entrained with the plating. It was on this consideration of "Impulse to cut-off" that the theoretical expressions were derived.

Shots were fired, as described previously, to give information on the effect of variations of weight of charge, distance of charge, and orientation of charge on the characteristics of the shock motion. It is shown that within the elastic range of the plating the characteristics of the motion imparted to equipment supported by the ship's bottom vary as $(\frac{W \sin \theta}{D})^{1/2}$ where θ is the angle of incidence of the pressure pulse on the shell plating; W is the weight of charge and D is the distance of the charge from the plating.

The following formulae derived for the characteristics are shown to be ap-

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proximately correct by comparing them with observed results.

$$\frac{10^3}{(M)^{1/2}} Q_A \text{ feet per second}$$

$$\text{Maximum Acceleration} = \frac{135(S_1)^{1/2}}{M} Q_A$$

feet per second per second

$$\text{Maximum Deceleration} = \frac{150(S_2)^{1/2}}{M} Q_A$$

feet per second per second

$$\text{First Peak of Displacement} = \frac{3.8 \times 10^3}{(S_2)^{1/2}} Q_A \text{ inches}$$

$$\text{Where } Q_A = \frac{(W \sin \theta)^{1/2}}{D} - \text{a small quantity (.015)}$$

S_1 = Stiffness of the panels of the shell plating relative to framing (Pounds per foot per square foot of plating).

S_2 = Stiffness of hull framework relative to C. G. of section of the ship (Pounds per foot per square foot of shell plating).

M = Weight of the item plus its foundation and frames (Pounds per square foot of bottom).

When diffraction enters in, the factor Q_A is replaced by the factor Q_D , which is

$$\text{equal to } \frac{(W)^{1/2}}{D} \left(\frac{1 + \sin \theta}{2} \right) \dots 0.15. \text{ For angles}$$

greater than 30° , Q_A and Q_D are almost identical.

These equations show that the foundations for machinery should not "spread" the load over a large area of the bottom for this practice would reduce the value of M in the above equations. Reducing M increases the value of the characteristics of the shock motion since it appears in the denominator of the expressions

Figure 3 is a plot of the maximum acceleration of a casting, on a special foundation supported by the ship's bottom, vs. the shock criterion. The accelerations found from the peak reading accelerometers are higher than those derived from the velocity-time records.

Figure 4 shows maximum deceleration for the same condition as Figure 3. Figure 5 is a plot of resonance meter deflections vs the shock criterion. Figures 3, 4, and 5 are examples of the dependence upon this criterion of the various characteristics of the shock motion of equipment supported by the ship's bottom.

It is of interest to note that this criterion $\frac{W^{1/2}}{D}$ lies between peak pressure which is proportional to $\frac{W^{1/3}}{D}$ and momentum which is proportional to $\frac{D}{W^{2/3}}$.

It has been shown that the maximum velocity of a mass supported on the ship's bottom varies as $\frac{(W \sin \theta)^{1/2}}{D}$, hence its kinetic energy varies as $\frac{W \sin \theta}{D^2}$ which is proportional to energy flux per square foot of shell plating. This energy relation is of interest since the equations were based on impulse considerations.

HULL STRUCTURE

The section of the Report on the hull structure contains a detailed account of the structural damage sustained by the ship, a comparison of this damage with the results of enemy action and previous trials, and an analysis of velocity meter records.

Shot 11D (298 pounds of explosive, 64 feet abeam of bulkhead 99, 78 feet deep, $\frac{(W \sin \theta)^{1/2}}{D} = 0.15$) was the first shot

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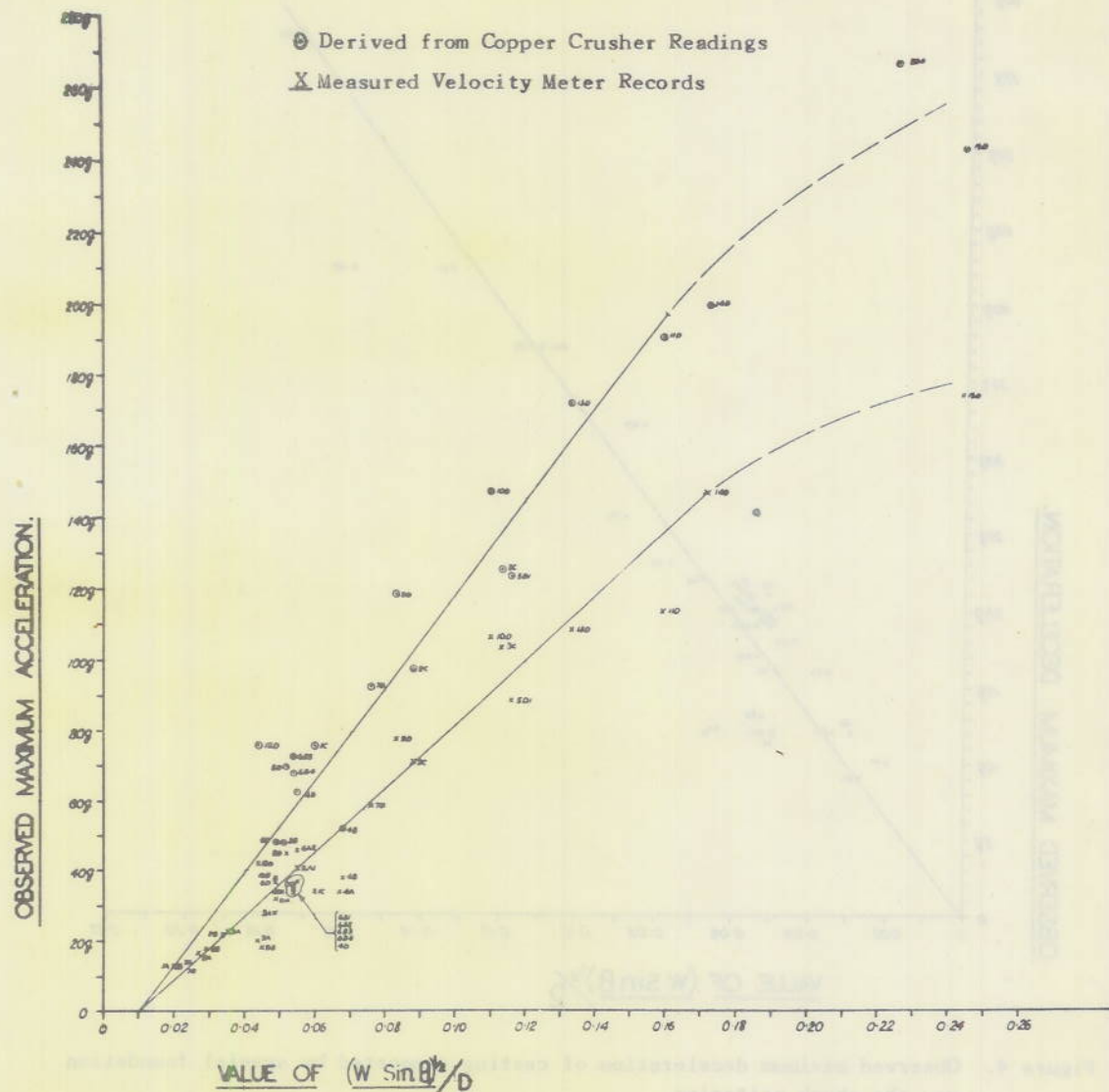


Figure 3. Observed maximum acceleration of casting supported by special foundation vs. the shock criterion.

to cause structural damage which could not be attributed to existing structural weakness. After this shot it was found that the framing at the turn of the bilge on the starboard side showed a marked tendency to tear away from the shell plating.

It is of interest to note that in the Taylor Model Basin report by Thomas and

Parkinson on "The Depth Charge Structural Firing Test of the Destroyer BELL" it is concluded that only minor damage would result in this type of ship for weights of charges and orientations which give $(W \sin \theta)^{1/2}$ a value of 0.12, approximately.

^DFrom the analysis of hull data, it was found that values of maximum initial

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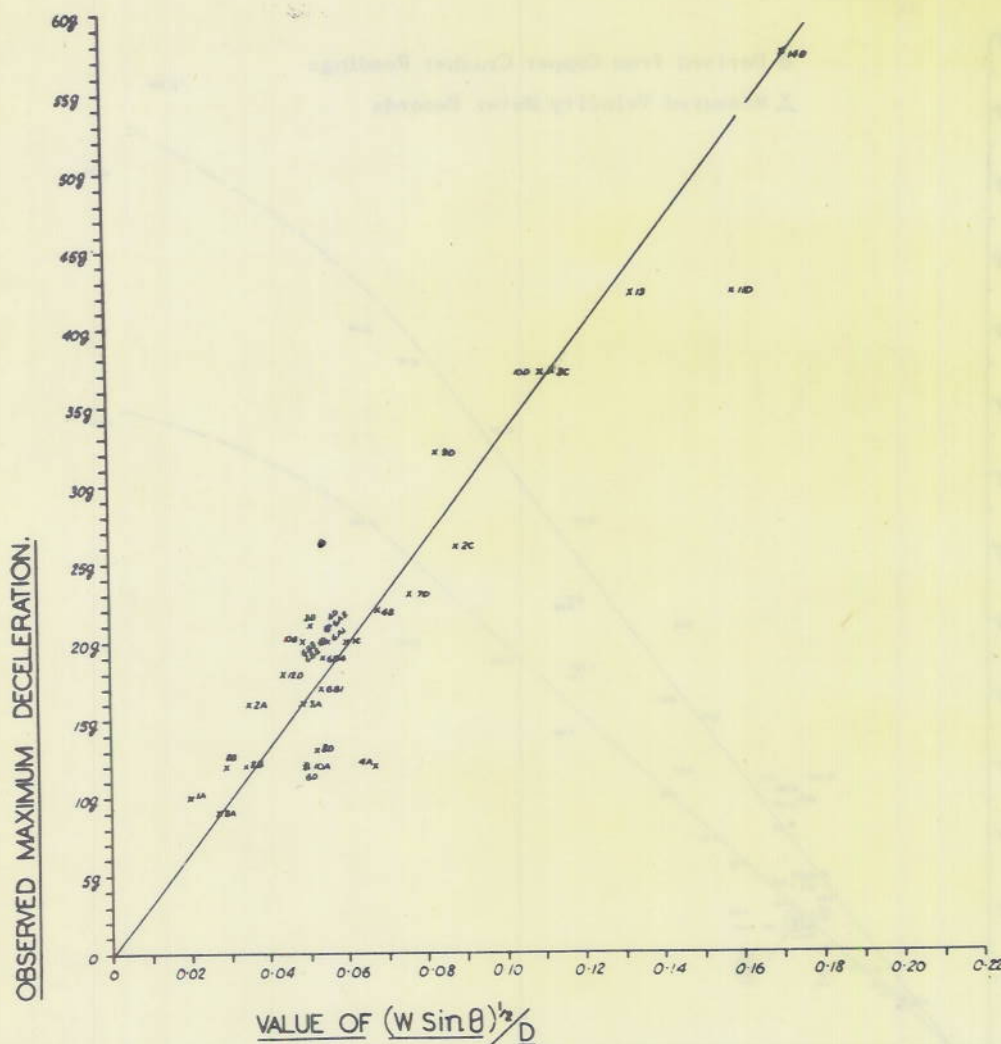


