LECTURES ON

ADVANCED TECHNOLOGIES

U.S. NAVAL ACADEMY
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LECTURES
ON
ADVANCED TECHNOLOGIES

A. E. BOCK
EDITOR

AT
U.S. NAVAL ACADEMY
1985-1987

SPONSORED BY:

ADVANCED TECHNOLOGIES RESEARCH GROUP
U.S. NAVAL ACADEMY
ANNAPOLIS, MARYLAND 21402

SUPPORTED BY:

OFFICE OF CHIEF OF NAVAL OPERATIONS, NOP-987

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INTRODUCTION

These papers

The papers included in this collection were selected from those presented in the 1985-86 and 1986-87 Naval Academy Advanced Technologies Seminar Series. These interdisciplinary seminars were presented at approximately monthly intervals to faculty and midshipmen, at times in separate groups and, at other times, in combined groups. The topics presented were those deemed to have particular relevance to the Navy in either its short-term or long-term planning. The presenters were informed of the interdisciplinary nature of both the faculty and the midshipmen groups and asked to speak informally, accepting questions from the audience as they might arise.

Previous seminars in this interdisciplinary series have dealt with the environment, with energy problems of supply and conservation, and the political and economic impacts of these issues on the world, the country in general and the Navy in particular. In these times of rapid development in the scientific and technical aspects of engineering materials, electronics, communications, automatic controls and many other technologies, it seemed appropriate to arrange this seminar series to bring into focus, as far as possible, what is taking place on the cutting edge of technology today.

While it is impossible to describe, adequately, the atmosphere existing during the presentations, the questions, the lively give and take of the discussions and the frequent debates generated attest to the timeliness of the topics and the interest of the audiences in those topics.

These presentations have been informative, foresighted, and incisive in their portrayal of technical advances about to become operative and those that will, or should, appear in the near future. Not only the devices themselves, or the systems in which they operate, were discussed, but also the political and economic consequences they were likely to introduce. Each of the presenters has made a strong contribution to the educational process at the Academy. Our profound thanks to all those who have given of their time and talents by coming to Annapolis and participating in our Advanced Technologies Seminar program.

Arthur E. Bock
Professor Emeritus
Naval Systems Engineering Dept.

DEVELOPMENT OF
THE CURTISS WRIGHT V/STOL AIRPLANES

by

HENRY V. BORST*

Good afternoon. It gives me great pleasure to be here to talk to you about vertical take off and landing aircraft. These aircraft were designed and built in the late 1950's and into the mid 1960's. Two airplanes were involved; the X-100, a concept demonstrator vehicle, and the X-19 which turned out to be the vehicle that Curtiss Wright had hoped to sell to the services for surveillance and all sorts of duties that are possible with a high speed vertical take off airplane. This project illustrates the problems and pitfalls involved in making the alternatives available that we don't have today. I

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*Henry V. Borst is owner and operator of Henry V. Borst and Associates, engineering consultants in Wayne, Pennsylvania. Mr. Borst graduated from Rensselaer Polytechnic Institute with a degree in Aeronautical Engineering. He is a nationally recognized expert in Propellers, Ducted Fans and Axial Flow Compressors.

feel that a review of the project is worthwhile even though in some ways it was successful and in other ways it wasn't. It's worthwhile to illustrate what one runs into trying to come up with a new project.

Without engineering and research our aircraft today might look like the Wright flyer of 1901, Figure 1. Of course we've done a little bit of research since that time and even back then they did some work and came up with new airplanes. In the early days Glen Curtiss, Alexander Bell, F. W. Baldwin and a Canadian engineer by the name of McCurdy got together to form the Aeronautical Research Group and built several airplanes leading to the Junebug, Figure 2 which flew in 1909. This shows our progress that was made by research, even though it was by trial and error. In those early days they even came up with an airplane that didn't fly. It was a trainer airplane which was built in the early days for teaching pilots how to fly, Figure 3. Fortunately, we've done some research and development since the first aircraft and in 1919, I believe, NACA was formed. They

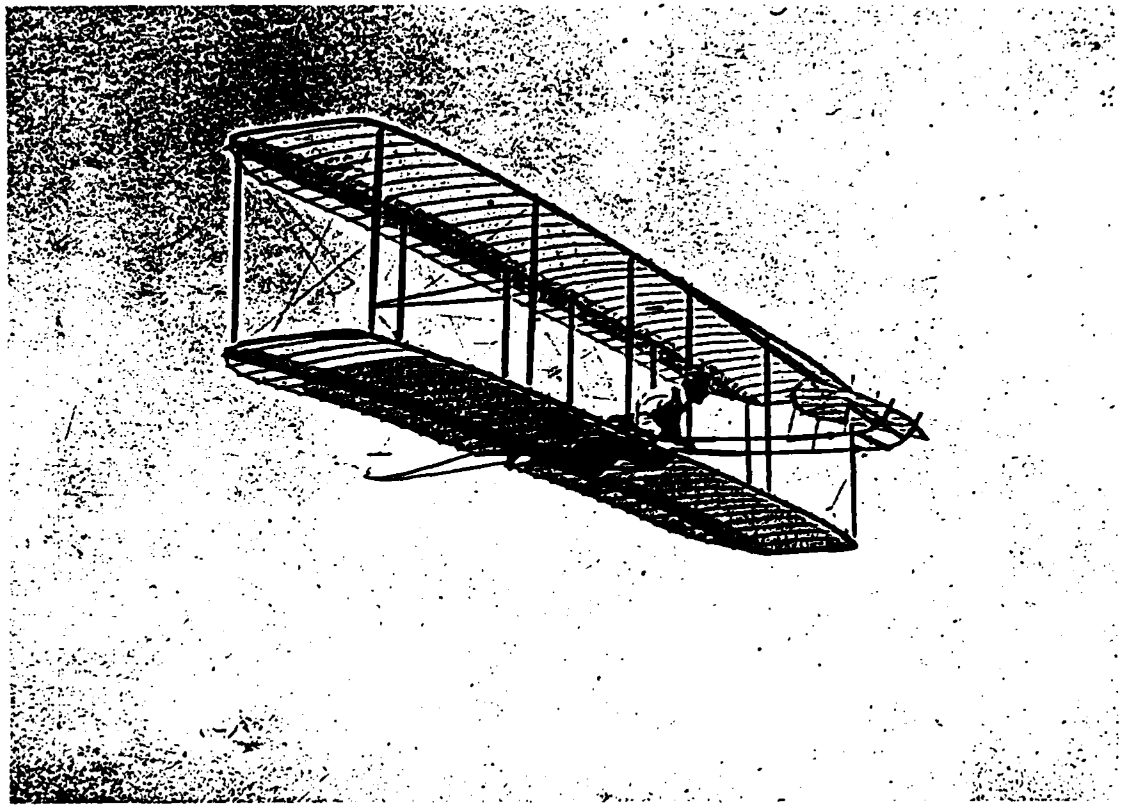


Figure 1. Wright Flyer of 1901

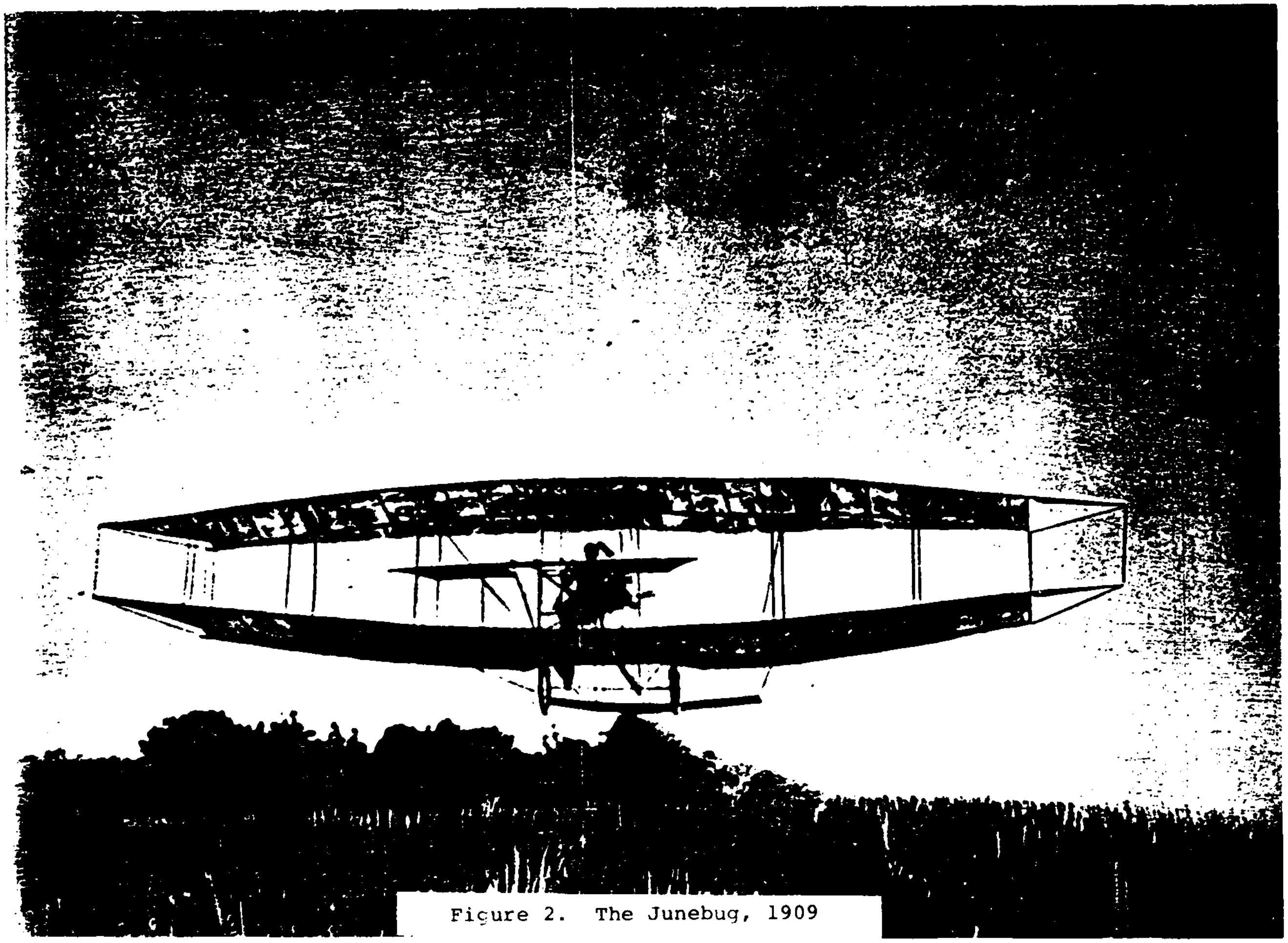


Figure 2. The Junebug, 1909

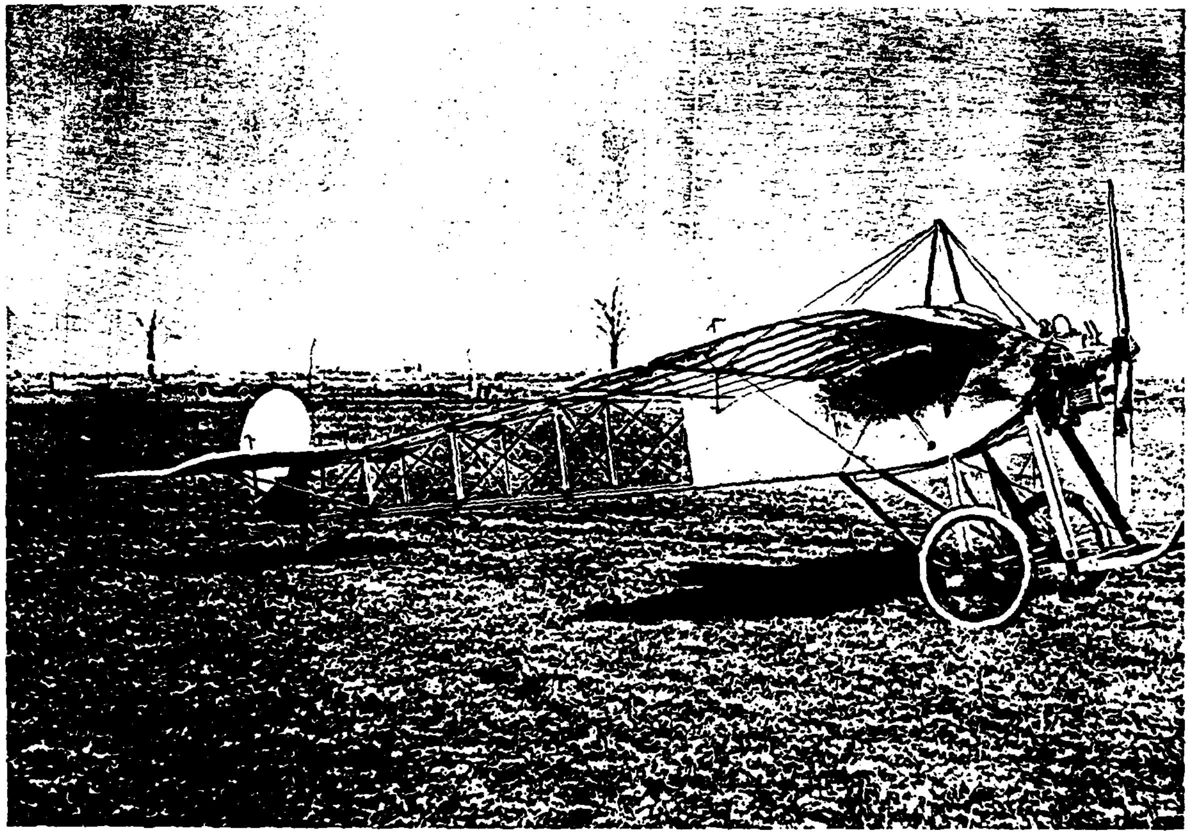


Figure 3. Early Pilot Trainer

did research and development, and aircraft companies did research and development and this finally led to improved airplanes, one of which is rather interesting for its day, the Curtiss-Wright Tanager, Figure 4. Notice that this airplane has leading edge slots on the upper wings which are for high lift, and full span flaps which have full aileron control. This airplane was built in 1929 and won the Guggenheim airplane contest for flight safety. It flew for 15 minutes hands off at 30 miles per hour, which is quite remarkable for the day, and showed excellent stability characteristics.

Today, with the high cost of doing research, it appears that we can only make small improvements in our aircraft. The days of big break-through such as the development of swept wings and turbine engines are behind us. So to develop aircraft that will do the job that we want to do in terms of V/STOL we will have to make some important break-through again. Some people look at the boys in the lab to come up with something big and so the caption on Figure 5 says "it looks like R & D is up to

Figure 4. The Curtiss-Wright Tanager

"Looks like R. & D. is onto something big."

Figure 5.

something big." I hope so, but at times the R & D boys do come up with something big that is less than practical. Here, Figure 6, we have a helicopter, designed by a guy named Bleecker and sold to Curtiss Wright. It had propellers that drove the wings to give the RPM necessary for vertical lift. Where have we seen this idea again? I've seen it several times since then and it's always a so-called new idea. Well, the idea of using propellers to drive the helicopter blades was not practical either for many reasons. So this was an idea that they came up with and a lot of time was spent but we didn't get a workable helicopter from it as the *concept* was flawed from the beginning.

The problems involved in a break-through are well illustrated by our efforts in the V/STOL area. I can think of at least twelve projects that were started in V/STOL where the airplane projects had a lot of money spent on them, a lot of enthusiasm went into them and all except the Harrier were unsuccessful. When the British Harrier came along everybody in this country sort of

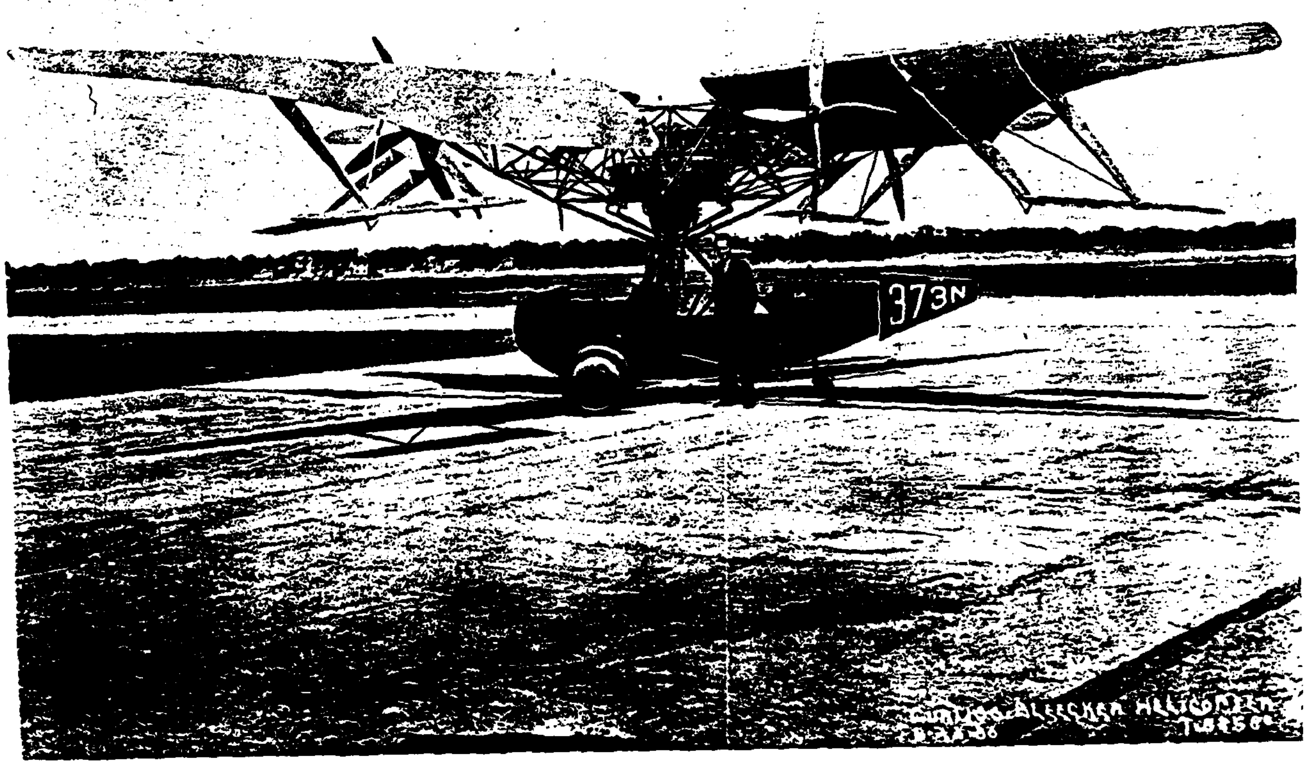


Figure 6. Bleecker Helicopter with propeller driven wings

pooh-poohed it. Oh! I can remember the people at Boeing and many other places saying , "Oh this thing is no good. It doesn't have any redundancy in the case of an engine failure. Besides, it burns up the grass and has no range, no payload, nothing." Well, the British kept working the problems and little by little they solved all the problems involved, and today we have an operational airplane. I'm sure there are a lot of people who say that it's not so good, but at least we have a V/STOL airplane that is operational.

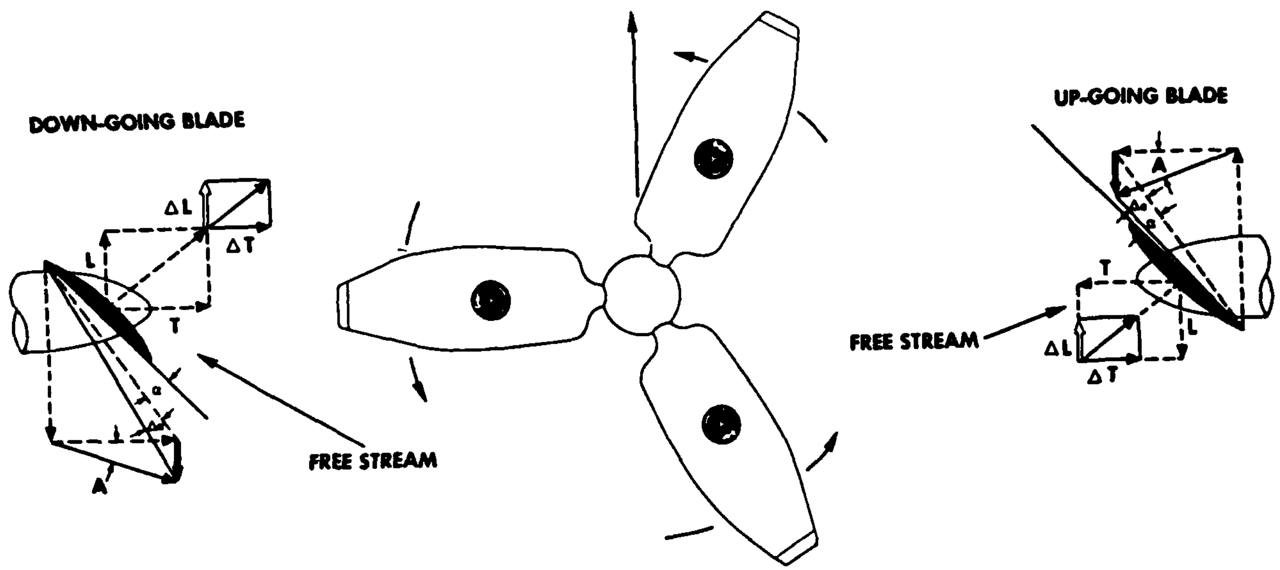
Well, in talking about the problems involved in a new configuration or a new idea, the X-100 and X-19 V/STOL aircraft projects are good examples of some of the things that you can run into, and so I'm going to talk about the early background of these airplanes and what we went through to try to come up with a successful machine. I'm going to try to show you where we went wrong or where we developed what I call "foundations for failure," and I know that's very negative, but I hope that from these foundations for failure we can develop foundations for success.

In the case of the X-100 airplane, it all started with a very simple idea. Let's take the propeller and make it do as much as possible in supplying thrust and lift. The propeller is known to be capable of developing thrust that can be used for vertical lift in hover and can be used to generate propulsion thrust in forward flight. A lot of people know the propeller generates a force in the plane of the disk called side force, and people that have done stability and control studies of propeller driven aircraft say that side force has always been a problem. Well, we started with the idea that maybe this side force, if we worked on it a little bit, could be used to supplement the lift of the wing during the conversion process from the hover mode to the cruise condition. So, we came up with the idea of using propeller side force or radial force for developing lift.

Now I'm not going to try to go through the force diagram that shows the propeller will produce not only a thrust force but also a radial force in the plane of its disc. It is shown here on Figure 7 how the force is developed and this can be the subject for a lecture that runs for about an hour or so. But the fact is the propeller does develop radial force, and if you design the propeller properly, with a very wide chord inboard, you can design the propeller to give you this force practically for free. This idea led to a study to see whether this radial force could indeed be used to design an airplane that would have the characteristics of taking off vertically and flying at relatively high speed in the normal flight mode. The propeller goes from a shaft angle of 90 degrees to a shaft angle of zero degrees or so.

Well, a preliminary design group was put together to study the concept after we demonstrated the radial force principal with a very simple device known as a ceiling walker. Today they are called space darts. These models consist of two propellers on a stick with a rubber band between them. I don't have one today or I'd demonstrate it. If you weight the thing in front, you can hold it

RADIAL FORCE PRINCIPLE



VECTOR DIAGRAM
SHOWING RADIAL OR LIFT FORCES ON PROP

Figure 7

down with the propellers in the horizontal plane and it will take off vertically. Then it will fall over and fly in the horizontal mode quite fast going across the room. This demonstrates that the propeller does produce a radial lift force and that it is quite significant. When we demonstrated this to our management they gave us money for a preliminary design study. Not more than two months went by and it became obvious to me that our preliminary design study was going to be successful, whether we liked it or not, because the president of the CW organization needed a project that had some glamour and because he was about to get thrown out on his tail. So we had lots of encouragement, and money and, of course we were enthusiastic young engineers who wanted a project too. So we came up with a design that we felt might demonstrate the feasibility of the concept, and this design eventually became known as the X-100 airplane.

The X-100 was an airplane which ended up weighing about thirty-five hundred pounds and had a T-53 turbine engine. It had radial force propellers mounted side by side and is illustrated in Figure 8. While we were designing this airplane, we also developed our own foundations for failure. These foundations were four in number. One was that the control of the propellers was to be only collective pitch. The cyclic pitch idea was a no-no by upper management even though the airplane could have used it badly. The blade to be used was a new light weight design where we had no research and development background or test data. Nobody had ever done it before and the boys in the R & D lab had a bright idea that they could do it by putting fiberglass over a steel shank and then pouring foam into the fiberglass shell to stabilize the blade. The process was very ingenious and it seemed like a good concept for a light weight blade that was needed. But, at the end, we didn't have the kind of background that was needed to really go ahead with this new concept. The third thing I can think of was the use of magcastings for gearboxes and other load carrying structures on the airplane. Finally, the fourth decision that was part of the foundations for failure was the

Figure 8.

CURTISS-WRIGHT X-100 TEST VEHICLE ON THE GROUND
CP-13582-4

management decree that we could have no outside help in terms of people from NACA which was then in existence or NASA or any of the other government labs.

So we designed and built this aircraft and this was all done in a year. It takes more than a year now to get a contract from anybody, but this is what happens when you've got almost an infinite amount of money available to do something within reason. (One thing that I wanted to mention about the radial force concept is that the variation of lift with shaft angle is almost linear all the way up to 90 degrees and this is a big plus in the case of the VTOL aircraft).

The X-100 airplane, as shown in Figure 8, is now down at Silver Hill in Washington if you want to see it, and it has some interesting background. When we rolled it out we found that without the flying wires shown, the wings deflect up so that the gearboxes, used to drive the propellers, would be in trouble. It turned out when we investigated as to why this had happened, that the engineer who calculated the deflection of the load carrying beam of the wing was so used to working with steel that he used the modulus of elasticity of steel for analyzing the aluminum structure. (Naturally, it did deflect). The airplane was fixed with those so-called flying wires. After all, the only thing we wanted to demonstrate was that the airplane could take off vertically and that it could, with the propellers tilted down, convert and fly at a horizontal flight condition.

The airplane, as it was rolled out, was thirty inches shorter than shown in Figure 8. A fuselage length was increased in front of the engine because we lost control of the cg. We had to move the pilot forward so we could get our cg back under control. The hover flight controls of the airplane were propeller collective pitch for vertical take-off, differential pitch for roll control and a jetavator mounted aft on the fuselage directing the engine exhaust flow either vertically or horizontally for pitch and yaw control. The controls used in horizontal flight were conventional. The design of a jetavator of this kind was horrible but it did work well enough to demonstrate the aircraft principals.

Well, the airplane did fly, Figure 9, and made a conversion from the hover condition to forward flight condition and was one of the fastest rotor V/STOL aircraft of its time. It did one hundred eighty miles an hour and the propellers were tilted down to only 15 degrees. It could have gone well over two hundred miles per hour had we had the guts to tilt the propellers all the way down. We were concerned about the flutter characteristics of the T-tail and therefore limited the forward speed. But, anyway, it did fly and it did everything it was supposed to do. Three pilots flew it, two Curtiss Wright pilots and a pilot from the NASA by the name of Reader. Reader expected a lot from the airplane and gave it a very poor rating regarding stability and control. But it wasn't supposed to have good flight characteristics at the time.

Well, the X-100 project went along and I can tell you some interesting things about its earlier testing and trying to hover the unstable aircraft in a tether rig, and all the reasons why you shouldn't do that. Also, before

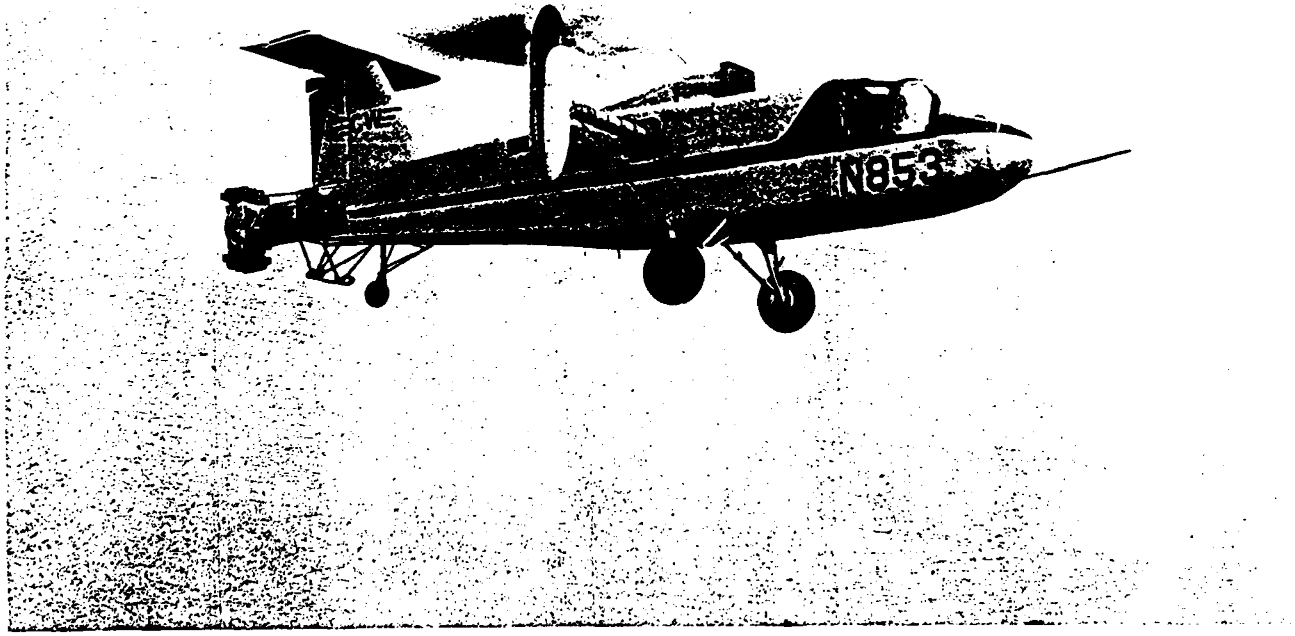


Figure 9. One of earliest rotor V/STOL aircraft

we even proved the radial lift concept with the X-100, we were directed to start a much more ambitious project in terms of an executive transport that eventually became the X-19.

During the early part of the X-19 development, while our original backer was still at Curtiss Wright, he went to Germany and bought the rights to the Wankel rotating combustion engine. He thought the Wankel rotating engine would be ideal for vertical take-off aircraft as well as other applications. The engine was lightweight, after all, and it was simple with fewer parts and all those other good things. (Twenty five years later it is finally developed to the point where it may be used in general aviation aircraft). So the boss called a big meeting and said, "Hey, I want an executive transport aircraft and the aircraft will have a four hundred miles per hour cruise speed along with vertical take-off and landing. We are to use the Wankel engine." Well, there's a nice political decision to build another set of foundation failure blocks. Well, anyway, we got started with the X airplane with a preliminary design. I wouldn't call it the X-19 until it gets further along. I was asked if I could design a propeller that would have a high efficiency at a 400 mph cruise with the required thrust to power ratio at hover. Calculations confirmed that this could be done and the next thing I knew four hundred miles per hour became four hundred knots and that made it a little bit more difficult, but it seemed as though we could do it.

So we started the X project with an airplane that was designed to eliminate some of the problems that we had with the X-100 which had poor control in pitch and yaw. Since we were not allowed to consider ;yclic control for the propellers, and since the use of differential pitch for roll control was very effective on the X-100 airplane, it appeared that a four propeller airplane could be designed to do the job. An airplane with two propellers in front, and two propellers in the rear will give the desired control characteristics in pitch and roll at the hover condition. Never mind the control problems at transition, the horizontal flight mode and flight stability, with a tandem wing airplane we will solve those problems. Nor should we worry about all the propellers, gear boxes and shafts that are required, we will work the problem. These design problems, along with the use of an unproven engine, should have led to the abandonment of the project. The problem of the use of the rotating combustion engine went away when the head of CW was fired and the idea of the executive transport was dropped.

The new management reviewed the project and felt because of the money already invested, they should approach the military and offer to build the machine at CW's expense if they would pay for its testing and development. This was agreed to and so the Triservice X-19 with two T-55 turbine engines came in to being. The airplane was still to be a four poster, Figure 10, using differential pitch propeller control for pitch and roll. Obviously you can get a lot of control in pitch and roll from such a system. For yaw control, if you tilt the front propellers back and the rear propellers forward, you can develop a yaw moment from the components of force in

Figure 10. Curtiss-Wright X-19 High-Speed VTOL Aircraft

the direction of flight as shown on Figure 11. This control system, as used on the X-19 airplane, did work at the hover and low speed conditions, but the rigging of this system on the airplane was just a horror. What we needed was fly by wire.

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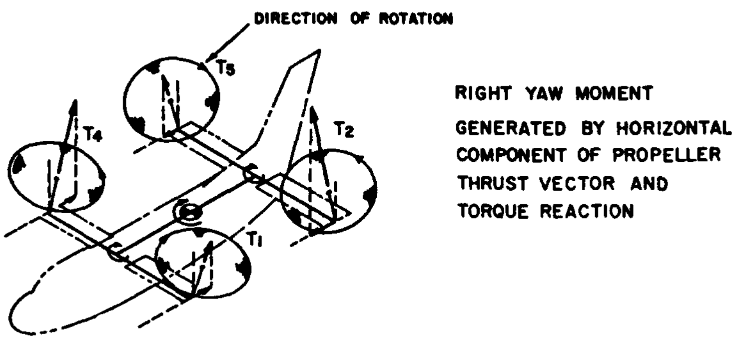


FIGURE 11 Yaw moment.