Figure 4. Observed maximum deceleration of casting supported by special foundation vs. the shock criterion.

velocity and maximum initial displacement for positions on shell plating, frames, and keel tops were proportional to $\frac{(W \sin \theta)^{1/2}}{D}$ where W is weight of charge

in pounds, θ is angle of incidence of the pressure pulse on the shell, and D is the distance of the charge from the point being considered. The maximum initial velocity of shell plating reached values of the order of 35 feet per second for val-

ues of $\frac{(W \sin \theta)^{1/2}}{D}$ of 0.167. Typical displacement-time curves are shown in Figure 6. The various velocity meter positions are shown:

- IV_v = Vertical, center of bulkhead 99
- 2V_v = Vertical on special casting on ship's bottom between frames 93 and 94
- 30V_v = Vertical on keel top - frame 88

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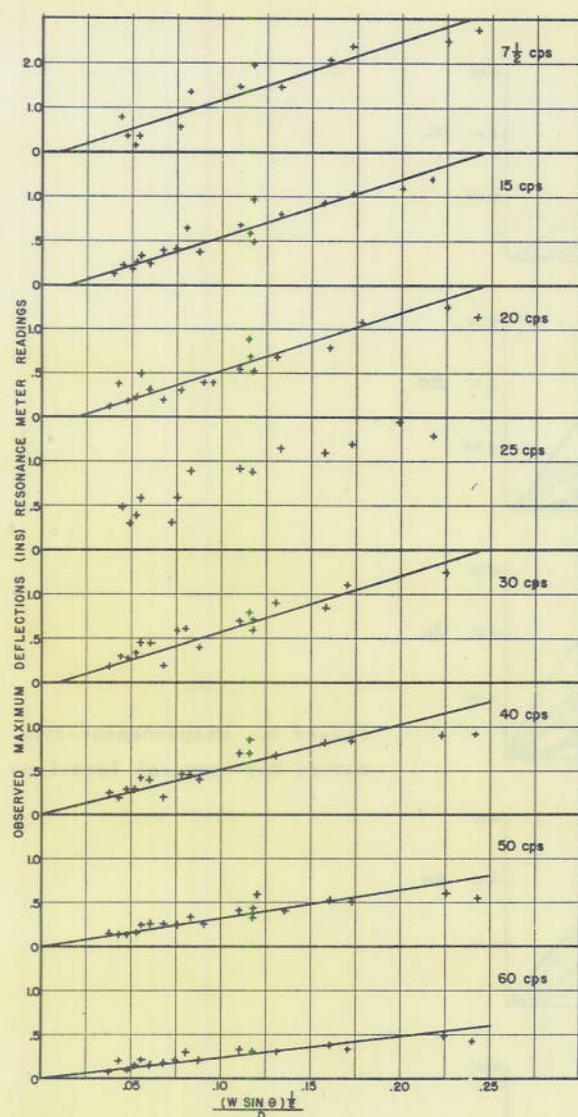


Figure 5. Resonance meter readings vs. shock criterion for one casting on special foundation vertical motion.

38V_v = Normal to shell plating

39V_v = " " " "

40V_n = Normal to top of floor angle -
frame 101

It is shown by the slope of these displacement curves that while external parts of the ship are subjected to high

initial velocities, internal parts of the ship and relatively heavy items attached to these external parts of the ship have much lower velocities.

Critical Severities of Shock

A ship's equipment should be resistant to shock up to a point at which hull damage causes uncontrollable flooding. The range of the CAMERON tests was such that little permanent damage of the hull was caused.

There is evidence from action damage and experimental results that a major rupture occurs in the bottom of single hull ships when the value of the shock

criterion $\frac{(W)^{1/2}}{D}$ is about 0.7 (when $\theta = 1$).

The inner bottom of capital ships will probably rupture when the shock factor is approximately 1.1.

Since the results of the CAMERON trials give information only up to values of .2 for the shock criterion, the designer must extrapolate the results up to the value for uncontrollable flooding.

If the hull were elastic up to the point of failure, it would be reasonable to suppose that the various characteristics would be linear with the shock criterion. Since the hull is not elastic up to the point of failure linear extrapolation is not permissible. For the single hull vessel there is some slight evidence that the various characteristics of the shock motion can be extrapolated from values of the shock criterion at 0.2 to values at 0.7 by making the slope of the line from 0.2 to 0.7 one half of the slope of the line from zero to 0.2.

CHARACTERISTICS OF SHOCK ON BULKHEADS AND DECKS

The characteristics of the shock motion on three bulkheads and three decks

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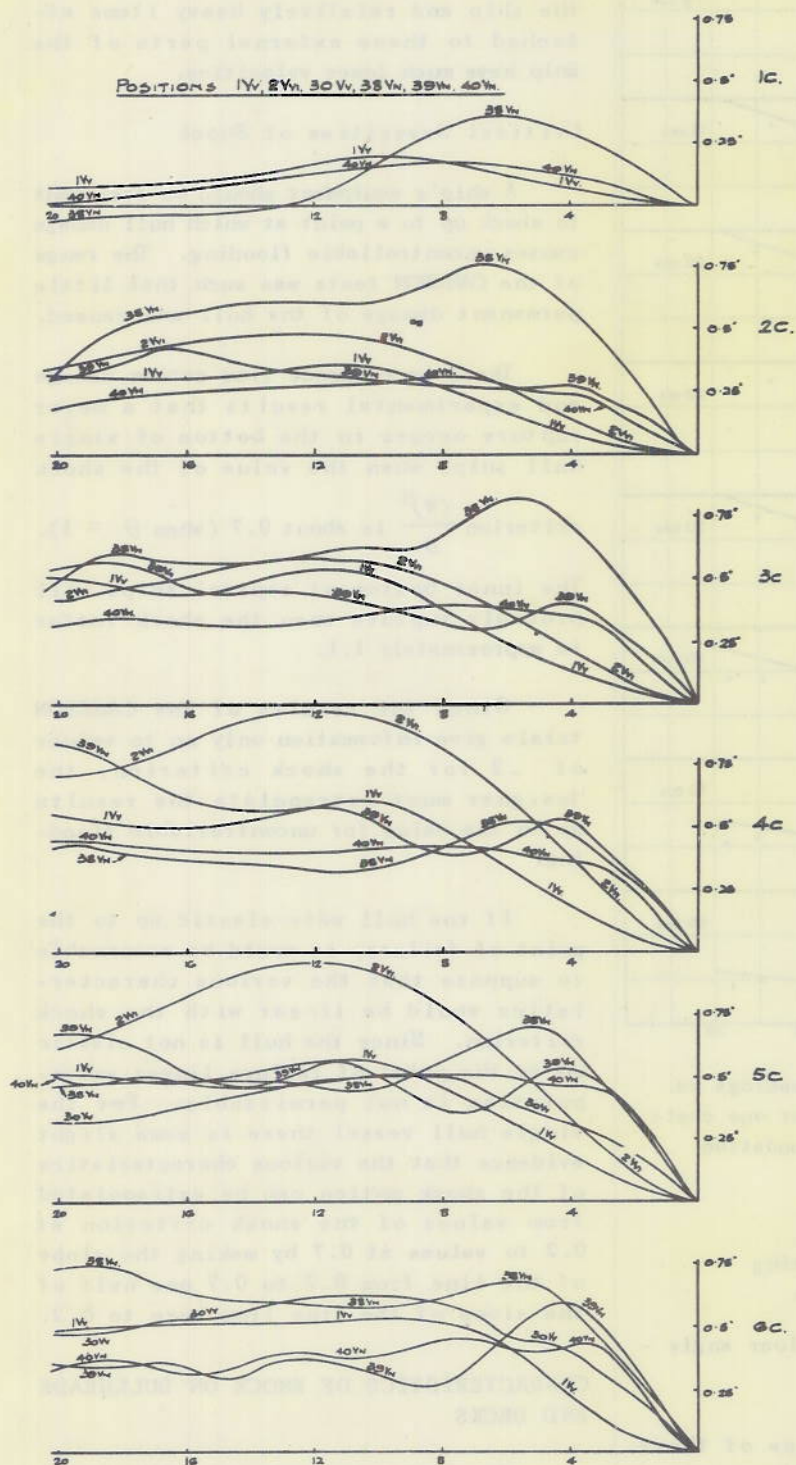


Figure 6. Displacement-time curves for several locations.