In the sixties we were talking about fly by wire and Curtiss built electric propellers but we had no guts to go ahead and put fly by wire in the airplane at this time. So, we tried to do it all mechanically, and that turned out to be a real horror to get the kind of accuracy that was needed for controlling the propeller. To give you an idea, the blade angle travel between full power, and zero power at the cruise condition, was only eight tenths of a degree. This gives you an idea of the kind of accuracy that the system needed to obtain the desired control. Further, with this configuration we had two engines in the aircraft, mounted midships, so you had a gear box connecting the engines, gearboxes fore and aft plus gear boxes at each propeller or a total of seven gear boxes in all. That's an awful price to pay for the lack of cyclic control. Another problem with the aircraft was the down-load on the wings from the propeller slipstream which reduced the take off gross weight. We did manage to reduce the down-load losses to about four percent of the lift of the propellers. That wasn't too bad.

The aircraft finally was rolled out and a lot of people thought it was kind of a good looking aircraft, and of course the guys that worked on it thought it was super, Figure 10. It went through a series of flight tests, and it did have the capabilities that we were looking for at low speeds. It flew quite well at low speeds and had good STOL flight characteristics. It could fly backward and forward and operate in side winds. The yaw control was some what inadequate, but our pilot thought it was okay. I'm sure the service pilots would have thought the yaw control was not enough. But they were never satisfied with yaw control in those days. Well, the airplane did fly and Figure 12 is a picture of the X-19 in the hover mode. You will notice the forward propellers are tilted backwards, and the rear propellers are tilted forward with the flaps front and rear deflected to reduce the down load on the wing.

Well, we had retained our foundations for failure in the X-19 airplane that were formed in the X-100 and added a few more. We had magcastings in all seven gearboxes. We had fiberglass blades, foam filled, and the foam was always shifting giving us fits. The aircraft grew in

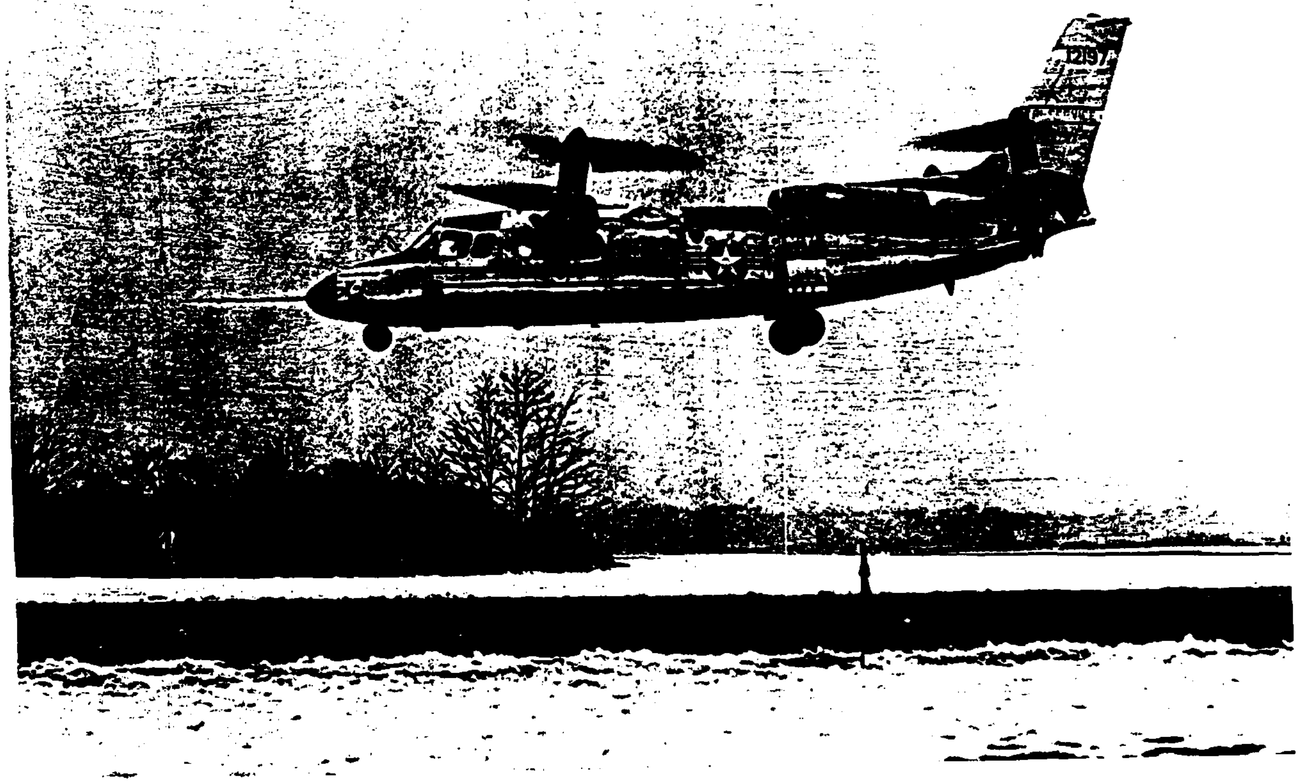
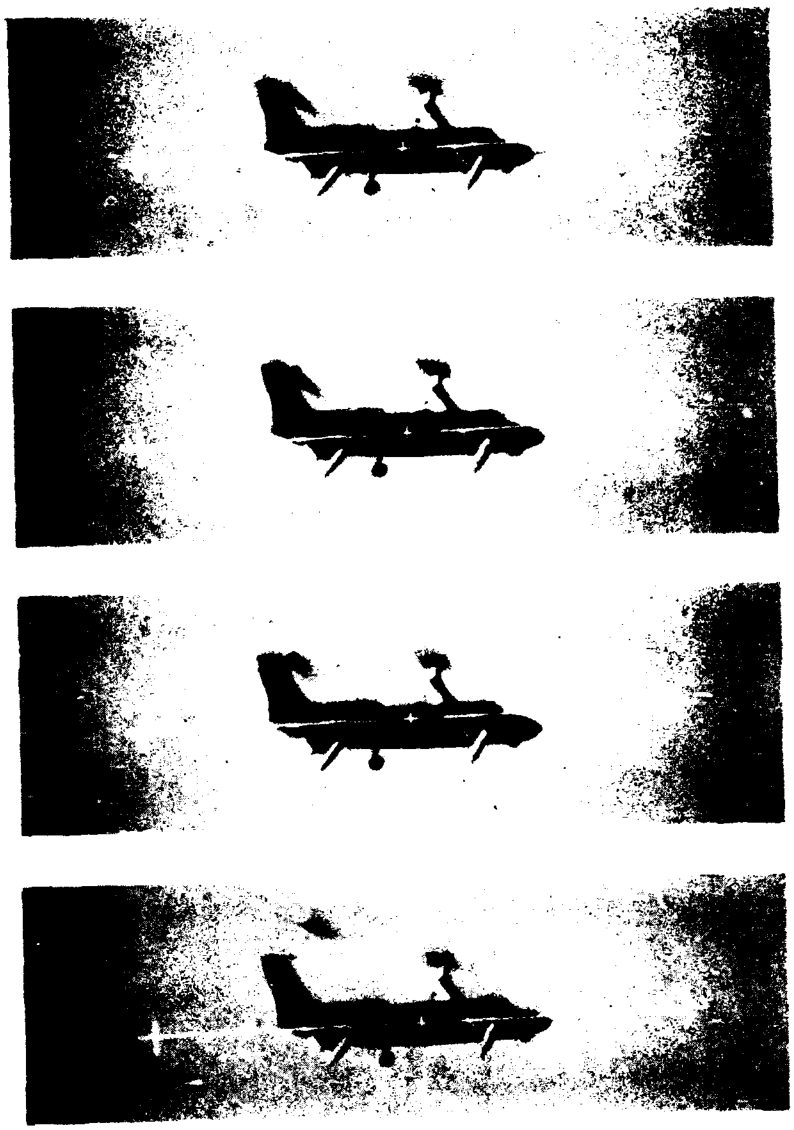


Figure 12. X-19 aircraft in the hover mode

weight for many reasons one of which was the very heavy fuselage due to the tandem wing with four propellers at the wing tips. This produced very high loads and thus a high weight. The gear boxes, shafts and controls were also heavy. All reducing the advantage of the radial force system and adding to the foundations for failure. We didn't have the background or resources that we should have had to really develop an aircraft of this type and this is an understatement.

Well, we went ahead and flew it at speeds up to 100 mph at our local airport in Northern New Jersey, then took it to the FAA facility at Atlantic City, NAFEC, for further testing. Here, after 50 flights, we let everyone know that we were planning to go through transition and with everybody watching managed to have somewhat of a disaster. In the series of pictures, Figures 13-18, the left rear propeller is first to leave the airplane. This caused the airplane to pitch up and roll and things start happening fast, as all the propellers leave the airplane, all at an altitude of 400 feet. The chase pilot remarked



Figures 13 - 18 show disintegration of X-19 aircraft as all four propellers leave the plane.

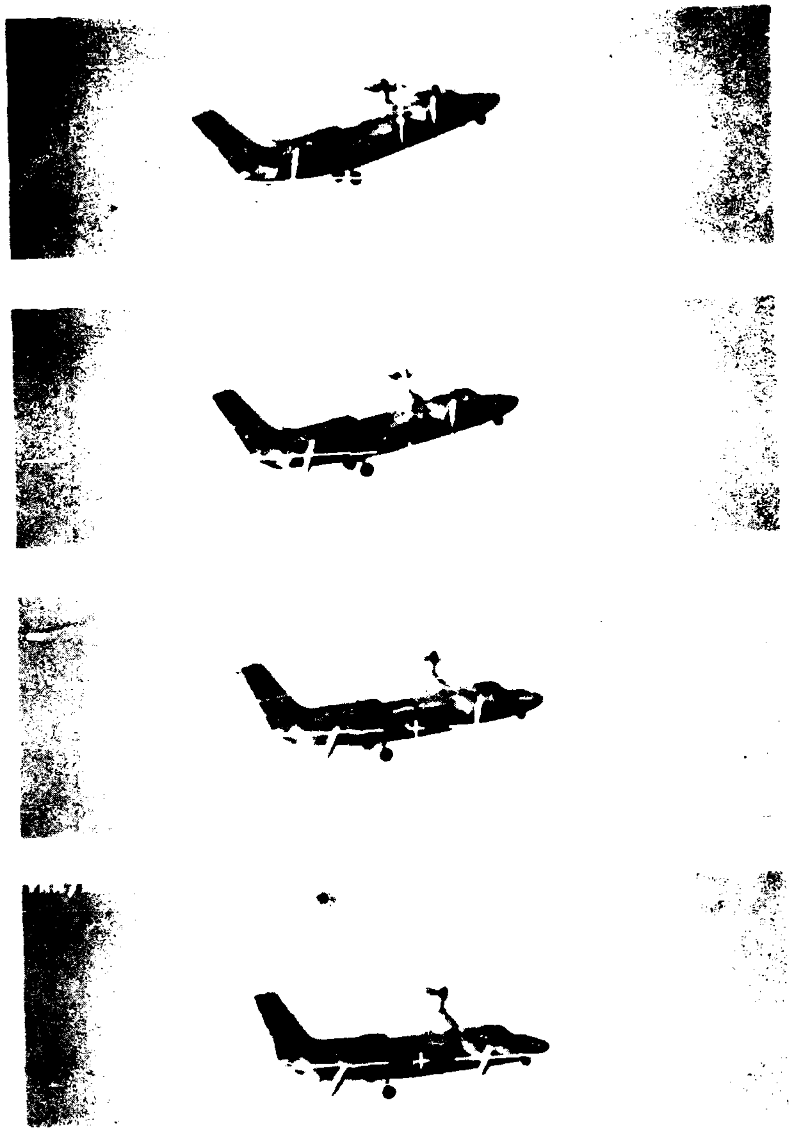


Figure 14

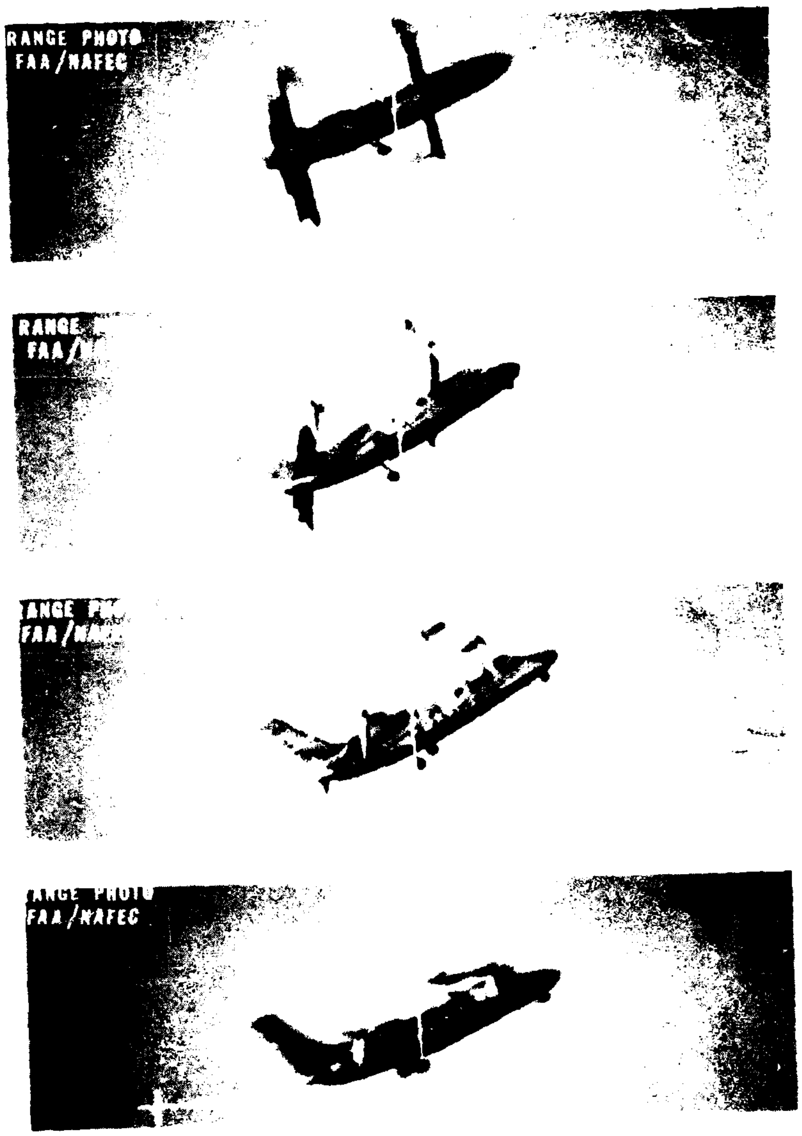


Figure 15

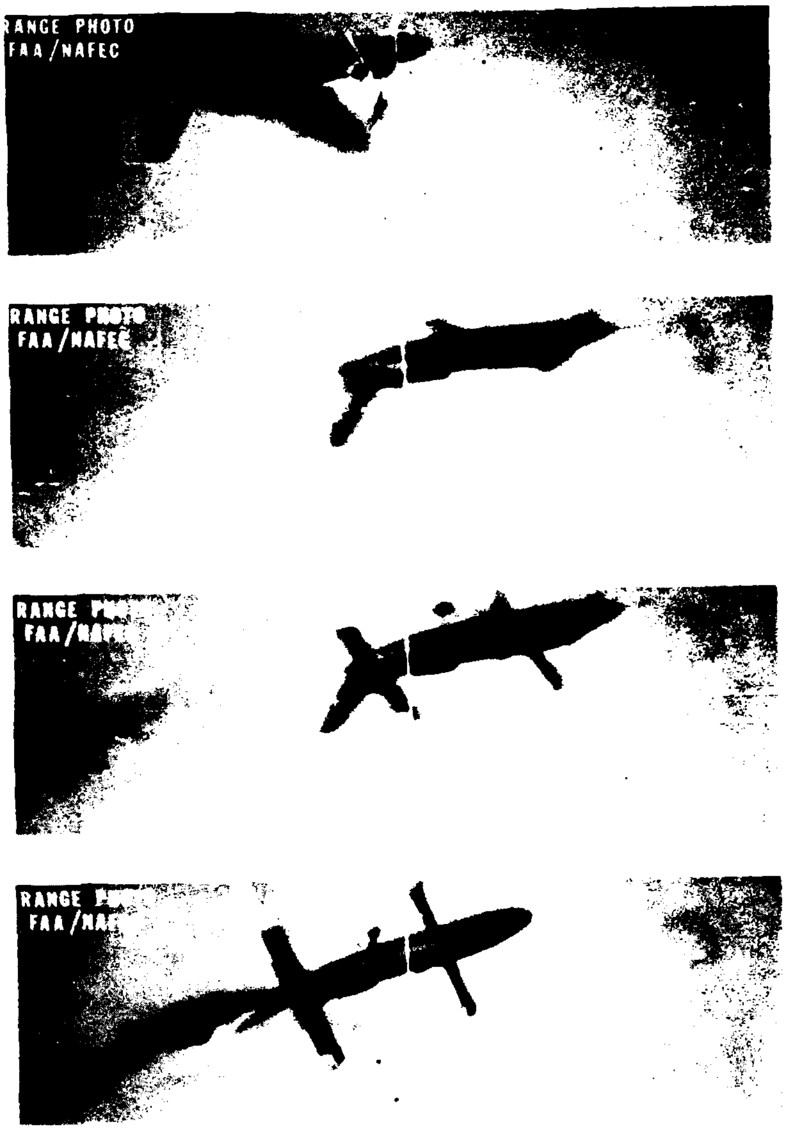


Figure 16

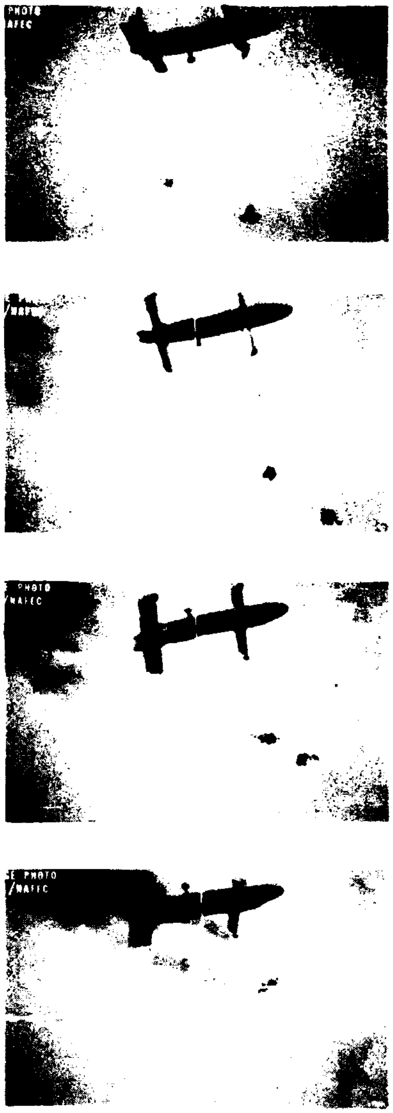


Figure 17

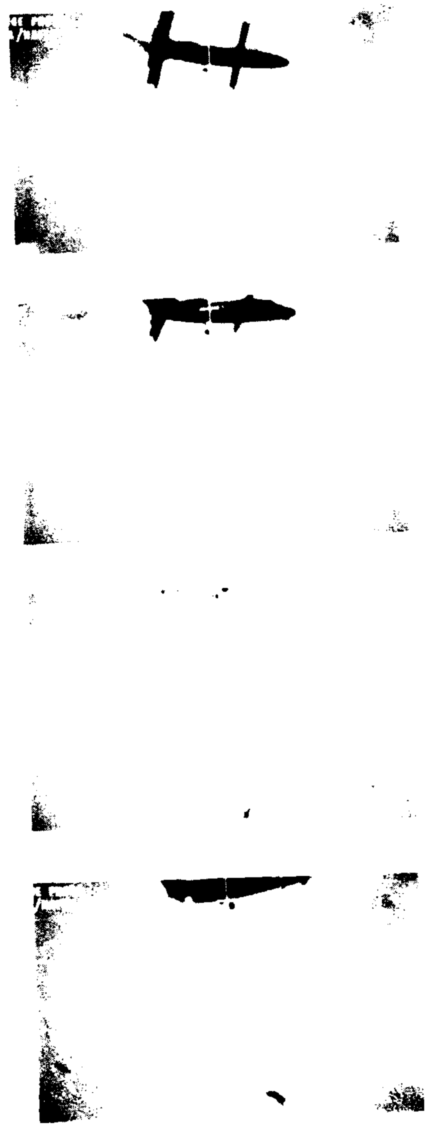


Figure 18

afterwards, "God the sky was full of rotating propellers." The X-19 flipped over on its back and, the minute that the first propeller came off, the pilots pulled the "D" handle and the ejection seats worked perfectly. You can see from the pictures the parachutes opening so the pilots lived to tell all about the failures.

So that was almost the end of the X-19 project. Why did the mounting of the propellers fail? The propeller was nose mounted on a magcasting and magcastings are well known to have defects and these led to a low cycle fatigue failure in the casting and the propellers came off. The project was reviewed by the Air Force. The Air Force wanted to continue with the project, Curtiss Wright had enough spending of their money in building it so decided to cancel the project. At about the same time McNamara came along and said "That V/STOL airplanes are not for this country," so in spite of all the efforts on V/STOL, we didn't have the alternatives available and all V/STOL projects came to an end including the XC-142, a tilt-wing V/STOL airplane. It is believed that the XC-142, had it been carried through its development like the Harrier, would have been a success.

V/STOL airplanes were proposed for a number of applications and when I went to work for Boeing we proposed a V/STOL tilt-wing propeller driven airplane for LIT. We brought that concept right up to the point of selling it to the Air Force but they were very negative on propellers and said you can't build an airplane of this type because the propeller technology is not there. So the Air Force provided a million dollars for developing the necessary propeller technology. By the time this effort was completed everyone involved disappeared, including the LIT project, and our efforts to develop V/STOL airplanes came to an end.

At that same time, late in the 1960's, Woody Cook and a group of NASA engineers thought that the tilt-rotor airplane, as being proposed by Bell, with the cyclic pitch rotor was the way to go for V/STOL airplanes to give improved performance relative to helicopters. So they started a low key development and today we have the XV-15

V/STOL which is the forerunner of the V-22 advanced vertical—lift aircraft program. Everyone wants this new tilt-rotor airplane today because of its advanced characteristics and this is what we hoped to have back in the 1960's and could have had with proper management, and research and development.

The X-19 program certainly is not unique in its final disaster and its foundations for failure. You can look all over at various aircraft programs and see similar situations. I hate to be negative, but I'm trying to point out that you've got to do your homework in both R & D as well as in management and political issues to develop a successful new aircraft concept. We were hurt as much by political problems as we were by technical problems. I feel that if we do our homework properly, we can avoid unsuccessful projects and this is my message. Thank you very much.

INTRODUCING NEW TECHNOLOGY INTO THE NAVY

by

PETER J. MANTLE*

Good afternoon. With degrees in aerodynamics it's only natural that I should spend most of my career working on ships. That's how things go in this business. When I was asked to talk on how to bring in new technology, that's such an obtuse subject, I was a little hard pressed on how to tackle that subject, especially with a group such as yourselves. You have covered many aspects of the same problem and been involved in the process yourselves.

I want to share with you a couple perspectives; the technological side, the administrative side, the industry side, and the government side. All of these groups play

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*Peter J. Mantle is Director of Strategic Planning for the Lockheed Marine Systems Group of companies in Seattle Washington, Oregon and California. Prior to that he held senior positions in the U. S. Navy as Director of Technology Assessment in the Office of Chief of Naval Operations and a similar position in the Office of the Secretary of the Navy.

an important part. I wanted to make sure it wasn't a generic presentation so I want to pick a subject that I have spent some time on. I also wanted to make sure that I didn't just walk through a bunch of problems. Discussing the problems of introducing technology wouldn't be very useful if I just said what the problems were, if I didn't give some indication of what some solutions might be. As you might expect, there are no easy solutions, but I think it is worthwhile trying to share with you and maybe get into a question and answer session of how some of the rules of thumb might be. Also, to make sure that it is not just a generic discussion, I'd make it specific on the particular area of advanced hullforms and various high technology impacts that we have been playing with the last 30 years or so, 25 years or so on high technology ships.

From those specific examples we'll see how they also apply in a broader scope and give some examples there. Then get down to what it is all about and that is try to grapple with some of the rules and what we've learned from all of this. It boils down to number one, perseverance. You're going to hear me talk about how introducing anything takes a tremendous amount of perseverance from those who would introduce it, and one measures the progress not by DSARC (Defense System Acquisition Review Council) cycles but by careers. Also, it's not just a matter of perseverance, but one also has to be aware of what is going on around one. If you've got the world's best technologists in square holes, they are not going to be very good technologists or innovators. They must be aware of what's going on in the related fields and sometimes even in unrelated fields. Also, if one is going to work with the Navy, he had better understand the system. There is no such thing as you tell me the threat and I'll tell you the solution, then we go ahead and build it. It doesn't work that way, and so, then, the last item would be absolutely non-controversial; you all agree with me on everything I say, on some rules to use on how to do the job. That was a joke.

Without further ado, let me just remind you of some of the advanced shipforms that I'll talk about; air cushion vehicles, amphibious vehicles, surface-effect ships, catamarans, and of course the SES 100, wherever I should point, over at the Annapolis NSRDC where it is up on blocks now. That type of ship and, of course, the advances in other hull forms. The Navy has started to break away from traditional hull forms in several areas and has taken almost one quarter of a century to get here, but here is one particular example. The air cushion landing craft program has now come out of research and development and is under way in a SCN, or procurement, program and the Marines want to see about 108 of these craft. The program is just starting after 25 years of getting there. These craft have the unique features of operating over land carrying the tanks and water for landings from the amphibious ships hard over the horizon. These 15 knot vessels take the tanks and the Marines straight into shore, straight over the beach and behind the shoreline without stopping at the vulnerable shoreline.

A new form is starting to take hold again. The Navy is getting very interested in this technology, the SWATH technology, small water-plane area, twin hull. This concept has only been around since about 1930 when it was introduced by a Scotsman and an Englishman into the British Navy and didn't get very far. Tried it in the U.S. Navy and didn't get very far, and we haven't done anything since 1974, really, in the SWATH business. The Japanese have taken off in this arena and just delivered their craft, a 3,500 ton displacement SWATH vessel, to the Japanese government last October. That is an interesting technology and there is a lot of history and heartbreak concerned with that also. The surface effect ship over here at the NSRDC has spawned two programs, early programs of a gang that came out of R&D, the mine sweeper craft, a fiberglass version being built in New Orleans and a special warfare craft. A swimmer-delivery vehicle, that is being done in California. These are some examples. But the thing I want to talk about, getting to the nub of the problem, is introducing technology.

The first rule is that the first observation very rarely has the technology, in this case the platform technology, as envisaged by the inventor or the innovator, or the pioneer. Very rarely has the end use turned out the way he said it would. Some examples are things we're all familiar with, all old hat and been around forever - an airplane, a supersonic, carrier-borne F14 aircraft. The hydrofoil, the PHN hydrofoil, 6 of them, a squadron of these down in Key West, Florida, and of course, one of the best fighting machines we have, the submarine, the strategic submarine. They all started back when they were advanced technology, when they were the dreams in people's heads. They were not envisaged to be used in any way, shape or form the way that we use them today. The aircraft was developed militarily by the Army as a spotting platform for people to send up to go see what the enemy soldiers were up to, report back to the general on the ground so the general knew what to do when the real fighting was to take place. There was no thought of using the airplane as a fighting machine.

When the airplane first came out, they forgot to invent airfields, and so the thought occurred about how would we land these things that we fly. First thoughts were that they should land and take off from water. On the hydro airplane they were developing landing gear mechanisms to put on flying machines to land in the water, and that was the origin of the hydrofoil. That was a far cry from the missile-carrying hydrofoil that you can see it has developed into.

The submarine has come closed circle, from being the weapon itself to a weapon carrier. The original invention of the submarine was the weapon of the Civil War days to go up and bang up against a ship and blow up. It was the torpedo, and we've now come full circle to where it carries the torpedo, or missile, in this case. This is observation number one. The other one, this usually will get me fired. This is the one that says I believe there is enough money in the system and what we need to know is how to manage it better. We all complain about the economy budget. We don't have enough money to do research and development. I might just point out that the Navy's R&D is running about 10 billion dollars a year, now, and has been steadily increasing since the end of World War Two. There have been ups and downs and hiccups to the local events, but we've been increasing rapidly. I pointed out that what's really happening to us, bureaucratically, is that in the 1948 planning system we just divided the R&D up in three chunks. You were either systems or technology, and it was managed that way. In our penchant to get more efficiency, we decided to break it up into accounts now. We have six accounts; 6/1, 6/2, 6/3, 6/4, 6/5, 6/6, and, just to make things more complicated, we have 6/3a, for prototyping and a few other things in between, and I maintain that what's happening now is that if you had three guys in charge here, you now need six guys in charge here, and six squared times your use cycles and you can draw your own conclusion from that.

I'll just digress for a second here. People have been talking about, and I've even read some papers about, the decline in the technology base. But, of course, what we've really been doing is just redefining whether a thing is a prototype, or an exploratory development or what it is. The technology is still basically the same. We have not re-invented what science or technology is. We just changed the accounting system and we'll find a lot of things that we now do in 6/3 we used to do in 6/2. There is a lot of bureaucracy starting to creep in when you get a little close to home on how to play with technology. How long does it take? Unfortunately, one measures these things in career paths and generations, and the hard part is the time for acceptance. To show what I mean there, if I stick with the official process of introducing a good idea, we start with milestone zero. We talk about the threat, the need, then we go through concept design, preliminary design, contract design, detail design, build something, then get on the follow ships. Ship, airplane, missile, it tends to read the same. A lot of study boards, defense science boards, a few other groups have been studying this problem of how to get started, and conclude that it has been getting a little longer over the years, three to four years to get from the bright light to starting a design. That's the official schedule, but I would like to sow a seed that is not quite right, because if you go back and, instead of analyzing just the last ten years or twenty years, you go back to the last two hundred years, you'll find, yes, even though we didn't have SESOC in those days, we can track the ideas first introduced, when the first designs started, and yes, its true that three years or so is about right. It hasn't changed much since two hundred years ago. But the first time it has been used militarily, typically, has taken twenty-two years or more, and some of them are hydrofoil, thirty-five years, submarine twenty-five years, and this was first introduced by Hitler when, after the Swiss had been planning hydrofoils for some time, Rommel was getting into trouble in Africa, Hitler wanted to get the supplies to Rommel, and so that's what started the first military use back in those days. Some of them were amazingly short. That was probably tied to the two factors in the particular case of the airplane when I maintain (a) it was a natural, that's why I believe the air cushion vehicle is surviving, because it is a natural for the amphibious marine corps operation. The airplane is the first time we get out of our third dimension, instead of crawling around two dimensionally. Secondly, (b), they declared war, and so that tended to help the subject there. So one could construct a rule on that for introducing technology. So, if I just summarize a second here, you can see in real time, that officially, it takes about seven years, but if you take this average, overall, the major things that airplane, ship, steam turbine, gas turbine, propellers and a whole host of things I didn't even include, you can see it takes three times that, and the problem appears to be, getting the idea accepted in the first place. You get lots of stops, going back to square one, starting again, and changing course. I can not pin point the time when officially, once you do this, once you get the system to accept that it is worthwhile doing.

So let me give you some examples of why I think this occurs, and part of it, unfortunately, is human nature. None of us likes to deal with things that we are not familiar with. If we are STATUS QUO, even if we are technologists working in a new lab, pushing a new idea, if the guy in the lab down the hall is working on a new technology that might outstrip ours, we find it hard to accept that. Let me give you some examples; this is a case when ships have got used to the idea of paddle wheels and this revolutionary idea of putting this little propeller on the back end of the ship could push it forward. This was introduced to the British Navy and this is what the head of the British Navy, like the Naval Studies Board of that day, said about the screw propeller. It won't work. I wanted you to pay attention to the date, it is 1837.

Here is another example in the U.S. Navy. The Naval Studies Board of that day had written a very eloquent paragraph that said going from sail to steam is not the way to train naval officers. If the commanding officer of the ship did not have total control up there on the deck, that was obviously not the way to go. If you realize that was written in 1869, and don't forget I've shown you the example of 1837, they have already accepted the fact of power driven boats, but now they are arguing about the propeller. So here is a long gap during which one side is still debating whether or not it should have been a power boat in the first place.

A little closer to home, the famous National Academy of Science's quote, headed up by Von Karman, said that gas turbine engine will never fly. This was a year after the Germans were already flying their jet airplanes in 1939. I found an interesting story about Von Karman. I read his autobiography some time ago, and he is very embarrassed about this because he was the chairman of the committee and, in his autobiography, he mentioned that he was on travel on the day they wrote up the final draft and he blames his stupid underlings. So I would like to give you a modern-day DSARC example of what happens to a typical program from the basic concepts as it goes through the normal DSARC process, the approval chain, the competition chain, and so on. Except it isn't really a modern day example. I'm going to give you the Holland submarine story.

In 1875 John Holland had this idea for a submarine. He took it to the War College and he was called a lunatic and was told to go away. He went by one day talking to some Irishmen who wanted to overthrow the British, and they were called the Fenians. They gave him some money to build a craft that would defeat the British fleet. They could then bring the Irish rule back to Ireland. He took the money and started to build his submarine. Admiral M. Sicard, Chief of the Bureau of Ordance, was impressed by the boat. The local secretary had this great idea then that the Navy issue an RFP. In the normal wisdom of things, taking this nurturing idea, is it ok? We now issue an RFP and you have to put up a certified check and five percent of the bid to accompany it. The goverment, upon acceptance, will require sixty percent of the bid for a performance bond. They want specifications of 15 knots on the surface for 30 hours, 8 knots submerged for 2 hours, and many other details and requirements. Holland said "You've got to be kidding, we're introducing new technology."