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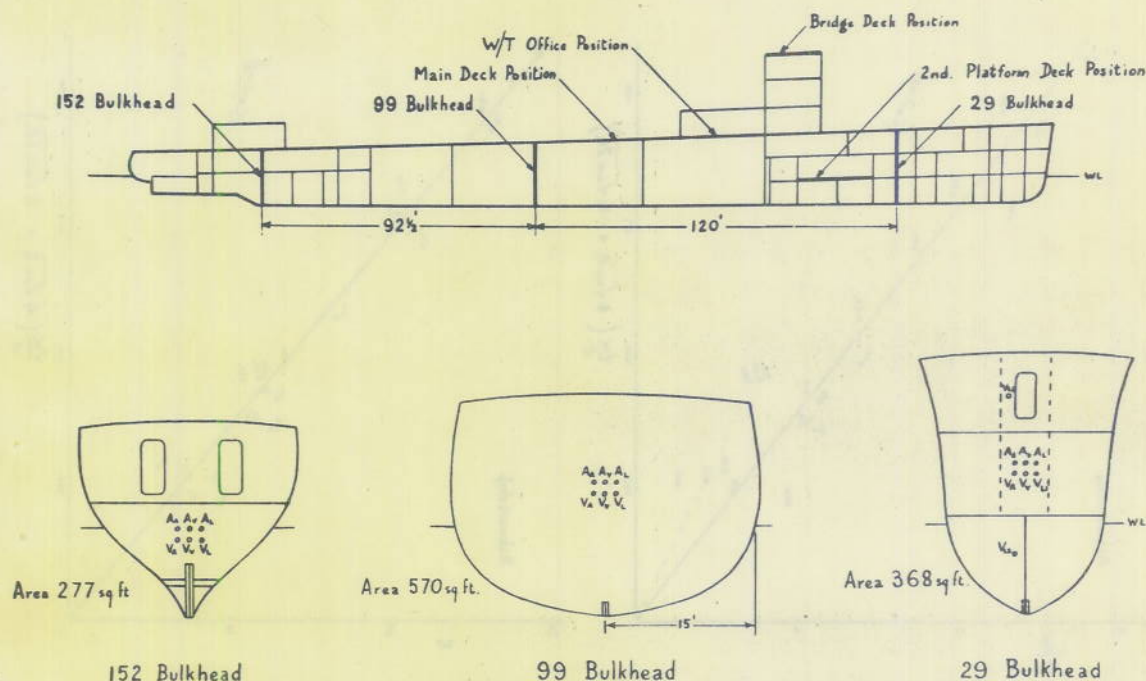


Figure 7. Location of decks and bulkheads instrumented.

were measured. The locations of these bulkheads and decks are shown in Figure 7.

The instruments were, in general, located on brackets and bases on the bulkheads and decks. A few measurements were made on a half ton casting on bulkhead 99. On the second platform deck the velocity meters were mounted on bases secured to the deck and also on a half ton casting on this deck. On the main deck, the characteristics were recorded on a one ton casting and on the top deck of the superstructure the velocity meters were mounted on a two ton casting.

The report contains: (1) typical examples of the velocity meter records obtained at these positions, and (2) plots which show the effect of distance, weight and orientation of charge upon the maximum values of displacement, velocity, and accelerations, as well as tabulated values of these characteristics.

Bulkheads (See Figures 8 and 9)

It is shown that the shock characteristics of the bulkheads in the vertical, and fore and aft directions are proportional to $\frac{(W \sin \theta_1)^2}{D}$. Where W is the

weight of the charge, θ_1 is the angle between the horizontal and a line joining the center line of the bulkhead at the water line and the charge, and D is the distance from the center line of the bulkhead at the water line to the charge. Notice that θ_1 is different from θ . It was found that the maximum values of velocity and accelerations in the athwartships direction are proportional to $\frac{W^{1/2}}{D} [0.4(\sin \theta_1)^{1/2} + 0.6(\sin 2\theta_1)^{1/2}]$.

The frequencies found on the velocity meter record depend upon the direction in which the measurement was taken. In the case of vertical measurements the fre-

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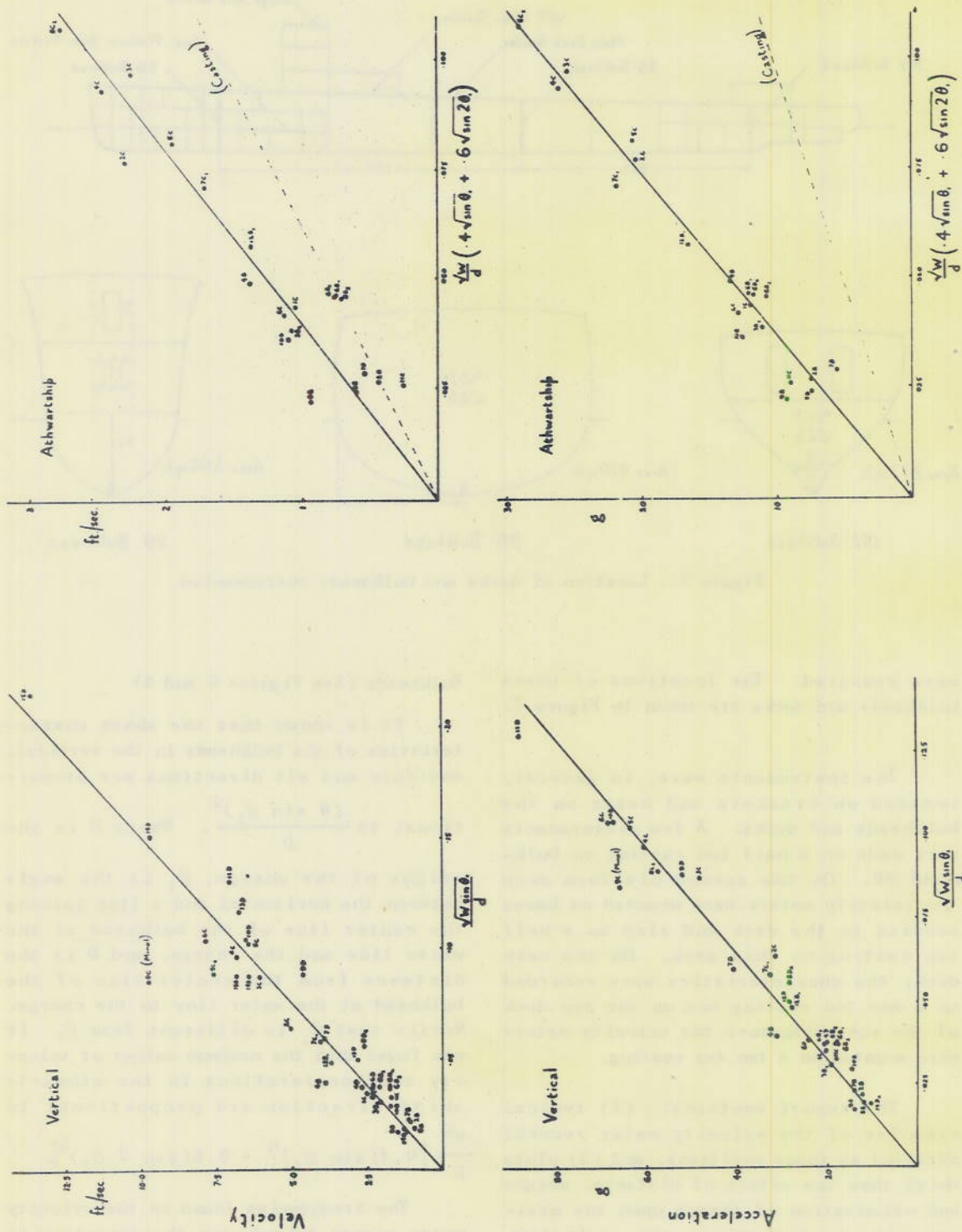


Figure 8. Observed values of the characteristics of the shock motion on bulkhead 99 vs. the shock criterion.

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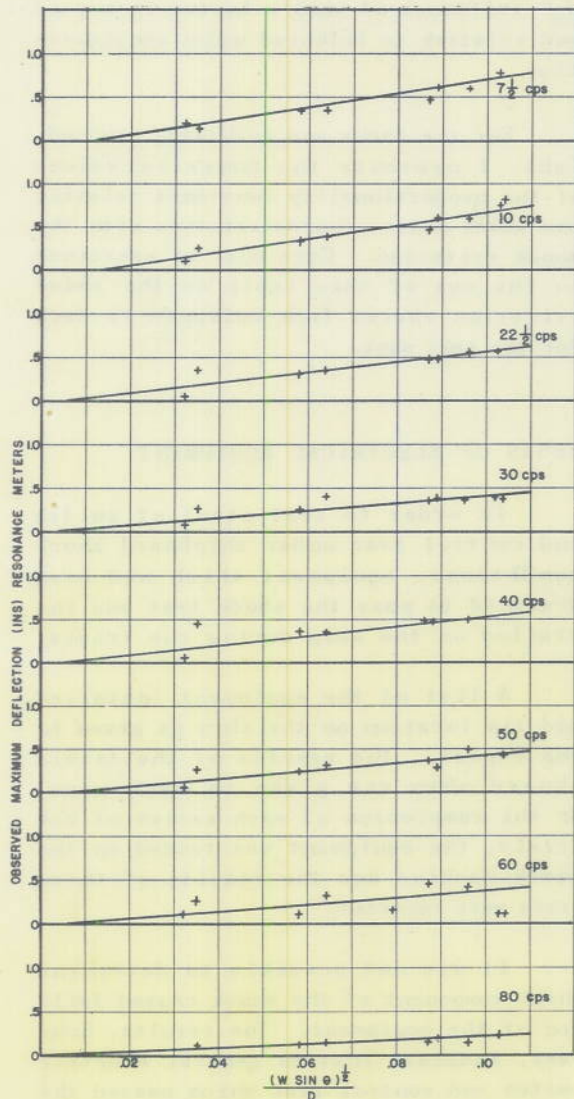


Figure 9. Resonance meter readings vs. shock criterion for bulkhead 99 vertical motion.

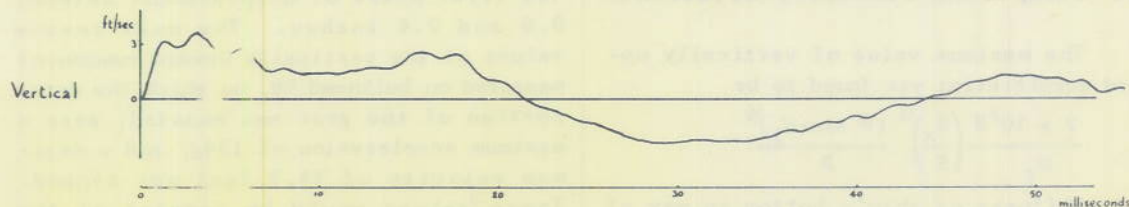


Figure 10. Typical velocity-time record taken on the main deck.

quency of oscillation was between 80 and 100 cps, and an oscillation at a frequency of 2-3 cps due to whipping. The fore and aft component had a frequency of about 80-100 cps and a lower frequency component due to the vibration of the bulkhead as a diaphragm at frequencies between 20-50 cps. The frequency in the athwartship direction was about the same as the vertical.