Two bids were received, one from Holland, one from Cramp Shipbuilders Co. Neither company would agree to the performance bond so the Navy rejected the bids. This sounds like modern day programs as they go on, more RFP's are issued, more people bid. A man who doesn't know much about it will bid a propeller drive for a ship driven by propellers. The Navy says we need more competition in our procurement acquisition programs and set going on this one.

About this time we have another change of administration and the submarine appropriations are being diverted to other uses. Various groups witness the trials of the bad boat and turn it down so the Navy issues more RFP's. Eleven bids are received. It goes on, an Admiral disagrees with the board's findings, but Congress supports the idea anyway, and it goes on and on and on. So now the Navy finally gives a contract to go ahead and do it, to Holland. Then John Holland gets ill. He can't monitor the design, so NavSea of the day monitors the design and adds some improvements to the design including the features of the bad design that was rejected by everybody else. They could not get the ship built. John Holland witnesses the corruption of the design, so he goes ahead, sets a new design, builds that, launches it, the Navy sees it, they like it and say that's it. Then that starts the submarine program at the time. They purchase the Holland, place the order for six boats of this "Adder" class and, only after they got that one going, did they finally finish the other one which is probably sitting in a museum somewhere.

When we first started to dig this example out, we were so impressed with the efficiency of the submarine community we said what we should do is see how the submarine was introduced, because this would be a good example of efficiency and how some things should be done. This was the result. I think there are a lot of lessons in this.

Hydrofoils are typical and fall in the same traps, and I can say these disparaging remarks, because when I was putting this stuff together, I started to go back and read some of my own papers. I've been caught in the same traps. We built hydrofoils back in this time period and, based on this, we published papers in ASNE journals and various other places projecting what could be done. A four thousand ton hydrofoil is going to be operating in 1980. If that didn't happen, of course, a whole new generation of programs, new career starts and new people coming into the game would make new projections. We get that story. Typically, we are about 15 years off. Technologists have been off in the hydrofoil world for about 15 years, too optimistic. So we go to another group, air cushion vehicles people and, lo and behold, we get exactly the same answer.

Certain air cushion vehicles are built, we build them in England and other places, we make projections and we're going to have 4,000 ton SES's operating in 1980. Again, it didn't materialize. They weren't paying attention to what the technology was really offering and what the user really wanted, and so that hasn't come about and we are 15 years off on that projection.

I think that one of the forgotten things, quite frankly, by the technologist who is wrapped up with designing a new type of platform, is that he has forgotten that a fighting machine is a combination of the platform characteristics plus the combat system characteristics. There have been fantastic improvements in both the weapons and the sensors over the last fixed time period, whereas the developments in the platforms measured in the same terms have not been quite so dramatic. That is one of the key things that the platform technologists have tended to forget. Giving you some examples very quickly, the platform in steam in WW2, today, future, is typically 10-30 knots. It is only in very special cases, say in 50 knot hydrofoils, that we have improved the speed by a factor of about 2 to 1. Whereas, in our eyes, and weapons, and accuracy and so on, we find orders of magnitude of 10 to 1, 20 to 1, 30 to 1, and, just for tongue-in-cheek, throw in directed energy at 39,000 to 1. Of course, there are a lot of military operations analysts who will tell you that the farther you can see, the farther you can shoot, the farther back you want to get from the scene of the action and so, therefore, why do you need all this speed built in to the platform? You can see, in real terms, what that has meant in a couple of major areas of the Navy. The Navy has spent some 450 million dollars developing 80 knot platforms and then canceled the programs. You can see this really comes home to roost when you talk about the impact of technology. What the Navy wanted to do was go 30 knots, well, and not 80 knots because it was a neat thing to do. Everyone loves to go 80 knots, but we could never show the military effectiveness of that. As I say, I have written papers saying that you need to go that fast, and I've had to revise some of my thoughts in the light of a grander picture of what the technology is doing to the Navy, and what the threat is doing to the Navy, and how we must respond. In this case I think we're just ahead of the time in the platform. It will come in certain missions, but it is going to be very specialized, and it will have to be very carefully controlled.

We tend to think, the technologist tends to think, a little differently. Life cycle cost of any system is made up of R&D cost, the cost of the thing itself, operating spares, and so on. Then you throw it away. It is very difficult to see the impact of our technology decisions in here on the acquisition, and there is a tendency to forget the true impact on the operational Navy of the new technologies. We tend to think life cycle, and we didn't have seminars on the subject, but everybody makes decisions on acquisitions. Nobody makes decisions from life cycle costs, I don't care what the reports say. I buy my car so much down, so much a week. I buy my house so much down, so much a month. If they told me how much my house would cost in life cycle cost, I probably would be a renter. Then, of course, the congressional budget cycle is exactly the same way, but we must know the impact of these decisions out here. A cost chart would show the cost is going up. Thirty-five knots air cushion vehicles, hydrofoils 70 knots, commercial 80 knots ships and you see we go up the logarithmic scale as we apply cost and it has not been proven in many instances that the military effectiveness has gone up by equal amounts.

Without getting into all the details to back up each of these statements, I maintain that this tells me we should pursue only small steps at a time instead of getting starry-eyed on massive improvements in size or capability. The system that we're working with can handle smaller increments in size. We should also make sure that, if we have the greatest idea going, that there is somebody out there who needs it. We have to make sure we match it with a need. Once you've got that, you have to recognize that we live in a check-and-balance world, and you can blame George the 3rd for that. He had the efficient system, but a bunch of guys decided that was not the way to run a country. What we need is a check and balance system. A legislative system, being out-voted by the legal system, being out-voted by the administration, and so we have a check and balance system that we live under.

In the R&D world we must get back into allowing people to fail. We must let them make their mistakes, learn why they made the mistakes, and then go back to the prototype, try it out, learn a little bit and move on. And just to make the point of perseverance, I'd just like to leave this thought that we must recognize the fact that one just has to hang in there, keep pushing on a particular idea, recognize all the rules of the game that apply, the technological reasons, political reasons, congressional reasons, systematic reasons, but keep trying anyway. Thank you.

AUTOMATION, ROBOTICS, AND
NAVAL OPPORTUNITIES

by

DR. ROBERT A. FROSCH*

My definition of Robotics and Automation is by design extremely elastic. I am not specifically talking about Robots as things that necessarily look like arms or like people, but rather of the direction in which the simultaneous, extraodinary development of communications, computational capability and control theory has begun to push the technology of objects that can be made to do things. I'm purposely speaking in that abstract and

*Dr. Frosch earned Bachelor and Master of Arts Degrees and a Ph.D. in Theoretical Physics from Columbia University. He joined Columbia University's Hudson Research Lab, where he worked on Naval Research projects. Following that he was appointed Director of Nuclear Test Detection for ARPA (Advanced Research Projects Agency) and then became Assistant Secretary of the Navy for Research and Development. From there he was selected Assistant Executive Director of the United Nations Environment Program with rank of Assistant Secretary General of the United Nations. He was Administrator of NASA from 1977-1981 and in 1981 was selected Vice President of General Motors Corporation in charge of General Motors Research Laboratories.

general a set of terms because, from the point of view of manufacturing, and I think from the eventual point of view of the Navy, the mere constructing of arms that can behave in a human-like way is the least of the interesting things that can be done.

The most interesting robots are the ones that are undetectable because they don't look like anything. They are simply running a system in a way in which people would run a system. That is to say, in a sense, that in the long run the key thing about technology is the thought, rather than the manipulation, and so the central theme really is the ability to sense, the ability to communicate, the ability to do logic, or to draw conclusions, to think in some sense, and then to take action on the basis of the thought and, frequently, to close the loop on the basis of the action to sense and so on. And, in that general sense, I'm talking about actions which are taken by, let me say, clever machines. In spite of the use of the term artificial intelligence I have so much trouble understanding, as nobody understands what natural intelligence is, that I'm not quite sure what to do with machine intelligence. As I commented in my earlier talk, sitting on the top of the PC I use in the office is a blown up version of a cartoon that appeared in American Scientist in which two people are looking at an obvious computer screen and keyboard and one says to the other, "Well it figures. If there were artificial intelligence there had to be at least some artificial stupidity." What is happening in the industrial scene is that we have begun to use computational power, and the power to use computation and computer capabilities, to control things and to interpret the results of sensors to do tasks all over the manufacturing and engineering process and, both naturally and by design, this is driving in a direction of a somewhat different kind of marriage of engineers and machines, and productivity and machines than we have had before. In fact we're driving in the direction in which the entire process of design analysis, production specification and production control is a process which takes place in a sequence of computer operations with human interaction along the line. We have not quite been able to do the part that starts with the style designer drawing, although we have some research things which enable an artist to create a realistic looking shape with the property that, at the same time, it is a well defined mathematical object as well as a drawing of precisely the properties that are convenient for engineering analysis.

In the next stage we have begun to use computational power very heavily in the design of structures, in the optimization of structures, so that we have algorithms that can take a design specification and an initial sketch, and optimize to a minimum weight within structural and material constraints automatically. And we can do the same sorts of things with electromagnetic devices and so on. So we're beginning to be in a situation where the design process is itself heavily automated. Not in the sense that you specify and you take what you get, but in the sense that you specify the machine does a well-defined series of processes and the question is "Do you like what it did?", and if you don't like it, then you iterate with another set of rules. This is automatically having the property that design processes, which were previously not simultaneous or were simultaneous in a way that was uncoordinated, so that you had somebody designing suspensions and somebody else designing steering systems, and it was only two weeks later that you discover that the suspension system had changed three times while you were doing the steering system and now there was an interference. So you had to go back and redesign both and, in fact, sometimes you didn't find out until you took the blue prints and did the first prototype. That's now beginning to come under the control where everytime there's a change in the one system, the other guy who was working with the corresponding system can automatically know about the change. We're not quite at that point, but the point is close when we finally get everybody to adopt all the same languages so all the computer systems can talk to each other - at least the same protocols for communication. So that, in fact, the flagging of interference as a simple problem will be done totally automatically. There are the beginnings of taking the result of such a design, when analyzed, and being able to convert that into the specifications for a production program, machining program, and converting that into the software which will control the fine set of machine operations. I'm grossly simplifying. There are things other than machine operations, and the real picture you ought to have is that I'm constructing a well-defined stream of operations which come together to the control of production, but if you visualize that stream and then put little dots on it here and there that are in green, those are the places we've actually done something, and there are all sorts of pieces to be connected. But it is clear what the direction and trend are and we have begun experiments with things that are referred to as factory of the future, although they're very near becoming factory of the present. Here you have a flexible machining system which can move material around and, within a fairly elastic set of specifications, if you wanted to machine ten objects in a row rather different from each other, the system can recognize what it's been asked to do and changes its tools, changes its set-ups and does that for you, and if you want to make another set of objects you can reprogram to do that. So we're rapidly moving in the direction of that level of flexibility of automation. This incorporates, by the way, machine vision as a routine part of the operation, both to recognize and pick out objects, to measure objects, and to decide afterwards whether the process has done what it was told to do by looking at the objects and measuring them. As an essentially automatic process, which has the same flexibility, it can tell whether its a different part, and apply the correct measurements to the different part, and not say its not the same as the previous part you asked me to measure.

With that as a background, I want to move to the system level questions of the Navy. Here Dave Hazen knows too well, we did a study in the Naval Studies Board of the National Research Council several years ago, at the request of the CNO. We looked at the question as he asked it. What are the technologies that will have the greatest impact on naval aviation in the future? And we gave him an answer I think he was not prepared for, but which I think the Navy, at that level, has begun to embrace. What we said was that there will no doubt be major developments in aerodynamics, and engines, and airplanes, and missiles as objects, but the most significant set of changes for naval aviation would be the system in which both naval aviation and the surface navy can be embedded. We suggested a possible system design future for a lot of naval warfare, which is rather like, in some ways, the concept of the rather complex factory system that I was describing. At least the same technologies are inherent and the same kind of system direction thinking is involved. I didn't say in the factory comments that I think it is obvious that with current communication methods there is no particular reason for all of the parts of the system I described to be in any particular place. Obviously, when you come to material handling and the actual mechanical operation, you put those all in the same place for good and sufficient reasons. But there's no particular reason for the computers to be in that place, although they may be, or for the engineers to be in that place, or in any particular place, although they may be. So what one ends up with, designing in a natural fashion, is a rather distributed network system with pieces of machine intelligence and human intelligence distributed in a variety of places connected by some form of fairly elaborate communication network, which may itself have some intelligence embedded in it in order to do its part of the business. What we ended up pointing out was that the availability of all of these technologies and their natural development means that one can envision a naval system with some strengths that our current way of operating doesn't have. The strengths arising from the fact that if you ask, "What's the weapon?", the weapon is the system and one can, in fact, use the strengths of system diversity, of network resilience, and of the flexibility that comes from communication and control in a new set of ways, and control is intended as a pun, both to mean control in the system engineering and feedback control sense, and control in the sense of command and control. The point is that one can envision a naval task force, or any major element of the Navy, or a fleet, or the Navy itself, or a subset of any of those as consisting of a body of things that can be described as sensors. By that I mean intelligence objects, surveillance objects, historical data bases, intelligence data bases, current state of support information residing in a number of places. Some of them residing in intelligence or surveillance assets in real time which may be anywhere in space, on the ground, in air vehicles, or in ship vehicles, communicating with a command entity which has at its disposal both the communication network that connects all of this, and the intelligence machine assets capable of working with information and with the people involved and capable of translating this into command to systems which respond. But because one is thinking of a network with distributed and quality automated intelligence and capability, the possibilities for the placement and use of the asset, including the people in command and control, now become very diverse. Because if we introduce some kind of machine intelligence into some of the vehicles and into some of the weapons, and use as a communication system in a suitable network way, then you can conjure up some very interesting and unexpected military assets. I like to ask naval aviators, how they would like to fly an F-14 that carried no Phoenix but could fire 250. The point being that now that we have this kind of system possibility, there is no reason why the weapons have to be carried on the vehicle that controls them. That is, historically, what we had to do starting with the guns, then to the bomb, and so on. In fact the vehicle that does the control may be the least likely one to carry the weapon, because it may be the one that you want to put into a forward area and not burden with the weapon, but only burden with the task of sensing survival, evasion and control, which will be a lot easier without a lot of drag and weight around. And the supply of weapons can be infinite, so to speak, if there are weapon carriers around that can launch them and provide them. We can certainly build systems in which you have the control distributed in exactly that way. You now no longer are tied by the mechanics of the weapon to a restricted set of weapons that you can control for a vehicle because the control now is a question of software and communications and the launch may be separate. One might have multiple hand-offs and a weapon in the ccurse of the trajectory from wherever it was carried around to wherever it was supposed to end up, might pass through a number of hands, depending on what the situation was. One can, of course, say the same things about data weapons and the same things about air weapons because that's what we looked at, but one can talk about all kinds of other weapons in the same way. One automatically, now, has to ask a new set of questions about the operation of vehicles. We've all grown accustomed to the RPV. But an RPV which really does something is a difficult object to be totally relied upon, and all I'm saying, when I say this, is that the distinction between complete automation and complete automation less epsilon can be gigantic. To get to something which is almost totally automated, but has the possiblity of human intervention at either the machine's option or the human's option is very, very much easier than going to complete automaticity. Because it means that for the machine's intelligence you only need to take care of a restricted set of circumstances, and when the machine goes beyond that set of circumstances, it can yell, "Hey, boss, I need help." If you go complete automaticity, then you have to contemplate, somehow, the same range of circumstances that you would allow a military commander to contemplate, and we have no algorithms that are nearly as good as any military commanders. They aren't even close to being able to specify what it is you guys do, never mind trying to figure out how a machine does it. We know the differences among various people, but if you try to write down why it is one does this, and one does that, you're in deep trouble. So the difference between going all the way and part of the way is important.

But this brings in a whole new set of questions. I'll phrase one of them as follows: How many airplanes can somebody fly? Now if you put no intelligence into the airplane, then some airplanes may take more than one person to fly. If you begin to put automaticity and intelligence into an airplane, then even for complicated circumstances, you may, in effect, have it possible for one person to fly an aircraft. In the sense that most of the time, for a *given* aircraft, the control person is not flying the aircraft, that aircraft is operating under instructions. When the instructions are exceeded, the situation is different for the controllers, and a scan of the instruments tells them there's a problem. Then attention must be paid to that aircraft. Obviously, I have a statistical theorem here which is that you have to design this system so that everything doesn't happen to all aircraft at once. And battles are sometimes that way, so there may be some real problems, but I think there are many circumstances in which the relationship between who's flying what and what they are doing can suddenly get much richer and have many more possibilities than we've talked about. The same is true of ships, or vehicles, or weapons. That essentially is the idea. What is the automatic part is clear, what's the robotic part, well, all of these machines are, in essence, robots. That is, they do human-like tasks under defined instructions in a semi-intelligent way, and that, I think, is a robot. They may not look like people, they may look like airplanes, but that's what they are in any case.