Decks

The characteristics of the shock on the second platform deck included vibrations at frequencies of 190-200 cps, 60-65 cps, and 10 cps. The half ton casting on this deck received oscillations at 10 cps, the higher frequencies being sensibly absent. On the main deck the vibrations were at frequencies of 400-500 cps, 80-100 cps and 13-14 cps. The one ton mass on this deck received vibrations at 13 cps. Figure 10 is a typical velocity meter record taken on this deck. The two ton casting on the top superstructure deck oscillated at 18 cps.

The maximum values of acceleration, velocity and the first peak of displacement for a deck has been found to be proportional to the average of the shock criterions for the bulkheads forming the support for the deck.

Any attempt to predict the severity of shock on various bulkheads from a knowledge of the shock motions of one bulkhead, with any claim to rigor, would be very complex. It is possible, by making suitable approximations, to obtain an estimate of the vertical shock experienced on bulkheads from a knowledge of the

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behavior of one bulkhead under shock conditions. It was shown that the maximum velocity of an item supported by the ship's bottom is inversely proportional to the square root of the weight per square foot of shell plating. (See PARAMETERS, page 63.)

Treating athwartships bulkheads as items supported by the ship's bottom, assume that $V_m = \frac{k}{\left(\frac{M_t}{BX}\right)^{1/2}} \cdot \frac{(W \sin \theta_1)^{1/2}}{D}$

V_m = Maximum Vertical Velocity

M_t = total weight of bulkhead and gear on athwartships bulkhead

B = beam at water line at bulkhead section

X = effective width of shell plating from which the bulkhead receives its motion

K = some constant

or
$$V_m = \frac{K X^{1/2}}{\left(\frac{M_t}{B}\right)^{1/2}} \cdot \frac{(W \sin \theta_1)^{1/2}}{D}$$

From the tests $KX^{1/2}$ has been found to be

For bulkhead 99, $KX^{1/2} = 1,200$

For bulkhead 29, $KX^{1/2} = 1,220$

For bulkhead 152, $KX^{1/2} = 1,160$

It appears that the expression

$$V_m = \frac{1200}{\left(\frac{M_t}{B}\right)^{1/2}} \cdot \frac{(W \sin \theta_1)^{1/2}}{D}$$

gives the maximum velocity on any bulkhead to a fair degree of accuracy. The constants found from the data are in good agreement although the bulkheads chosen for study were radically different.

The maximum value of vertically upward acceleration was found to be

$$\frac{2 \times 10^5 B}{M_t} \left(\frac{S_x}{S}\right)^{1/2} \frac{(W \sin \theta_1)^{1/2}}{D}$$

S = stiffness of ship's bottom in way of and relative to bulkhead 99

S_x = stiffness of ship's bottom in way of and relative to bulkhead under consideration.

For the decks and bulkheads studied, Table I presents the numerical values of the proportionality constants relating the shock motion characteristics with the shock criterion. Care must be exercised in the use of this table as the shock criterion varies from bulkhead to deck for the same shot.

TESTS OF ELECTRICAL EQUIPMENT

In order to test items of switch and control gear under shipboard shock conditions, equipment which had been designed to pass the shock test was installed on the ship during the trials.

A list of the equipment installed and its location on the ship is given in the report. The results of the trials aboard ship are given in each case. At the completion of each series of the trials, the equipment was tested on the shock machine and the results of these tests were recorded.

It was not possible to determine which component of the shock caused failure of the equipment. The results, however, indicate that in general electric switch and control gear which passed the shock test started to fail when the value of the vertically upward components of acceleration derived from velocity meter records reached values of 70-90 g. Associated with these accelerations were maximum velocities of 7-10 feet per second and first peaks of displacement between 0.6 and 0.8 inches. The most severe values of the vertically upward component measured on bulkhead 99, on which the major portion of the gear was mounted, were a maximum acceleration of 134g, and a maximum velocity of 14.2 feet per second. These values would be greater at the critical severity of shock level.

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Table I. Values of "k" for estimating the various components of the shock.

INSTRUMENT POSITION		VELOCITY METERS									ACCELEROMETERS			COPPER CRUSHER
		VERTICAL			ATHWARTSHIP			FORE & AFT			VERTICAL	ATHWARTSHIP	FORE & AFT	VERTICAL
		Max Veloc. ft/sec	Max Acc g	Δ ins	Max Veloc. ft/sec	Max Acc g	Δ ins	Max Veloc. ft/sec	Max Acc g	Δ ins	Max Acc g	Max Acc g	Max Acc g	Max Acc g
99 Bulkhead	- Position 1	66	620	6	25	270	1.5	49	630		1200	670	1100	900
"	- Position 55 (Casting)	66	620	6	16	100		14	72					
29 Bulkhead	- Position 26 (1)	61	475	5	27.5	230		25	200					
"	- " (2)							67	840					
"	- " (3)							42	480					
152 Bulkhead	- Position 27	55	1820	4.5	24	129		53	500					
2nd Platform Deck	- Position 25 (Casting)	40	116	6										
"	- Position 34	62	900	4										
Main Deck	- Position 18 (Casting)	85	210	13.5										
Top (Bridge) Deck	- Position 49 (Casting)	54	175	10										

 Δ represents first peak of displacement

It is of interest to note that the shock test used by the British consists of a 5 foot blow with the vertical hammer and 2½ foot blows in the two horizontal directions. On the other hand, we use 5 foot blows in all directions for electrical equipment. It appears as if the two tests are equivalent, since the top blows are equal and it is in the vertical direction that equipment must be most shock resistant.

Since the values of the acceleration and velocity are a function of the weight of the section of the ship in which equipment is located, it is probable that equipment installed in larger types of ships may be subjected to less severe shock than that on the CAMERON. The severity of the shock test in the vertical direction is less than that which may be experienced by destroyers at sea, even though the characteristics are roughly similar.

SUMMARY

This report, which is divided into sections, deals with the nature and severity of shock in ships due to non-contact underwater explosions.

Introductory Section (B.R. 1314 (2))

This section reviews the problem, and gives short summaries of the work of other investigators, which have a direct bearing on the solution of the problem.

The main object of the Trials concerned the movement of the ship's structure, but various phenomena in the water were also dealt with.

Sections 11 and 12. (B.R.s1314 (15))

These sections deal with the magnitude and pressure-time history of the

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main pressure pulse indicated from various explosives, and the effects of bottom and surface reflection on the pulse.

Over the range of weights used, the maximum pressure in the pressure pulse is proportional to the cube root of charge weight, and inversely proportional to the distance from the charge.

In this section is described the form of the pressure-time curve and the efficiency of reflection from the sea bed.

A comparison is made between the effects produced in the ship by similar charges of Amatol, Torpex, Minol and gunpowder, and it is shown that the shock effects from Minol and Torpex are equivalent to those produced by between 140 percent and 150 percent of their own weight of Amatol. The shock effects produced by gunpowder were equivalent to those produced by one-tenth of the weight of Amatol.

Section 6. (B.R. 1314 (11))

This section deals with the secondary pulses radiated from the oscillating explosive bubble during its upward excursion towards the sea surface, and the surface phenomena domes and plumes which occur after an explosion.

Formulae are given for estimating the time interval between the first and second expansions of the bubble, and empirical formulae are given for the time interval between the main, second, third, and fourth pulses.

Tables and curves are given containing the following data for charge weights between 25 pounds and 1,600 pounds:-

- (1) Initial velocity of the dome.
- (2) Maximum diameter of the dome.
- (3) Maximum height of the dome.
- (4) Time to maximum height of the dome.

- (5) Maximum velocity of the plume.
- (6) Maximum height of the plume.
- (7) Time for the plume to break surface.

Section 1. Parts 1 and 2. (B.R.s 1314 (3 and 4))

This section gives a critical survey of the factors influencing the movements of the ship's structure and of items connected thereto.

The theoretical considerations leading to the adoption of the "Impulse to cut-off" method of analysing results is given, and a method is given for estimating the mass of water entrained with the shell plating for explosions at different orientations.

The effects of movements of the shell plating on the time to cut off, the effect of sea surface cut off, and cases where diffraction is likely to be of importance are considered at length.

A comparison is made between the observed values of the motion of various items installed for trials and values obtained from the theory.

The energy distribution is examined, and it would appear that about 50 percent of the total energy in that portion of the pressure pulse which is received by the hull plating (to which items are attached) appears as kinetic energy of the item.

Simplifying formulae are derived, and the movements of items are approximately proportional to $\frac{(W \sin \theta)^{1/2}}{D}$ when

diffraction can be neglected, and to

$\frac{W^{1/2}}{D} \left(\frac{1 - \sin \theta}{2} \right)$ when diffraction is of importance.

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Section 4. (B.R. 1314 (8))

This section gives the structural damage sustained by the ship, and also an analysis of certain velocity-time records taken on the hull structure.

The results of enemy action and of previous trials are surveyed, and it is shown that in the appropriate range the structural shock damage sustained in the CAMERON is of the same nature as that recorded in other instances with single hull ships. It appears from the survey of war damage that structural shock damage may reduce the watertightness of the internal structure of a ship sufficiently to cause appreciable extension of the flooding boundary. In cases where water does not enter the ship, serious flooding with oil fuel may occur.

For ships of the single hull destroyer type, the value of $\frac{(W)^{1/2}}{D}$ 0.7 is derived, at which maximum shock severity to machinery and fittings may be expected before uncontrollable flooding ensues.

Certain recommendations are put forward for consideration in connection with the design of main and auxiliary machinery seatings.

Section 5. (B.R. 1314 (10))

This section deals with the whipping of the ship, and gives the results of the analysis of cine films, showing the vertical oscillatory motion of the ship.

In certain cases the motion of the ship depends to a large extent on the pulses due to the oscillation of the gas bubble, as well as on the initial pulse.

A method for determining the nodal points and the frequency of vibration in the primary vertical mode are given.

The maximum estimated half amplitude which occurred on the trials was 1.7 inch amidships and 7.3 inch at the after end.

Section 3. (B.R. 1314 (7))

This section deals with the nature and severity of shock experienced on bulkheads and decks. An analysis is given of the accelerations, velocities, and first peak of displacement, together with the predominant initial and final frequencies of oscillation.

The effect of weight, distance and orientation of charge on the severity of the shock experienced was determined from the experimental results. Formulae were derived for estimating the severity of shock on bulkheads and decks in terms of weight, distance and orientation of charge, and mass and stiffness of the loaded structure.

Section 2. Parts 1 and 2. (B.R. 1314 (5 and 6))

This section deals with the shock effects received by machinery items. Part 1 gives the values of the components of motion obtained, and in Part 2 the various types of failure are analysed. Failures have almost invariably been more easily explicable as resulting from excessive bending moments, rather than by the passage of stress waves.

The theoretical effects of flexibility, the behavior of flexible mountings for machinery, and the effect of bodily upward motion of the ship on flexibly mounted items, are discussed and examples are given.

Section 8. (B.R. 1314 (13))

This section gives the results obtained on electrical items, including switch and control gear instruments, lamps and lighting fittings, radio and Asdic gear, L.P. batteries, etc.

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The practical results achieved by the use of resilient mountings are given, and a comparison is made between the characteristics of shock given by the Admiralty Shock Test for electrical switch and control gear, and those measured on this trial.

Section 4A. (B.R. 1314 (9))

This section gives a brief account of the behavior of certain fittings, including gearing and copper tubing, piping, ventilation gas flaps, W.C.s, bottlecrack clips, fire extinguisher clips, watertight door hinges, hatches, lattice mast, pumps, etc., installed for shock trials.

Section 9. (B.R. 1314 (14))

This section is theoretical, and deals with the shock effects likely to be experienced by items in the ship from noncontact explosions which would just cause uncontrollable flooding.

Section 7. (B.R. 1314 (12))

This section deals with the effect on the tensile properties of steel and

cast iron when the load was applied for the short interval of time caused by underwater explosions. It is shown that there is a considerable increase in the ratio of dynamic to static proof stresses for mild steel under these conditions, but considerable work still remains to be done before this problem is brought to a satisfactory conclusion.

Section 13. (B.R. 1314 (16))

This section gives the theory, advantages, and disadvantages of the different types of instruments employed for shock recording, and indicates that the electromagnet instrument of the seismographic type is probably the most suitable for shock recording.

Section 14. (B.R. 1314 (17))

The apparatus used and the layout of the instrument room are described in detail, and prints of the complete series of oscillograph records obtained on the trials are given in this section.

* * *

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EVALUATION OF INERTIAL OPERATED DEVICES

J. H. Armstrong, NOL

This talk, given at the Third Shock and Vibration Symposium, was not published with the other NOL papers in the preceding Bulletin because of its classification. The Committee considers this information of value even though printed apart from the NOL material.

Many of the principal types of weapons developed by the Bureau of Ordnance include one or more devices which depend for their operation upon the inertia forces developed in them by shock applied to the weapon of which they are a part. Familiar examples include contact torpedo exploders, base detonating shell fuzes, and bomb tail fuzes. Arming arrangements for projectile fuzes may be actuated by the set-back acceleration during firing of the projectile from the gun, or from the centrifugal spin force. Akin to strictly inertia-operated devices are bomb, rocket and projectile nose fuzes which are fired by a sudden, directly-applied force on a movable element, acting in conjunction with the inertia of the missile as a whole.

There are in general few widely-used standardized testing or evaluation procedures for such devices. This is because there are relatively few inertia-operated mechanisms in use, outside the field of ordnance. Two examples are: (1) inertia automobile starter clutching arrangements and (2) shipboard antishock circuit breaker locks. The Naval Ordnance Laboratory has therefore had to develop several special machines and techniques for determining the conditions under which such devices will and will not function as intended.

The basic principles of operation by which inertia operated devices may function are too varied for ready classification. Examples are: (1) shearing of a wire, (2) closure of a spring-loaded electric switch, (3) displacement of the magnet or coil in a magneto, and (4) triggering of a spring-loaded firing pin. For the sake of convenience in presentation the evaluation methods discussed here are those we apply to torpedo exploders.

In the first place, the exploder is tested to make sure that it will not be damaged by service shocks and vibrations incidental to getting the torpedo started on its run. The problems here are the same as for any other torpedo component, except that the moving elements in inertia devices are more than usually susceptible to damage. Long-duration, high-energy shocks such as those from water impact in aircraft launched torpedoes may produce battering of the moving elements. We use the air guns, with their large available accelerating energy, to make these tests since drop testers used to give the same peak acceleration would not have sufficient duration of shock to insure uncovering possible failures in parts with considerable travel. Likewise, the exploder is subjected to the standard transportation vibration tests. Sensitivity checks on the operation of the exploder are made before and after all tests to

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reveal any effects. A resonance-point investigation made on the vibrator is also of more than usual importance because of the moving parts involved which are likely to be vulnerable to such damage. With respect to possible damage from rough handling, the goal is to develop a device that will not be operationally affected by any rough handling unless it is sufficient to cause visible external damage. The damage must be severe enough to insure its visible recognition and the device not used without repair or retesting.

As in all other ordnance detonating mechanisms, the exploder must be safe against accidental firing from vibration or extreme rough handling when it is in the unarmed or safe condition. In the safety tests, which consist chiefly of severe drop tests in several directions with live loaded components, the exploder is not required to operate after test but it must not fire or become unsafe from the shock.

When the torpedo is making its run and the exploder has armed, the critical part of the exploder performance has arrived; the inertia elements and auxiliary associated devices are then required to exercise proper discretion and fire the warhead only on target shock.

Maneuvers of the torpedo must of course not fire the exploder. The same type of spurious firing possibility also exists in aerial guided missiles. To simulate this condition, we take advantage of the fact that such accelerations are applied relatively slowly as compared to the natural frequency of the exploder inertia system. A centrifuge is used to determine the steadily-applied acceleration required to cause actuation. Since there is a definite hydrodynamic or aerodynamic limit to the possible violence of these maneuvers, an equally definite lower limit to the permissible sensitivity of the exploder can be set and conformance checked centrifugally. The direction of the

maneuvering acceleration is also known, so the positional sensitivity can be designed to give satisfactory sensitivity to target shock along with the necessary insensitivity to maneuvers.

Torpedoes traveling at shallow depth sometimes broach and leave the water. Upon striking the surface at reentry the torpedo experiences a shock of relatively low order but one which can fire a too-sensitive exploder. It may also be subject to countermining shocks from nearby underwater explosions such as from other torpedoes or depth charges. Since a large enough charge exploding at a short enough distance will countermine fire an exploder of any sensitivity, the sensitivity in practice must be adjusted to a compromise value. This will prevent undesired countermine firing but permit a satisfactory target performance. If the desired conditions are such that this is impossible, a separate anti-countermining device must be used which will be actuated by shock and temporarily render the firing mechanism inoperative. The importance of accurate evaluation methods in setting such a compromise sensitivity or testing an anticountermining device is evident. Because the target, broaching, and countermining sensitivities are related in such a close way, they are considered together in setting up a test and evaluation program.

We must also test the exploder to make sure that vibrations occurring during the run will not cause firing when it is in the armed condition. There is a certain amount of vibration present from torpedo power plant operation. Because of resonance possibilities, these tests are necessary even where the minimum acceleration to fire the exploder is far above that present in the applied vibrations. We therefore take curves of the vibration acceleration required to cause firing at various frequencies. Figure 1 shows data obtained on a test of a typical spring-loaded ball-switch type of electrical firing device. Three regions of

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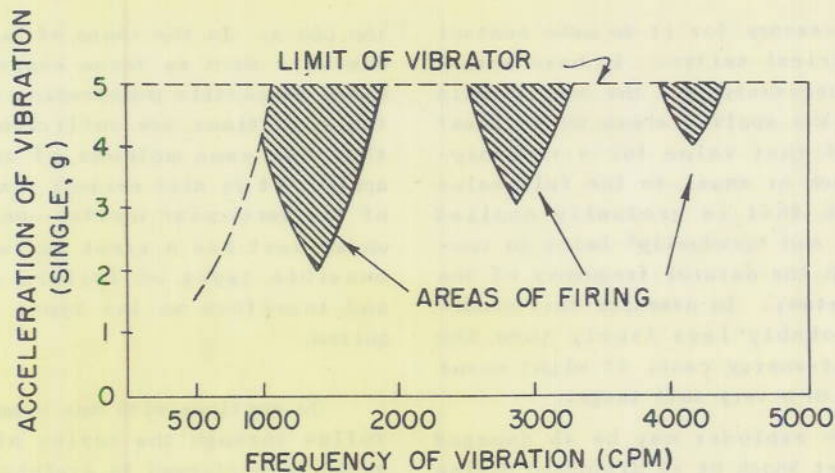


Figure 1. Vibration Firing Test of Exploder

closure within the 500 to 5000 cps range are shown. A similar record is made in two other perpendicular directions of vibration. The actual minimum points in this test are high enough to preclude vibration firing in any normally-operating torpedo. Had the exploder proved much more sensitive to vibration a redesign would have been necessary, or else the vibration ceiling in the torpedo would have had to have been determined with greater precision. In plotting the vibrational sensitivity we use acceleration rather than displacement as the measure of vibration intensity. This is due to a general tendency for the acceleration of service vibrations to remain in the same order in different situations regardless of frequency.

The pattern of shock applied to an exploder by target impact may vary within extremely wide limits. It is affected by the speeds of the torpedo and target, the angle of target impact, the design of the warhead and the weight of the torpedo, the shape and construction of the target, and the point of impact. There are so many possible combinations of the affecting factors that recording all the resulting shock patterns in the field, even with equipment more highly developed than available at present, would be a virtually hopeless task.

Fortunately, there are only a few limiting conditions which determine whether or not the exploder operation is satisfactory. By measuring or calculating these conditions and determining the performance capabilities of the exploder at or somewhat beyond them, we are able to evaluate the operation of the device for all significant conditions.