So that, I think, is essentially the system level picture of a possible kind of future pattern to think about. And I don't know how far one ought to go. I can see lots of difficulties, if you're going to depend on a network communication system for these tasks instead of point to point. By the way, it would be much more resilient if it's a phone company, than if it's a hot line. Then you have to be sure that in spite of the high resilience of the network, that it really is pretty good against jamming, and pretty good against disruption of part of the system and so on. That's a definable technical problem that can be attacked. It has to be clear that you really do have control of the weapons whether you are sitting in the vechicle or not, and that control can not be taken away from you, that you don't have accidental cases. That, too, is a defined technical problem. So I think there are some difficulties to be faced and some tremendous possible advantages to be looked at in each of these technologies.

Now let me come, finally, to the object that I said nobody pays much attention to. I don't mean that in the sense that we don't have elegant attention paid to whole design, to an exotic hull design, to the basic propulsion machinery and, of course, all of the technology I'm talking about is used for navigation and communication, and is certainly used for the weapons systems that are put on the ships. But unless something has suddenly changed in the past year or so, none of these is used for the ship. That is to say something changed when we put gas turbines into ships. But I bet there's a watertender still down there in the engine room, and we certainly did not decide that current technology means that almost never does there have to be anybody in the engine room. And almost never probably ought to mean for the whole cruise.

It's a long time since anybody sat in the engine room of a 747. In fact its a long time between looks under the engine cowling. It's true you have a chance to get at it, but you have a chance to get at it on shipboard too. Even the automobile companies, who are much higher technology than they have the reputation for, have not had a mechanic under the hood with the engine for a very long time. And, in fact, you go quite a number of hours if you neglect the car. You go a remarkable number of hours before you really have to worry about it. Sometimes you have to do some damage control, sometimes you have to do some maintenance, but most of the time you don't need anybody there, and I don't understand why we haven't done that with engine rooms.

The bridges of naval vessels are like they were designed in the middle of the 19th century by the same guys who do the control rooms for utility plants. We have moved to a better technology in aircraft because we can't stand the space and weight. The trouble with ships is that they are really rather forgiving, and so if you're a little prodigal of space and weight and how you spread things out, well, its another millimeter of freeboard. So we have not had any forces to improve that, but the idea that a bridge still has instruments all over it that do all sorts of things that ought to be integrated, and are never integrated well except in the skipper's head, if he can succeed in listening to all those voices, seems to me a bit weird. That ought to be a design system of information from all over the ship, and it isn't. Flag plot is the same way, navigation is the same way. We're doing what we have done for a couple of hundred years. Now I think it's beyond the time to change that. It could change efficiencies a lot.

There are a lot of other things in ships that can stand this technology and even some automation. My vision of the sort of spread in the problem is the vision of a member of the crew struggling up a ladder with a crate of oranges or potatoes on his shoulder as he moves by the electronic cabinetry of a totally automated missile system. That's a silly way to run a railroad. We just haven't automated any of those mundane tasks. It is marvelous that one can do underway replenishment, and I understand the problems of winches very well. The controls systems have come a long way since the time when it was necessary to muster half the crew to handle lines, in order to play games with a rope that connects two ships and carries a pipe. We had better look at that one again in terms of automatic machinery. We're in a new generation of that. We had better look at that.

Now the consequences of all that are not trivial, and I'm familiar with most of the counter arguments. The first counter argument is you have to have all those people on the ship anyway because of damage control. In part that's because nobody has thought about damage control in terms of modern technology in the past 40 years. There are new generations of materials, new generations of design possibilities. I very much doubt that we're going to spend, that it's sensible to spend, 50 men and a lot of timber as a way of dealing with the energy of a ship. We may have to, but I can think of lots of things that really haven't been looked at. And I'm not sure if it's all that manpower intensive to begin with. I really just think there should be another look at it. Because the old reasons don't go, and the fundamental reason is it's too expensive, and I don't mean money, to carry all those people around on a ship, most of whom are not necessary to any modern task. It's expensive not only in money, but its expensive because it radically biases the design of the ship, the marginal cost of a person on a ship is the food, the weight, the space, the living, the attention of the management, and the logistics train that goes with the persons, which is excruciating. If one can make a radical difference in the number of people you need to run a ship, peace, war, and damage, and you have to look at the whole damn set of possibilities, then you can make a radical difference in how you start out to design the ship. In fact one may even have to examine the boundary between when-and I hope lightning doesn't strike me- when you give up the ship, and when you repair the ship, because the current circumstances need to be thought about again. The world may be a different place than it was when a ship was a totally autonomous object, and had no communications, and if it was damaged or lost, that was all the Navy you had in the Eastern Atlantic. Or five of them were lost, and you couldn't even tell anybody they weren't there any more.

Well, what I've tried to do was stimulate attention to the problem by describing where the technology is going anyway in the manufacturing business. I hope that is suggestive as to what I think some of the system possibilities are for naval forces, and also what it suggests about new things that can be done with particular naval objects, my favorite neglected object, the ship. Thank you.

POST WAR AIRCRAFT CARRIER INNOVATIONS AND THEIR INFLUENCE ON MODERN DEVELOPMENTS IN CARRIER AVIATION

by

CAPTAIN ERIC M. BROWN, RN*

I would like to first of all thank you for the invitation to this illustrious establishment and also for the privilege of being asked to address you here this afternoon. Now it was my intention to talk about just post war carrier innovations, but thinking it over, I have to lead in a little from the war times, so we're going to cover a bit of ground at fairly high speed this afternoon.

I would like to say to you that in my opinion, Advanced Technology is essentially development of the

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*Captain Brown graduated with a Master of Arts Degree from Edinburgh University after completing an Honors Degree Course. One year later, as a Fleet Fighter Pilot, he was sunk in H.M.S. AUDACITY during World War II. In the years that followed he accomplished more aviation "firsts" and awards than space is available to mention. Two of these are the first twin-engined aircraft landing on a carrier deck and the first twin-engined jet aeroplane landing on a carrier deck. He was elected Fellow of the Royal Aeronautical Society and later became its President. Additionally, he was elected Vice President of the International Helicopter Committee of the International Aviation Federation. While gathering these honors he also found time to publish seven books on aviation and is presently contracted for still another.

potential of innovatory ideas. Some of these, incredibly simple in concept, very often are followed by circumstantial pressures such as a crucial war-time situation or a peace-time budgetary cut, which bring them to fruition. It can be either type of thing and this is all splendidly illustrated in the area of aircraft carrier aviation, where the objectives are to enhance the performance of carrier aircraft while keeping the carrier flight deck compatible with safe operation. Because of the numerous limiting parameters that dictate carrier size, technical problems concerning the safe operation of aircraft mainly relate to short take-off and landing. So what I am going to do is examine these in a chronological order. So I go to my first slide, Figure 1.

Now, your President Franklin D. Roosevelt and our Prime Minister Winston Churchill, both agreed that if World War Two was to be progressed to a successful outcome, the most critical factor was first to win the battle of the Atlantic and keep open this vital supply line that was being harrassed continuously by German U-Boats and air

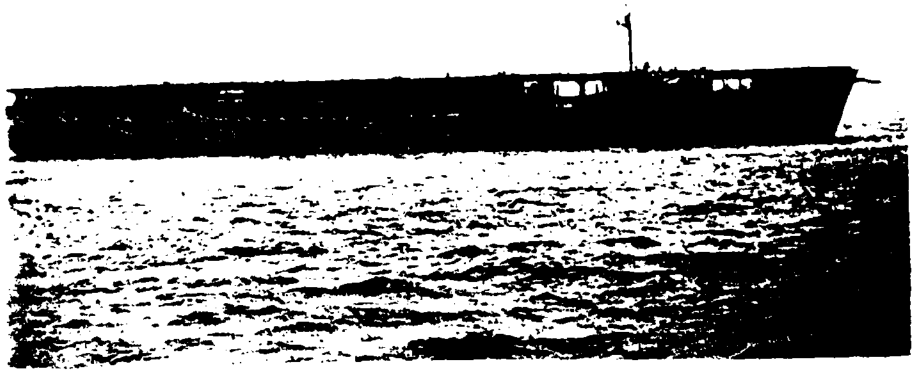


Figure 1

reconnaissance vehicles. It was essential therefore that our convoys had to be provided with air cover and so the idea of the escort carrier was born. And this is the first of these such vessels that was used operationally and is probably the smallest aircraft carrier ever to be so used. It was named H.M.S. AUDACITY. It was, in fact, a captured German banana boat, and it was brought to Britain and the top sliced off and a flight deck put on. The flight deck was only 420 feet long by 60 feet wide. There was no hangar; it had a deck-park for 6 or 8 fighters. There were only 2 arrester wires and a third wire which was connected to the barrier, so if you caught the third wire, which was colorfully called the "for Christ's sake wire," you then pulled the barrier down so you were able to run over it. Now this was a highly successful vessel. It only did 3 months of operations before it was sunk and yet, at the end of its time, Grand Admiral Doenitz himself said that "the appearance of this type of vessel was the biggest worry that was ever introduced into his operation command." Now its success was largely made by virtue of the type of aircraft that was used, which happily was provided by your great country under the Lend-Lease situation, and the Grumman Wildcat had the requisite power and performance to operate successfuly on such a small platform (Figure 2).

There was no British aircraft that really could have done the job at that time. So much has to be said for this wonderful little machine, and, of course, it introduced

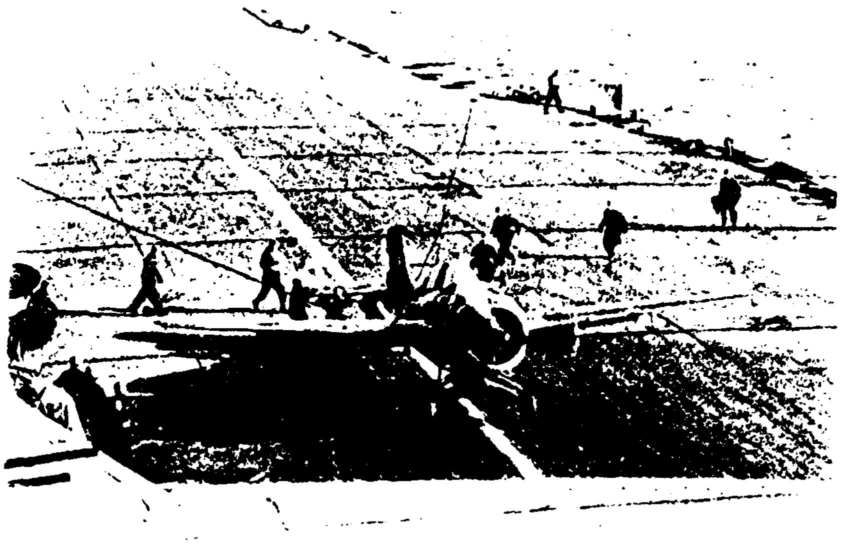


Figure 2

something quite innovatory to us in the form of the sting which you have here at the back end of the machine. One has to admit the performance of the Wildcat, good as it was against certain types of weather, was not good enough to cope with the fighters currently in the European theatre and so the British Admiralty turned to look at higher performance aircraft which, of course, were land based. Since they had no ability to operate from a carrier, we had to resort to devices such as this. Now here you have what is called the CAM ship (catapult aircraft merchant ship), and that is our Hawker-Hurricane high performance fighter on a 65 feet long rocket catapult (Figure 3).

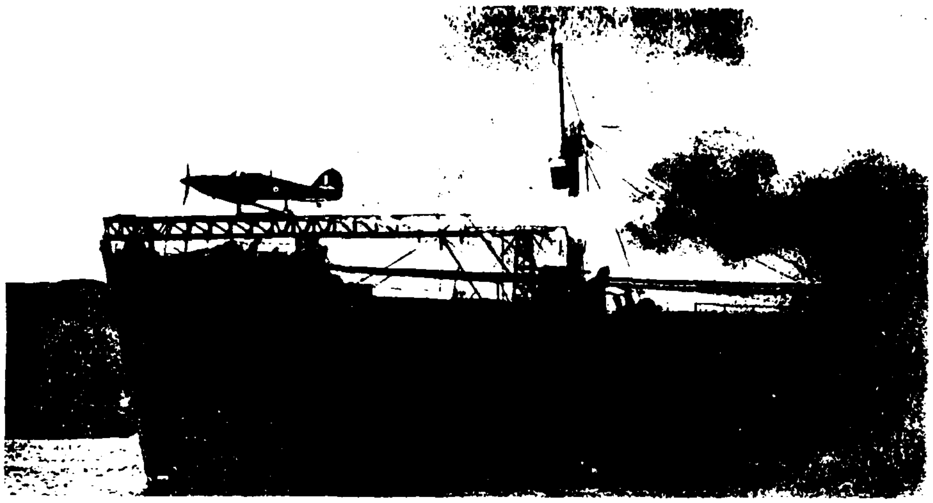


Figure 3

It attained 70 knots in that 65 feet and was launched whenever our convoy was approached by an enemy bomber or a reconnaissance aircraft or, indeed, an enemy fighter if it got close to shore. The snag in this was of course that the plane, unless you were close to shore, was lost and the pilot had to bail out because the Hurricane had the ditching characteristics of a submarine and therefore, you had to part company with it. We also tried the same thing with the Spitfire. Here you see the Spitfire on the rocket catapult (Figure 4). In all these pictures I am the pilot, I have to tell you, so if any mistakes are made, they are all mine. You will notice we had a very cumbersome method of catapulting in those days, which was a cradle on a trolley and you had to have four weighty spools, two on each side of the aircraft, fore and aft, to fit into the slots of this type of cradle. The trolley had at its front end two prongs which went into two tubes filled with water and these tubes had a fibre disk at their open end and the 10 feet long prongs penetrated the tube and this arrested the trolley in a distance of 10 feet.

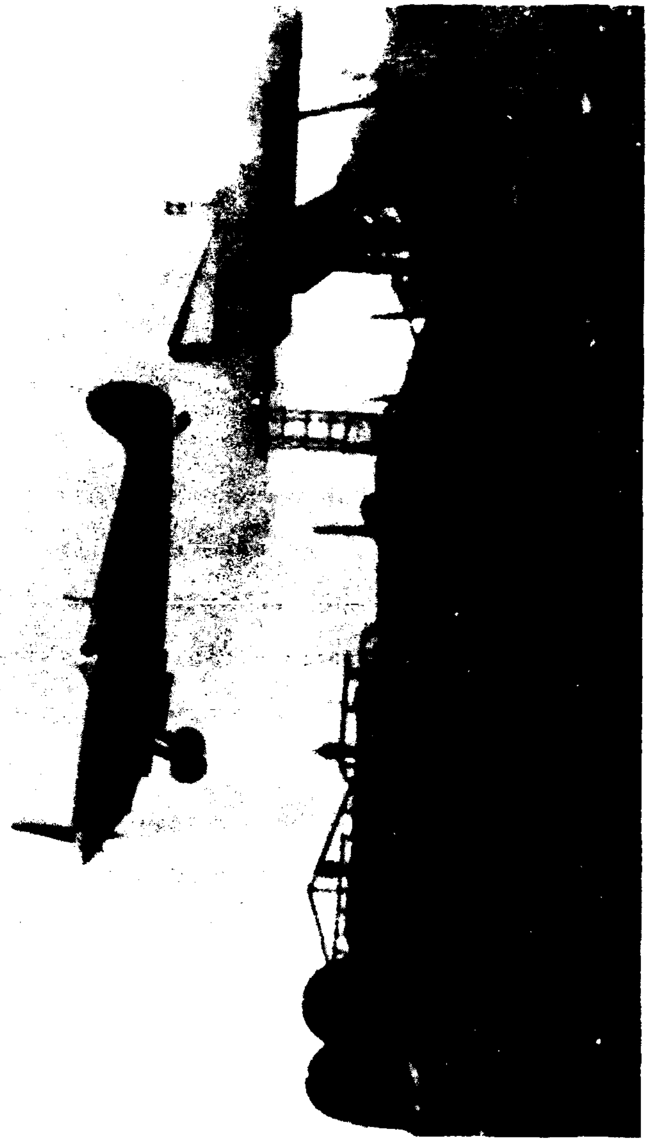


Figure 4. Spitfire on Rocket Catapult

I'm going to show you now what happened (Figure 5)

Figure 5. Errant Trolley in Faulty Rocket Launch

when a chap forgot to put the water in one day. The trolley smashes through the tubes and remains attached to the aircraft with the rockets still going strong but fortunately you see the trolley beginning to depart from me. It stayed with me for quite a few feet before it finally came away. Now, as I said, these land based aircraft could not be brought off a carrier by any normal means, so if we begin to operate them and convert them to be able to have arrester gear they had to be assisted by rocket take-off gear. These were fitted, two rockets on each side of the aircraft (Figure 6) to give the requisite short take-off on the smaller type of carriers. It was a good idea also to have an aircraft fitted with this sort of rocket gear sitting on deck for deck interception; that is to say if you got very, very limited time warning of the approach of an enemy aircraft the fighter was immediately available to take-off instantaneously. Fire the rockets and away you go. Now the alternative to using rocket assisted take-off was of course the hydraulic catapult which you will see here. This is a Hellcat, a Grumman Hellcat (Figure 7), and again you introduced us to something entirely new, innovatory, which we latched onto at once.