The principal limiting conditions of target impact which may result in impaired operation are these:

- (1) The energy transfer during impact may be insufficient to operate the exploder. The velocity change to which the exploder is subjected is the measure of the energy available to displace the active elements of the device against friction, spring loading, and their own inertia. If this energy is insufficient, even a very high momentary acceleration cannot cause operation. An example of a type of target impact which may provide insufficient velocity change is a contact between torpedo and target where their relative velocity is very low.

2. The acceleration of the exploder produced by the impact may be insufficient to develop enough inertia force to actuate the exploder mechanism. A certain calculable force is required, for example, to extend a spring-and-mass system the

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distance necessary for it to make contact in an electrical switch. To have actuation it is necessary that the peak inertia force from the applied shock be at least one-half of that value for a suddenly-applied shock or equal to the full value for a snock that is gradually applied ("suddenly" and "gradually" being in comparison with the natural frequency of the exploder system). In practice this condition is probably less likely than the insufficient-energy case; it might occur on impact with a very soft target.

3. The exploder may be so damaged by the target shock or so distorted during impact that its functioning is prevented or delayed. On a hard target hit at high velocity the exploders may separate from the warhead because of the resulting crushing, and if the exploder does not fire within a certain time a dud will result. Delay may also become excessive from the increased friction on moving parts of the exploder as result of the high inertia forces. Parts of electrical circuits may be broken mechanically and normally-closed contacts may chatter, preventing firing.

4. If the exploder is of the type that depends on closing of an electrical circuit to fire a detonator, (on certain high-acceleration snocks of short duration) the contacts may not remain closed long enough to transfer sufficient electrical energy to fire the detonator.

These conditions have been here set up for current types of torpedo exploders. The limiting cases for projectile and other types of fuzes are generally analogous, though the corresponding extreme acceleration and velocity change figures are radically different. For example, the most severe acceleration received by a large torpedo exploder located toward the middle of a warhead of conventional construction will not exceed a few hundred g. on a hard target impact. This is due to the relatively low velocities involved and to the yielding structure of the warhead. The accelerations in a shell striking armor plate may be of the order of

100,000 g. In the range of light impacts, however, such as those experienced by a heavy projectile penetrating light plate, the conditions are sufficiently similar that the same methods of analysis may apply. It is also evident that the design of the particular inertia-operated device under test has a great influence on the possible types of failure of function and therefore on the types of test required.

To continue with our example, we will follow through the series of tests that would be performed to evaluate the target sensitivity of the exploder.

To determine its behavior under light impacts where failure to fire would be due to insufficient shock energy or acceleration, we test the exploder on four machines; the centrifuge, the square-wave tester, sine-wave tester, and the drop tester. The centrifuge produces a very slowly-applied uniform acceleration, thus determining the inertia force required to displace the moving parts of the exploder system sufficiently to cause firing. This information serves as a check on design calculations and as an accurate, rapid way to determine the uniformity of construction and assembly of a number of samples. Since many mechanisms are of a sealed type not subject to checking by measurement or static force measurement, this is a valuable test method. The centrifuge data also serves as a basis for subsequent theoretical calculations such as firing delay time, resonance frequency, and minimum firing energy estimates.

The minimum velocity change which will cause firing is then determined by a series of tests on the square-wave, sine-wave, and drop testers. The last test is used both with various thicknesses of lead pad and steel-on-steel. These tests as well as the centrifuge tests, are made at several angles with respect to the torpedo axis as dictated by symmetry considera-

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tions. This requires several hundred individual tests on the first of a series of exploders being tested, and perhaps dozens on later samples to determine uniformity of performance. We have therefore gone to great lengths to make the test machines as convenient and rapid in operation as possible. Means have been developed for immediate recording of the firing delay time, the duration of the applied acceleration, and the duration of closure or opening of electrical circuits.

The characteristic shapes of the acceleration-time patterns produced by the various testing machines are shown in Figure 2. As we go from the square-wave tester to the steel-on-steel drop tester the duration of the shock applied goes from about 20 milliseconds down to .4 millisecond, while the acceleration increases proportionally at any given velocity change. If the machine parameters (such as weight of carriage, thickness of lead pad, or length of tension rods, etc.) are kept constant in a series of tests on the sine-wave or drop testers as the height of drop is varied, the duration of the shock will remain constant. A series of tests is thus rapidly made, bracketing the point at which the exploder will barely fire, and the average

acceleration of the shock calculated from the duration and velocity change of the shock. In the square-wave tester both the acceleration and the duration of the shock are readily varied. The usual procedure is to make series of tests at constant accelerations, varying the duration until the minimum firing point is reached.

In Figure 3 the results of the whole series of tests on the four machines are plotted as a single curve with minimum velocity change to fire the ordinate and average acceleration of the applied shock as the abscissa. This curve is representative of those obtained from the ball-switch type of exploder shown in the upper right-hand corner of the figure. The spring-loaded ball, electrically insulated from the exploder cup, moves under shock, compresses the spring, touches the cup, completes a circuit and fires an electric detonator.

Over the greater part of the average acceleration range, from about 30 g. to the highest tested value, the exploder fires at a constant velocity change, showing that the energy requirement is the controlling factor. At very low accelerations the velocity change required in-

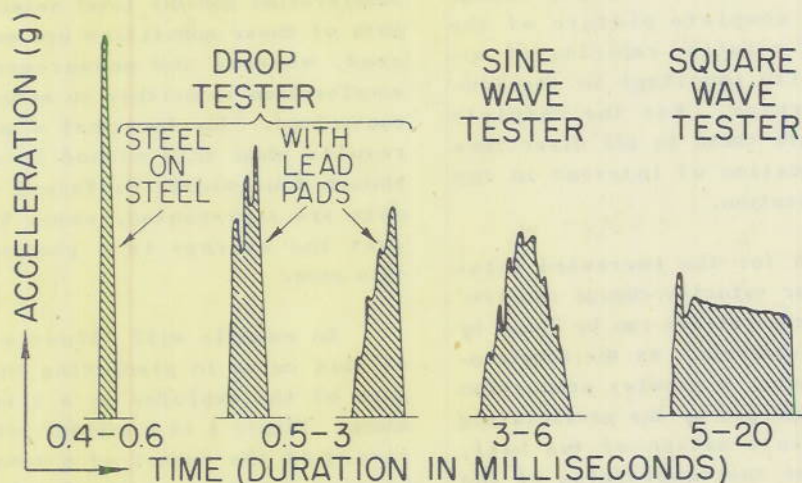


Figure 2. Comparative Acceleration Time Patterns

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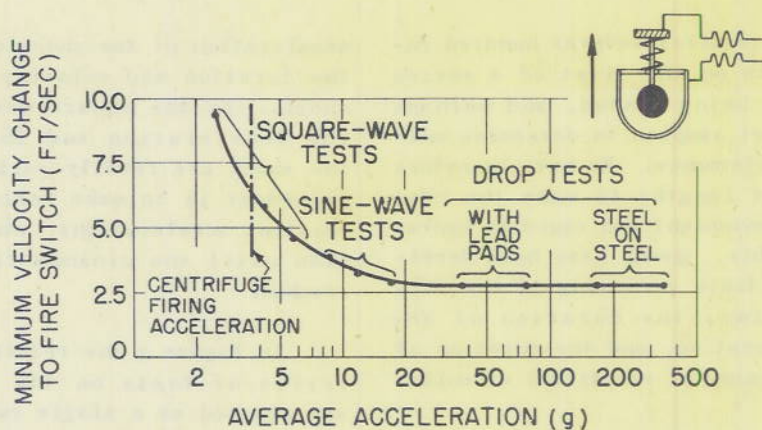


Figure 3. Exploder Switch Inertia Firing Tests

creases somewhat. Finally at about 2.5 g. the exploder will not fire under an acceleration of any duration. Note that this acceleration is considerably less than the centrifuge or gradually-applied acceleration necessary to cause firing. A shock which reaches its peak in less than one-fourth of the natural period of this type of mechanism can theoretically cause firing if its peak acceleration is one-half or more of that corresponding to the statically applied force required.

This curve illustrates the necessity for using several test methods. Obviously, neither acceleration nor velocity change alone gives a complete picture of the situation, and relative rapidity of application is also important in the low-acceleration range. For the complete tests, curves are taken in all directions of shock application of interest in the particular application.

The reason for the increased total applied energy or velocity change required at the lower accelerations can be found by a simple energy analysis. As the acceleration becomes lower, a greater proportion of the energy supplied by the accelerating force will go into motion of the ball, leaving less for the compression of the spring which must occur before firing can take place.

A mathematical analysis of the switch performance under all shock patterns can be made for the simple nose-on direction. Such comparison checks as we have made with experimental data have checked out closely. For angular directions of shock, the analysis in other than a qualitative way becomes impracticable and the test data furnishes the quantitative answer.

Average rather than peak acceleration is used for this plotting due to the difference in general shape of the shock patterns in the various tests and because we can determine average acceleration accurately by measuring the duration of the acceleration and the total velocity change. Both of these quantities are easily measured, whereas the measurement of peak acceleration is neither so accurate nor so convenient. The fact that a smooth curve results when this method is used, even though four widely different sources of data are represented, seems to indicate that the average is a good measure in this case.

An example will illustrate the use of this curve in predicting the performance of the exploder on a given type of shock. Figure 4 is a crystal accelerometer record of the impact of a towed torpedo hitting a target at about 5 knots. The pick-up was mounted directly on the ex-

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ploder base so that it indicates the shock pattern there, including any effects due to the structure of the warhead. There is a considerable amount of high-frequency "hash" in the pattern but the average acceleration, total velocity change, and duration of the shock motion can be determined. There are also high frequency components in the shocks produced by our testing machines. Since the overall response to these makes a smooth curve in good agreement with theoretical considerations, it seems reasonable to conclude that the effects, if any, of these components are minor on exploder systems of this natural period.

In Figure 3, page 82, the velocity change of 5.6 ft/sec. and the average acceleration of 7 g. obtained from the accelerometer record, we find that this point is above the minimum sensitivity curve and that therefore the exploder can be expected to fire on such a shock. Since the curves of exploder sensitivity are not restricted to any particular torpedo or warhead, they can be used for evaluating exploder performance in any new application, and of course are not even tied to its use in torpedoes. Likewise, field recordings of exploder-cavity impact characteristics can be used for any similarly tested exploder which might be considered for use. The relation be-

tween warhead structure and exploder location and the type of acceleration-time curve received at the exploder on a given impact is a subject of current study. If it should prove that warhead structure has little influence on shock transmission in low velocity impacts, as seems likely, we will find our curves on existing exploders immediately subject to wider application.