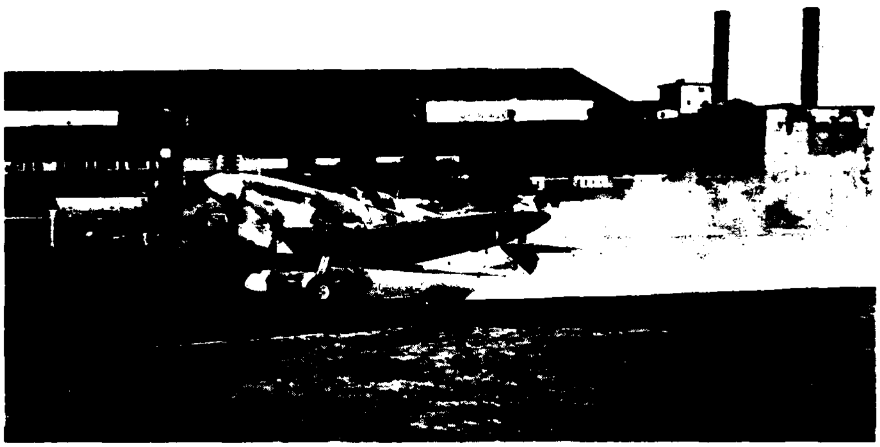


Figure 6. Double Rocket Attachment on Both Sides of Aircraft

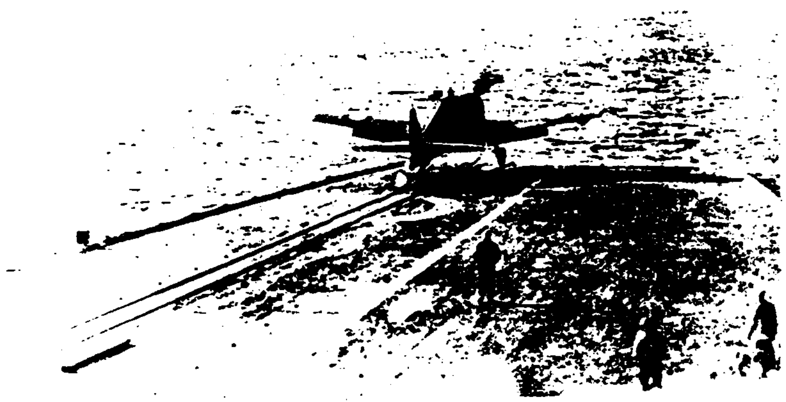


Figure 7

That is the two or three point launching method you had where the strop attaches a shuttle in the slot of the catapult then into a single hook or two hooks under the belly of the aircraft. So we got rid of that cumbersome trolley system, which I showed you earlier on and came onto this type of catapult. Now all these systems were useful in their own way, but they did show that the problem related to the fact that we required more power for take off. Fundamentally that was the shortcoming and one of the obvious things to do was to turn to the twin engine aircraft, where usually an excess of power was available, and we had in Britain at that time an aircraft called the

DeHavilland Mosquito. This was a very high performance fighter bomber, and we decided we would convert this and make a deck landing with it, and here I am making the first such landing (Figure 8). You see it's quite a big aircraft, and we thought at the time, like Professor Bock stated, that this was the first twin engine landing of an aircraft on a carrier, but in fact it proved not to be. It was the first operational aircraft, but actually the USN had made 8 or 10 landings as far back as August 1939 with an experimental,

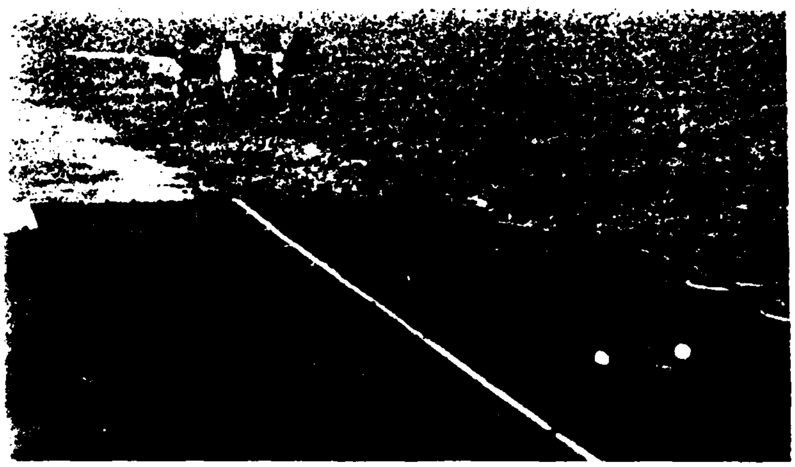


Figure 8. Deck Landing With DeHavilland Mosquito

rather a civlian-looking type of aircraft called the XJO. But the Mosquito was a very fast machine, and its normal landing speed ashore was 125 mph. Well, it was quite obvious there was no carrier gear around that was going to take this sort of thing, and we were about the first to use the lift control available in the engine power and the propellers by making the approach at a very high power setting, and in fact the first touch down which was just about to be made here was at 78 mph. Now to get an aircraft that lands normally at 125 mph down to that speed, I had to have a lot of power on, and therefore required fairly big draggy flaps as you see, and these flaps were specifically enlarged for this purpose. I should tell you that I managed to get this aircraft off in 52 yards, and it's a 20 thousand pound aircraft. Fifty-two yards with a wind speed of 34 knots, that is a combined wind speed and ship speed of 34 knots. So it really got off like a scalded cat. A big advantage of course was the view that the twin engine plane produced, but it gave also 1 or 2 snags, the main snag being how do you cope with an asymmetric landing if you lose 1 engine? This was an extremely difficult problem and one that was not readily solvable. The other problem was the span of the aircraft was such that in order to take off it had to be ranged with the port wheel very near the port edge of the deck so the starboard wing tip would avoid the island, and since the natural swing with the torque of the propellers was to port, there was very, very little margin for error on take-off. The aircraft was never, therefore, used operationally because we really couldn't solve the asymmetric problem, but I did about 30 or 40 landings with it and we really had no trouble during these landings. We therefore went to a hotted-up version of this called the Sea Hornet. This is a single-seat version of the two-seat Mosquito and it was probably one of the most overpowered aircraft ever built (Figure 9). These Rolls Royce engines had handed propellers going in opposite rotation so that no swing problem occurred. The view of course, as always, was magnificent with the twin. This thing had magnificent performance on one engine, and we did try to get down to single engine landings on a carrier, but time really was too short and we had to give it up, but the aircraft went into operational service because it had such long range that in the event of engine failure it almost certainly could make shore. It was booked for operations in the Far East at the end of the Japanese war and, therefore, had to have long range, but it was a remarkably fine aircraft. It is so overpowered I used to have an aerobatic display on this where I did a loop on both engines, a loop on one engine and finished up with a loop on no engines--always makes fun. The only thing you've got to put a little trust in is to be able to unfeather when you're coming off the bottom of the

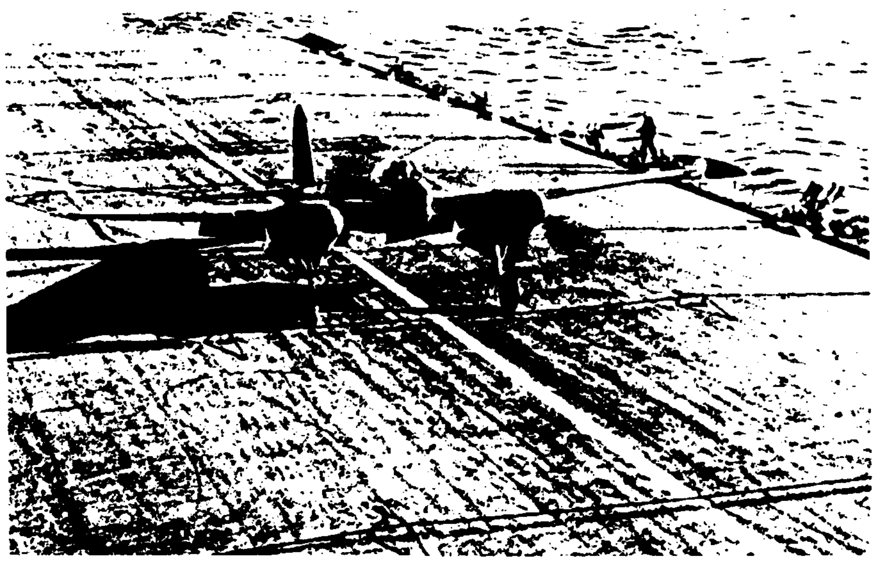


Figure 9

loop with no engines, otherwise, you're going to look rather silly. The advent of the jet in naval applications at the end of WW II looked as if it might solve a lot of our problems, certainly performance-wise, but it brought as many headaches as it brought relief from some of the other problems.

Here I am making the first pure jet landing on an aircraft carrier in December 1945 and once again a magnificent view as you can see (Figure 10). However, the

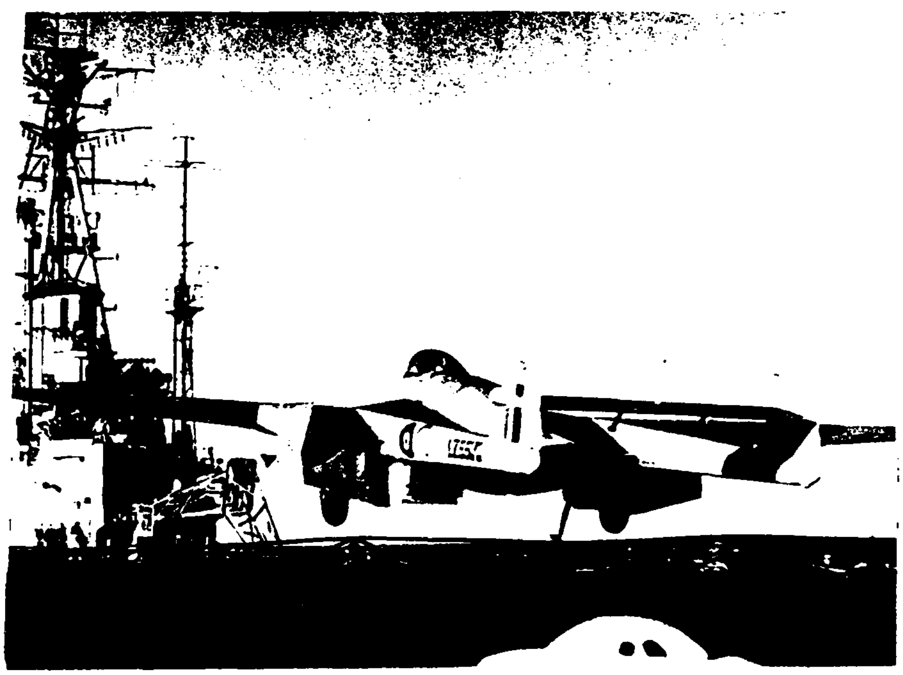


Figure 10

take-off performance left much to be desired because, of course, we had lost lift control which was provided by the propeller and the piston engine combination. Because of this, a very different type of approach had to be made, and the one I had devised at that time we called constant-attitude and constant-rate-of-descent. You wanted to have as few variables involved as possible because lift control was so poor. Now that system is still used today. There has been no change from that. I will show you the actual approach. Here is an approach being made in that constant-attitude and constant-rate-of-descent onto the deck. One thing, of course, the jet did solve was the asymmetric problem. In other words, if you had a twin jet, (This is not of course. This is a single engine jet and these are just double intakes.) but, if you had a jet engine you could bring it closer to the fuselage on either side and the loss of one power unit meant that you had very little offset asymmetric thrust and that problem was indeed very well solved.

Now at this time a rash of new ideas begin to come into our minds about the operation of jet aircraft and one of them, of course, was that the barrier had to be redesigned. The normal barrier, as you know, was a solid piece of cross-stranded wire and in the jet engine you have no piston engine and propeller situation ahead of you; you sit very close to the accident, so the idea was to have the stranded nylon cords shown here (Figure 11) and the nose just

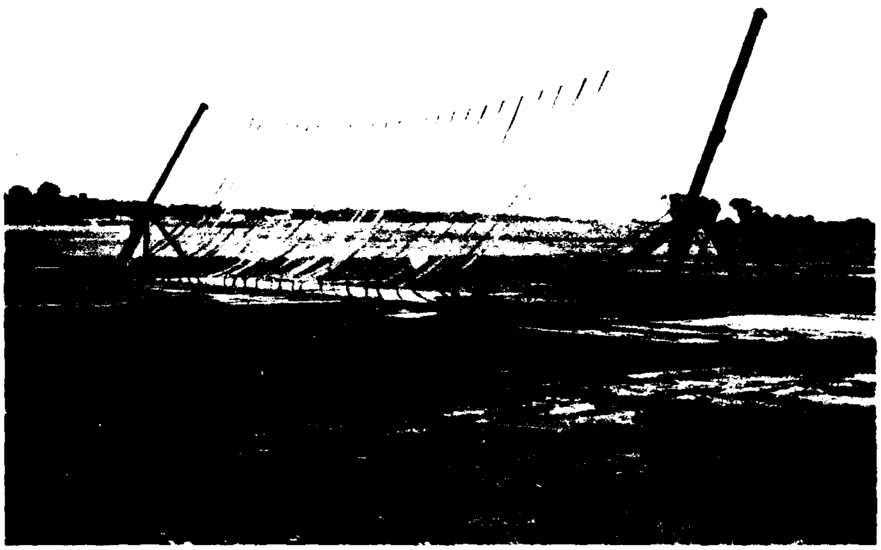


Figure 11

penetrated through them, and they wound themselves around the wing and brought the aircraft to a halt. A tedious operation, of course, was when you had mixed squadrons of jets and piston engines, because you had to have both types of barrier operating aboard. Therefore, one of our first thoughts was how do we get rid of this barrier situation. Here you have the normal carrier deck, you have the arresting wires, and normally as you know, we have two barriers to arrest anything, just in case one went through the first one. We also thought that perhaps we could have the aircraft approaching onto a single wire. We gave up the idea of the other two wires and we were going to have a single wire and a rubber deck, and remove the undercarriage from the aircraft because the undercarriage of the naval aircraft usually represents about seven percent of the all-up weight. So in one fell swoop we hoped to get rid of the problem of the barrier because we were not going to approach at a normal deck landing speed of about 1.1 to 1.15 times the stalling speed. The idea was to approach at 1.25 to 1.3 times the stalling speed and pick up the single wire and pitch on to the rubber deck. There was not going to be a barrier--that was also eliminated. This was the first idea and I'll show you the actual thing in action as it really came to be (Figure 12). Here you have the single wire; it was, of course, much higher than the normal wire which is approximately nine inches above the deck. In this case it

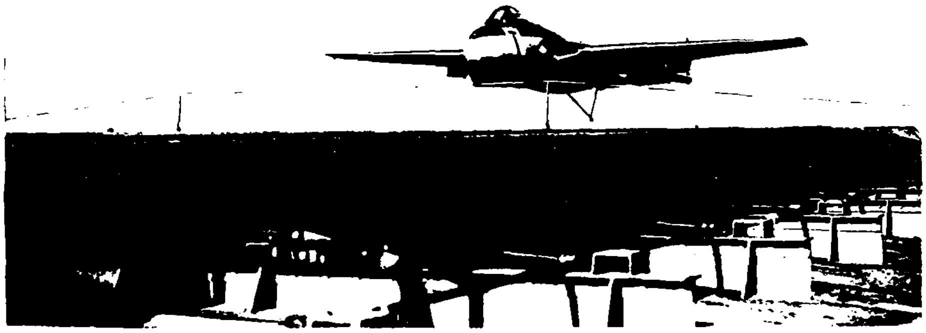
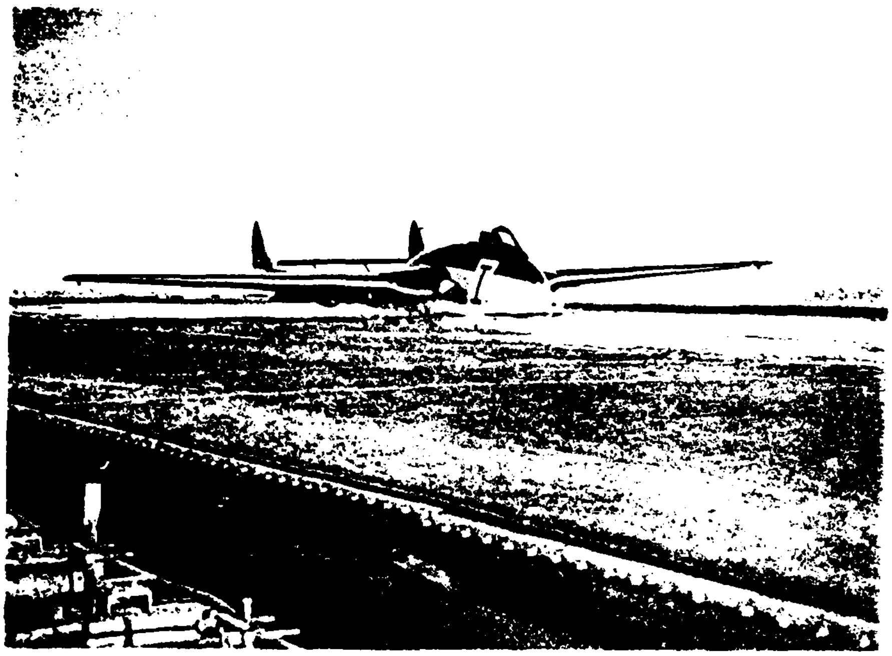


Figure 12

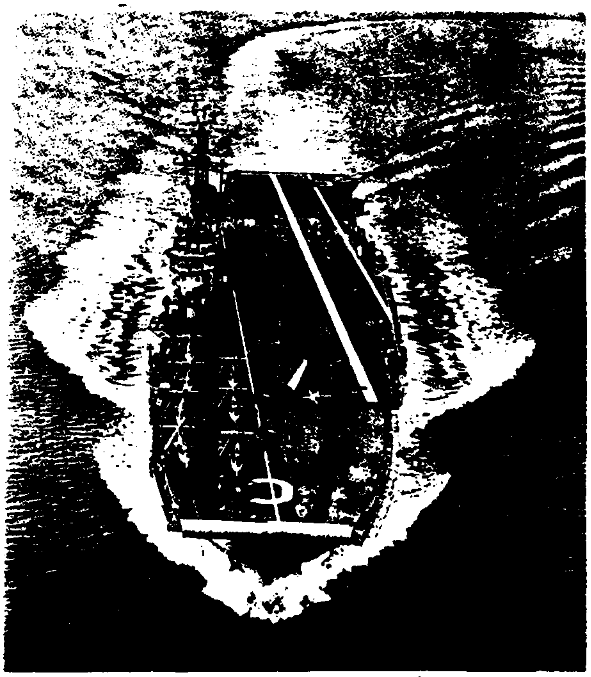
is about three feet above the deck. Coming in at about 1.25 times the stalling speed, there is the pick up and there is the landing. Flopping onto a rubber mat beneath which are five layers of firemen's hoses athwartships, at low pressure, pressures varying from six pounds per square inch to two and a half (Figure 13).