It is also possible to treat recorded countermining and broaching shocks in a similar manner in predicting from the laboratory data the response under these conditions. We have not as yet determined to our satisfaction whether or not any existing laboratory test on an exploder alone is a good countermining simulation. The effects of warhead construction are probably much more significant in the case of such short-duration shocks, but experiments are continuing to reduce the uncertainties. The same methods of comparing laboratory and field data will be applicable, but a new type of simulation equipment may be required.

In the ball switch which we have been considering there are no sliding members, and it can be assumed that no increase in friction due to high acceleration will impair its action on hard target shocks. We make tests at the maximum anticipated

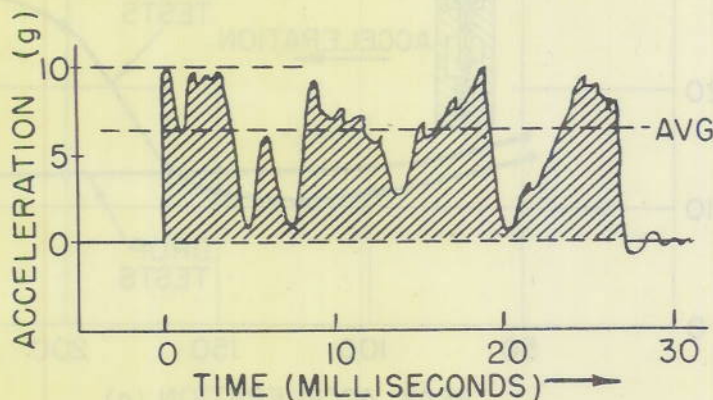


Figure 4. Typical Torpedo Target Impact Record
(Crystal Accelerometer)

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acceleration and velocity change, however, to determine the duration of contact between ball and cup. This is to make sure that there is time to insure firing the detonator. It is also necessary to check the possibility of shock opening of any normally-closed contacts in the electrical circuit at a time which might coincide with closure of the ball switch and thus prevent firing. We take oscillographic and counter-timer records of the performance of all switches in the circuit, as well as, make tests with a live detonator to show whether proper firing will occur under extreme conditions.

Consider the case of exploders that have spring propelled firing pins and travelling in guides. The effects of deformation of the exploder during shock may be damaging. This may result from binding of the pin and increased friction from inertia-force loading. Performance must be checked by tests simulating the acceleration and velocity change of the most severe target shock anticipated. The importance of simulating the duration of shock is shown in Figure 5. It represents data from tests on a firing-pin

type of exploder shown in the illustration. The firing pin is released by shock and then must travel upward under the spring force and strike the percussion cap with sufficient energy to fire it. The direction of travel is at right angles to the direction of the inertia force resulting from a nose-on hit of the torpedo.

The two curves show the time from the start of the applied acceleration to the firing of the cap. Notice that on drop test at increasing acceleration the delay time continues to decrease, primarily because of quicker releasing of the firing pin. In the air gun tests, however, the delay time increases seriously at 200 and 250 g. because of friction and binding of the pin. In the air gun tests the peak accelerations were the same but the duration was regulated so as to equal that from a full-speed torpedo hit and the shock continued during the time the pin was traveling up the guides, slowing the motion as shown. Since a delay of more than about 12 to 15 milliseconds means that the warhead will be too badly crushed for the main charge to be fired by the

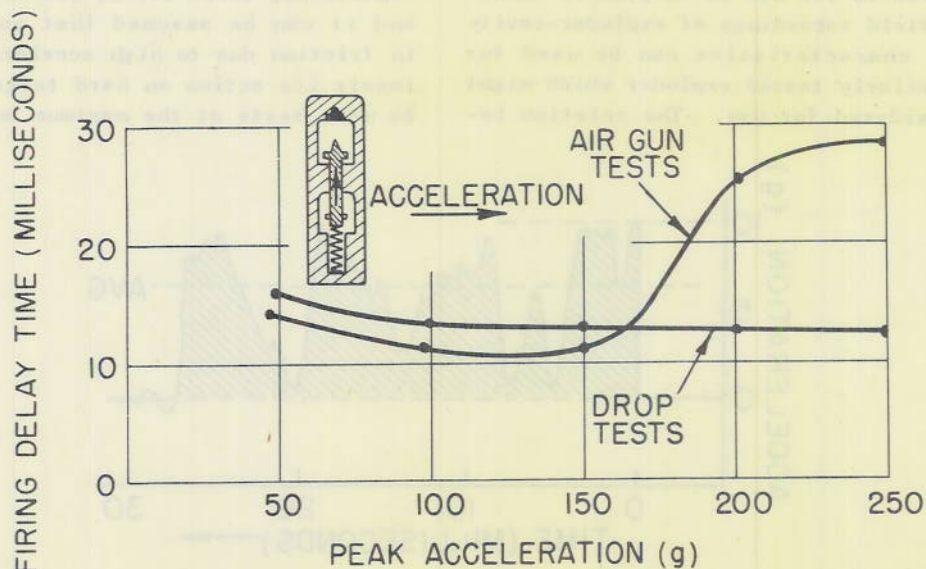


Figure 5. Exploder Firing Delay Time Tests

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exploder, this exploder would have failed on hard target impacts. Tests not simulating the velocity change as well as the acceleration of impact would have failed to indicate this possibility.

In performing similar hard-target tests on rocket and bomb fuzes which are subject to much higher-velocity impacts, we need even more drastic shocks than can be provided by the air guns in this conventional method of use. We need an effect similar to that which would be produced by a drop tester carriage striking a lead pad after a fall of a thousand feet or so. This would produce a shock of several thousand g. lasting through a velocity change of 200 or 300 feet per second. We attain these conditions without recourse to extensive architecture by using the air gun to accelerate an anvil against a light carriage, free to move with respect to the air gun piston and containing the fuze under test. The relative speeds at impact can be made equivalent to those resulting from a

1000 ft. free fall. While we are not able as yet to duplicate the maximum conditions that may be encountered in service, the severity of the impact has approached that goal by at least a factor of 25 over that attained in ordinary drop testers. The principal items of fuze performance which we check by this method are possibilities of chattering of contacts in electrical circuits and the delay time of actuation.

To summarize, we attack the problem of evaluating an inertia operated device for a given service use by determining the ways in which its performance can fail, by measuring or calculating the shock patterns corresponding to these ways of failure, and then by devising tests which will apply these conditions or others which can be demonstrated to be equivalent. We then try to find ways of presenting data in convincing, usable form; this is by no means the least of the problems involved.

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Report of the Committee on Definitions and Standards

As pointed out at the March meeting of the Shock and Vibration Symposium, the first task the Committee has assigned itself is the establishment of a list of definitions which can be used to classify observed phenomena in mechanical structures. The Committee is glad to report that sufficient progress has been made to warrant the publication of those terms agreed upon to date.

In establishing these definitions, an attempt was made to make the statements observational rather than casual. A further attempt was made to retain the generally accepted meanings of the terms and the statements appearing in the standard definitions used by the professional societies. Liberal use was made of the standards set up by the Institute of Radio Engineers and the Acoustical Society of America. Apparently, other societies have not established standard terminologies for describing motion in mechanical structures. Unfortunately, existing definitions often imply the existence of an isotropic medium, with an associated wave motion, or the direct observation of a force-like quantity. Neither of these conditions are satisfied in general when investigating a mechanical structure. Consequently, there are numerous instances in which it has not been feasible to retain the exact wording used by the professional societies, although the concepts involved are substantially the same.

The Committee welcomes any constructive criticism that members of the Sym-

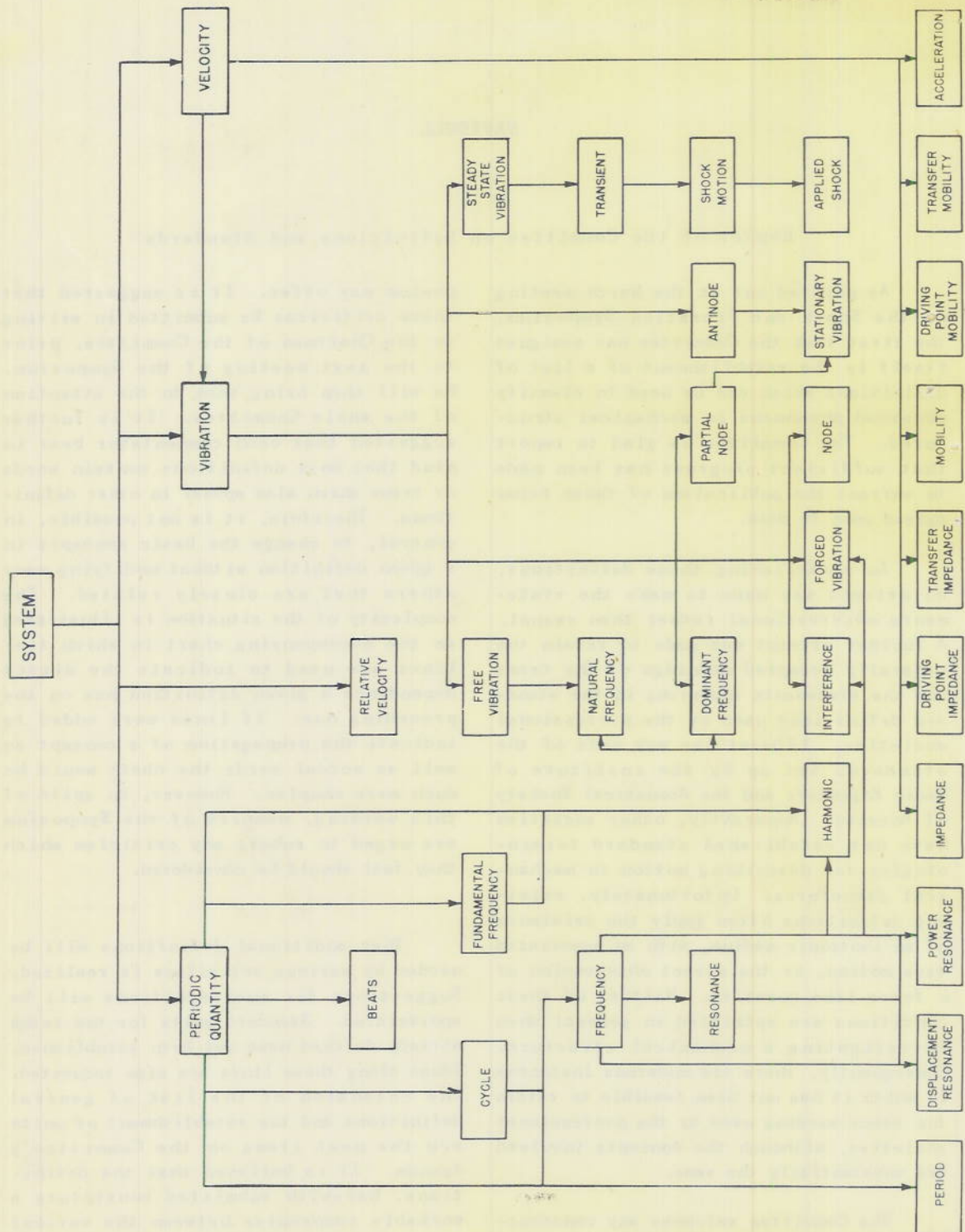
posium may offer. It is suggested that these criticisms be submitted in writing to the Chairman of the Committee, prior to the next meeting of the Symposium. He will then bring them to the attention of the whole Committee. It is further suggested that each commentator bear in mind that most definitions contain words or terms which also appear in other definitions. Therefore, it is not possible, in general, to change the basic concepts in a given definition without modifying many others that are closely related. The complexity of the situation is illustrated in the accompanying chart in which tie-lines are used to indicate the direct dependence a given definition has on the preceding one. If lines were added to indicate the propagation of a concept as well as actual words the chart would be much more complex. However, in spite of this warning, members of the Symposium are urged to submit any criticism which they feel should be considered.

That additional definitions will be needed by various activities is realized. Suggestions for such additions will be appreciated. Standard units for the terms already defined have not been established. Ideas along these lines are also requested. The extension of the list of general definitions and the establishment of units are the next items on the Committee's Agenda. It is believed that the definitions, herewith submitted constitute a workable compromise between the various suggestions received to date.

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The Committee wishes to express its appreciation to Messrs. Armstrong (NOL), Maxfield (NMRI), Wuerffel (NRL), and Thompson (NRL), who contributed much thought and effort to the establishment of these definitions. Appreciation is expressed, also, to those members of the Symposium who have submitted ideas in writing, thereby aiding the Committee in its deliberations.

Members of the Committee -

L. W. Ball, NOL
L. H. Fryer, BuShips
D. E. Goldman NMRI
H. M. Trent, NRL
F. F. Vane, DTMB
B. A. Wiener, BuAer

Proposed Definitions and Standards on Vibration and Shock in Naval Structures

1. Mechanical System

A mechanical system is a group of physically interconnected members, each of which possesses mass and elasticity.

2. Periodic Quantity

A periodic quantity is an oscillating quantity the values of which recur for increments of time.

Note: For a mathematical definition see American Standard Acoustical Terminology, paragraph 1.3; 24.1-1942.

3. Cycle 1. 2.

One complete set of the recurrent values of a periodic quantity comprises a cycle.

4. Period 1

The time required for one cycle of a periodic quantity is the period.

5. Frequency 1. 2.

Frequency is the number of cycles occurring per unit of time, or which would occur per unit of time if all subsequent cycles were identical with the cycle under consideration.

6. Fundamental Frequency 2.

The fundamental frequency is the lowest sinusoidal component frequency of a periodic quantity.

7. Harmonic 2

A harmonic is a sinusoidal component of a periodic quantity having a frequency which is an integral multiple of the fundamental frequency. For example, a component the frequency of which is twice the fundamental frequency is called the second harmonic.

1. The same as the American Standard Acoustical Terminology.

2. The same as proposed revision of Standards on Electroacoustics (IRE).

8. Velocity

The velocity of a point associated with a mechanical system is the time rate of change of position of that point with respect to an inertial frame.

Note: In most cases the approximation is made that coordinates fixed to the earth constitute an inertial frame.

9. Relative Velocity

The relative velocity of a point in a system with respect to a reference point

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is the time rate of change of position of that point with respect to the reference point.

10. Acceleration

The acceleration of a point is the time rate of change of the velocity of the point.

11. Vibratory Motion (Vibration)

Vibratory motion exists at a point in a system if the velocities of the point along the axes of an inertial frame are alternately greater and less than constant amounts.

12. Steady State Vibration

Steady state vibrations exist in a system if the vibratory motions existing at each point are described by a set of periodic quantities.

Note: This is frequently a special case of forced vibration.

13. Transient Motions

Transient motions exist in a system during the interval between two steady states.

14. Free Vibration

Free vibrations are those vibrations existing in a system when all the externally applied forces and moments are constants and their summations zero.

15. Natural Frequency

The natural frequencies of a system are the frequencies of free vibration of the system.

16. Dominant Frequencies

The dominant frequencies in any complex vibration are those frequencies having amplitudes of motion significantly

larger than the amplitudes at nearby frequencies.

17. Forced Vibration

A forced vibration is any vibration that is imposed upon a system by an external force and the frequency of which is controlled thereby.

18. Shock Motions

Mechanical shock motions exist in a system if the transient which occurs between two steady states produces significant relative displacements between points in the system.

19. Applied Shock

Any excitation which if applied to a system would produce shock motions within the system shall be classed as an applied shock.

20. Resonance

Resonance exists in a system subjected to an applied periodic excitation if any small change in the frequency of the applied excitation results in a decrease in the observed response.

21. Displacement Resonance

Displacement resonance exists in a system subjected to an applied periodic excitation of constant amplitude of displacement if any small change in the frequency of the applied excitation causes a decrease in the amplitude of observed displacement.

22. Power Resonance

Power resonance exists in a system subjected to a reaction type exciter driven at constant eccentricity if any small change in the frequency of the applied excitation causes a decrease in the power supplied to the driver.

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23. Interference

Interference in a system is characterized by a spacial distribution of amplitudes of motion and by the propagation of vibrations having the same frequencies in different directions.

24. Nodes

Nodes are the points, lines, or surfaces in a vibrating system at which the amplitudes of vibration are zero.

25. Partial Nodes

Partial nodes are the points, lines, or surfaces in a vibrating system at which the amplitudes of vibration are a minimum.

26. Antinodes

Antinodes are points, lines, or surfaces in a vibrating system at which the amplitudes of vibration are a maximum.

27. Stationary Vibrations (Standing Waves)

Stationary vibrations exist in a system if the spacial distribution of the motions is characterized by fixed alternate partial nodes and antinodes along the direction of propagation of energy.

28. Beats

Beats exist at a point in a system when the variation in the amplitude of a mechanical quantity is a periodic quantity describable as the superposition of disturbances having different frequencies.

Note on remaining definitions:

The remaining definitions pertain to single-frequency forces and velocities in the steady state, and to transmission systems having properties which are in-

dependent of the magnitudes of these forces and velocities. The forces and velocities can be represented mathematically by complex exponential functions of the time. Under these conditions the factors involving the time cancel out in the ratios called for in the definitions, leaving complex numbers independent of time. Calculations based on complex exponential functions give solutions for real sinusoidal oscillations.

29. Impedance

Impedance is the complex quotient of the force applied to a system by the resulting velocity.

30. Driving Point Impedance

Driving point impedance is the complex quotient at any driving point of the applied force by the resulting velocity.

31. Transfer Impedance

Transfer impedance from a driving point to a receiving point is the complex quotient of the force applied by the resulting velocity.

32. Mobility

Mobility is the complex quotient of the velocity of a point by the applied force producing the motion.

33. Driving Point Mobility

Driving point mobility is the complex quotient at a driving point of the velocity by the applied force.

34. Transfer Mobility

Transfer mobility from a driving point to a receiving point is the complex quotient of the resulting velocity to the applied force.

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Abstract from Ruggedization Paper

I. L. Cherrick, NRL

Four types of shock and vibration machines employed in the ruggedization of electron tubes are discussed.

The NRL High Impact "Flyweight" Machine for Electronic Devices (Peak accelerations 0-1500 g, impulse durations approximately 3/4 millisecond, velocity change three feet per second - ten feet per second) is described. Explanation is made of the NRL Standard Vibration Machine for Electronic Devices (0-60 cycles per second constant amplitudes of 0.04" and 0.10"). Resonators and fatigue vibrators used in the work are also included.

The basis for the development of rugged electron tubes is described as being due to the unreliability of ordinary electron tubes as compared to other components in military applications. Chief causes of failure are: (1) welds; (2) glass; (3) metal fatigue; (4) fractured elements and (5) structure alignment.

The paper lists 32 of present electron tube types under development on the rugged tube program and includes photographs of the developmental ruggedized 6AC7 and 6L6 tubes.

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TENTATIVE PROGRAM FOR SIXTH SYMPOSIUM

(Auditorium and other meeting details as well as more complete abstracts of the papers will be included in the final announcement of the symposium).

NAVAL ORDNANCE LABORATORY

Naval Gun Factory

1000, Wednesday, 17 September 1947

Schedule and Agenda

- 1000 Chairman's remarks
- 1015 Impact and Penetration of Water.
- An exposition of certain phases of fluid dynamics; a description of phenomena associated with water entry shock; the geometry of entry cavities; missile aspects and trajectories.
- 1145 Impact and Penetration of Solids.
- A study of the characteristics of shock experienced by tail fuzes during impact with hard target, the shock sequence on nose fuses, information about armor materials, and appropriate physics, such as the transmission from deformation to punch penetration.
- 1230 Lunch
- 1400 From British Admiralty Delegation.
- Metallurgical factors involved in the after effects of shock and vibration.
- 1445 Maneuvering Accelerations and Vibrations of Guided Missiles.
- An introductory consideration of the importance of this problem to future techniques.
- 1515 Accelerations and Forces in Interior Ballistics
- This paper is concerned with set-back accelerations on projectiles, shock forces experienced by the breech and barrel of a gun, variations in forces due to different propellents.
- 1530 Discussions and announcements of future meetings.

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