Success: Cmdr. Brown successfully demonstrating the flexible deck in a Vampire on H.M.S. *Warrior*

Figure 13

This rubber mat was the equivalent of the outer cover of a normal automobile tire. It was stretched under tension from both sides. Friction on the mat was very, very low, indeed: a very low co-efficient of friction. Now if you missed the wire, the idea was you had enough power on at 1.3 V_s to just carry on in a straight run, and have another go. The barrier we had was in fact an emergency barrier. If the time came you had so many goes you were running out of fuel, it had to be done, but in the normal operation, there was no intention of having a barrier associated with it at all. Now this idea of a flexible deck led us into another thought at this time. We thought this system is not really terribly practical because it's too radical in the sense that you would have to have ashore a lot of these rubber mat landing devices, so it was not too practical. However, we were intrigued by the fact we were not faced with barrier problems, because the barrier accidents in carrier aviation really are extremely high and extremely costly. So we were inevitably led into this thought: the angled deck. We thought the only problem with the flexible deck was you couldn't have a deck park ahead of it and we really wanted a deck park, so we thought well, why don't we just swing the landing area a bit and this is precisely what was done. We started off with five and one half degrees and when I brought the idea from Farnborough, where we had just dreamed it up, to Patuxent River in 1951, your people, with your usual phenomenal speed, latched onto it and you actually had one operating before we did. We had only painted one on one of our carriers, but we hadn't built the actual deck on. In fact there you see it just painted on a normal deck (Figure 14).

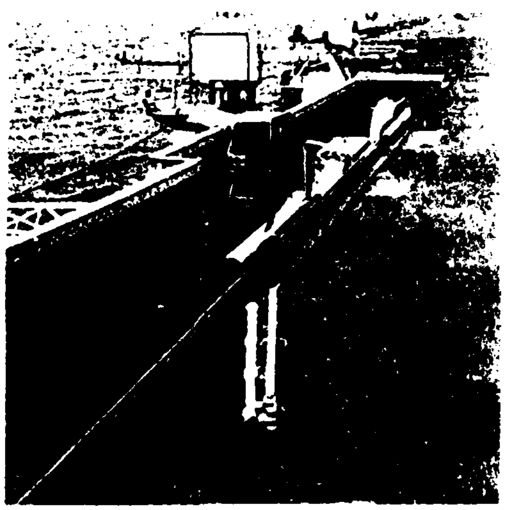


Sea Hawks on the first British angled deck aircraft carrier

Figure 14

This gave us the answer, of course, to getting rid of the barrier, and reducing the accident rate incredibly. But nothing is perfect, and there were two snags with it. One is this chunk of real estate on the front quarter doing nothing--wasted space. The other is there are certain problems lining up with the angle deck in bad weather. The first thing a pilot sees when he breaks into visibility range of a carrier in bad weather is the wake of the ship, and of course, the wake of a ship is dead astern and in this case you have to do a swift turn, if that is your guideline, to nine degrees in some cases, so that was not a perfect solution either. But nevertheless, it's one that stayed with us, and will remain with us, until something better is dreamt up. Now, at this particular time, we had, as I said, a rash of other ideas. One of them was a steam catapult. The steam catapult replaced the hydraulic catapult and it had this advantage. It was using a source of energy which was available and going to waste anyway: the ship's own steam. It also was much lighter than the hydraulic catapult and took up less space. It gave smoother acceleration but a higher g at the end of the run, and when we came over to demonstrate, again when I was at Patuxent, we sent the H.M.S. PERSEUS over here and I gave the first demonstration to your Navy in Philadelphia Navy Yard. We were tied up alongside, and the first launch I made in a F9-F3 was with an 8 knot tail wind and the end speed of the aircraft was 142 knots, so that shows you the performance of this catapult. It really was a quantum step forward.

The other idea that came about at this time of course, was what we called the deck mirror landing sight (Figure 15). I think you now call it a Fresnel lens, or something of



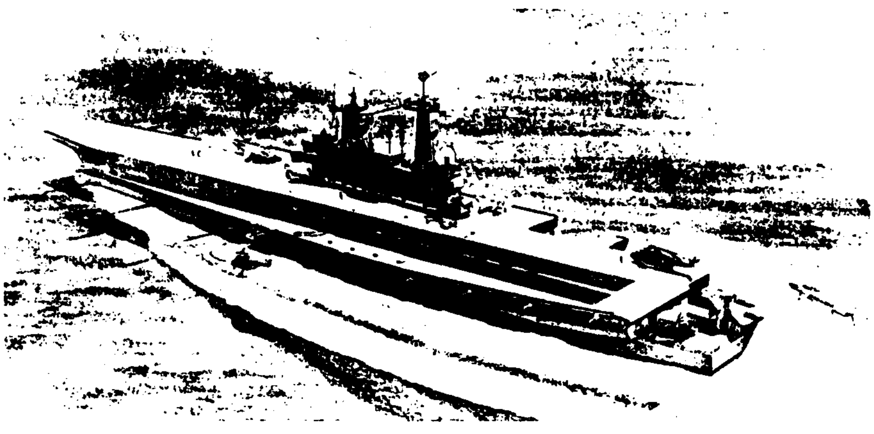
▲ *A view of the Mirror Landing Sight which superseded the use of the batsman in landing operations*

Figure 15

this order, but basically it is a light datum, with a meatball light source on the mirror, and the pilot, of course, if he's in the perfect angle at that constant-attitude, constant-rate-of-descent will have the meatball lined up with the datum line. If he gets low, this is shown by the position of the meatball which gives a mandatory signal. He must obey the signal therefore by bringing the meatball up by bringing his aircraft up; vice-versa if he's high it will show high and he must bring the meatball down by bringing his aircraft down. This system got rid of a very, very vulnerable human factor, the LSO or deck landing control officer. I say this with the hope that no ex-LSO or ex-DLC officers are here. They only compounded the problems of deck landing in my opinion, because it is a very, very difficult job to do. I'm not saying they didn't do a wonderful job, but it was far from a perfect job. You had a different system from us. Your LSO gave advisory signals where as ours gave mandatory signals. Both systems had equal drawbacks, so getting rid of the LSO I think was very useful. LSOs are still used of course as back-ups to this mirror system, so, provided they are well trained they can be an asset, but I really was referring to the war time situation when any pilot who was around and spare was just put on to be the LSO, and this is no way to run a railroad at all, and it certainly didn't pay off dividends during war time.

While we were looking for methods of shortening take-off, I began a series of trials at Farnborough and Sir Frank Whittle will remember these very well. First trials we were doing were on reheat on the jet engine--fairly basic at that time, just injecting fuel into the jet pipe and letting it catch a light there. It was done in a twin-engine jet aircraft which was a single-seat aircraft, but we built a cockpit behind my cockpit where we had a scientist who controlled the experiment, and when he recognized we were cooking too much he cut the fuel supply off--not to the main engine, but just to the reheat system. Pretty crude, but it was the first step towards full reheat and of course, as you're well aware, reheat is now one of the best methods of reducing take-off distance.

Now, we've been through the normal standard deck, we've been through the flexible deck, we've been through the angle deck, was there anything left? Well, here we had an idea that was revolutionary in design. This is CVA01 (Figure 16) which was never built, but I had charge of the think tank that devised this carrier layout and, in fact, the keel was laid and it was going to be built, when a change of government from conservative to labor killed it stone dead because they had decided that Britain was no longer going to get involved in fixed wing carrier aviation. But the idea was fundamentally a parallel deck system. In other words, you had a landing lane, and a take-off lane and they were quite separate and parallel. They weren't strictly parallel purely because of the physical limitations of the width of



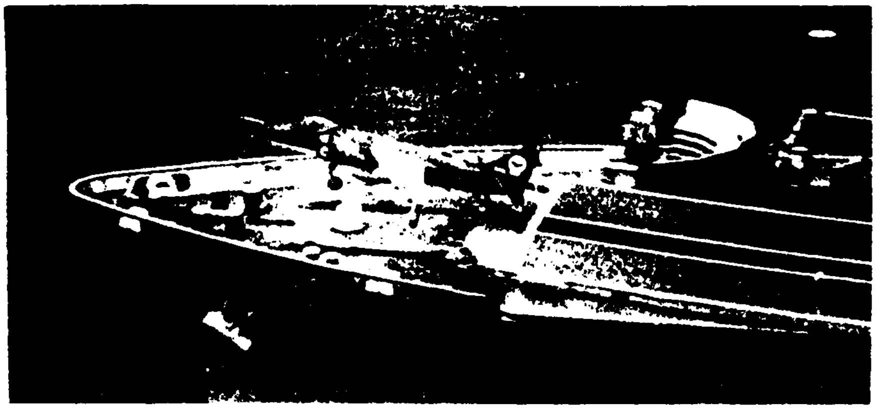
An artist's conception of the proposed British carrier CVA.01.

Figure 16

the carrier, which was 184 feet, and within that we, in fact, had to angle the landing lane 2 and 3/4 degrees. But the idea was that you landed on down this deck, unhooked, taxied out and taxied up along the outboard side of the island. This was a big island (I'll describe it in a minute) up to a point aft of the structure where you were re-armed and refueled, folded your wings, and taxied back down the inboard side of the island onto the 250 foot steam catapult. There was also a third 250 foot steam catapult here. The island was 200 feet long, and was set back 420 feet from the bow of the ship. This distance and size was determined after extensive wind tunnel tests. All the vehicles which were normally cluttering the flight deck were kept inside an arch on the island which housed these vehicles without any trouble at all. There were two lifts, one in the centre deck for'ard and a deck-edge lift aft. The circulatory flow system meant really that the deck should always be uncluttered and the advantage of course was that we got rid of the worst of the sterile area on the front quarter, which was kept specifically for the rescue helicopter. The other problem of the lining up was reduced of course considerably when you only have an angle of 2 and 3/4 degrees involved. We only had 4 arrest wires, and they were set much farther up the deck than normal for the constant-rate-of-descent type approach. The ship had a top speed of 28 knots, it was 53,000 tons and at that time, in 1960, would have cost 53 million pounds, a thousand pounds sterling per ton and it is a great shame it never went anywhere. We gave the idea over to your people, and whether you ever will do anything with it I don't know, because it's quite a revolutionary change, of course, to build a whole new concept of operating. It was also fitted with a very interesting type of arrester gear. This was a water spray arrester gear. Along the ship's side, under the deck, are very long tubes filled with water, and a piston in each tube connected to an arrester wire. When the arrester wire is caught the piston is pulled along the length of the tube. Since there are hundreds of little perforated holes in the tube, the water is ejected through these holes over the side of the ship, and that is how the energy is dissipated to reduce the landing speed and the pull-out of the aircraft.

The pull-out of this gear was constant for any landing speed or any landing weight within the performance envelope of the gear, so it was a very, very useful gear. It was installed eventually on H.M.S. ARK ROYAL and used there; so there are records of its usage.

Well, this type of ship would have been the last fixed-wing carrier we built, because as you know the helicopter was beginning to come very much into its own in naval aviation, and vertical take-off and landing was taking up everyone's attention. At the same time vertical take-off and landing was made possible on the fixed wing aspect by virtue of vectored thrust and we had the Harrier come into being. So we had a new type of carrier, which was built shortly after CVA01 was canceled. And in order to bamboozle the politicians, we called it a through deck cruiser. That is in fact its official title. But of course it's obviously a small aircraft carrier. Here (Figure 17) you have the Harrier lined up for vertical take-off and landing type of operation. That was also simplified with a very, very simple device called the ski jump, which you see here is a ramp going up to a maximum of about 8 degrees



With the benefit of the ski-jump, the RN can launch Sea Harriers for longer sorties

Figure 17

angle. Provided you have a short take-off run, you can increase the load enormously in a V/STOL aircraft. You can increase it even further if you can produce the energy here to throw it off the end into the air at an angle of attack which otherwise would have to have been achieved by rotation by the pilot. So this is the stage where we are today. Vertical take-off and helicopters operating from British carriers.

Now you, with your nuclear carriers, of course, still have magnificent fixed wing aircraft aboard, also mixed up with a content of helicopters inevitably. I hope that these will go on for a very long time, because whatever one says, there is no substitute for the high performance fixed wing airplane. We learned this in the Falklands where we had the Harrier, which did a very good job but because of short range it had to wait until the enemy got to it before we could nail him. If we had had Phantoms, F4's as we had in the ARK ROYAL, we could have gone out and nailed them half way between the Argentine and the Falklands so there are very big differences made there. Also, the absence of a fixed wing carrier meant that we had no airborne early warning. That was our biggest deficiency. It was something that, in fact, was a critical factor in the Falklands campaign. I have spoken at some length on the subject with the commander of the Falklands taskforce, and in his opinion, if we'd had a fixed wing carrier such as the ARK ROYAL, the whole operation could have been finished in ten days to 2 weeks, instead of the lengthy time it took. So, you are fortunate in having those and I sincerely hope, if we ever get into any operational situations again, we will be working side by side so that we can complement each other in these vital areas.

Committee on the Education and

Utilization of the Engineer (CEUE)

SUMMARY PRESENTATION OF THE CEUE REPORT

by

Jerrier A. Haddad*

*Jerrier Haddad earned a Bachelor's Degree in Electrical Engineering from Cornell University where he also served as a teaching assistant and later as chairman of its Engineering College Advisory Board Council. He later joined IBM Corporation and served in various technical capacities leading to his election as Vice President, Engineering, Programming and Technology in 1967. In 1981 he retired from IBM as Vice President, Technical Personnel Development. He is holder of 18 patents for inventions in the computer and electronic fields. In addition, he is a member of the National Academy of Engineering where he is chairman of the Committee on the Education and Utilization of the Engineer. He serves as a consultant to the National Science Foundation and has served on the NSF Advisory Council.

SUMMARY PRESENTATION OF THE CEUE REPORT

(FIGURE #1)

Engineering has played an indispensable role in establishing the position of the United States in the world. Our preeminence, while challenged before, is being sorely tested now. At times like these, we must focus on the role of engineering in maintaining United States power and influence by helping to ensure:

-a sufficient capability for national defense,
-a thriving domestic economy, and
-our international industrial competitiveness.

At the same time, engineering must maintain and improve the quality of life in the country. Lastly, engineering must continue to earn and maintain the public trust.

(FIGURE #2)

These tasks make up a considerable challenge, and in

CHALLENGES TO ENGINEERING

- Maintain National Defense Capability
- Maintain a Thriving Domestic Economy
- Maintain U.S. International Industrial Competitiveness
- Maintain/Improve the Quality of Life
- Maintain the Public Trust in Engineers and Technology

Figure 1

ISSUES NEEDING ATTENTION

- The Continuing Faculty Shortage
- The Need for More U.S.-Resident Graduate Students
- The Need to Restructure the Engineering Curriculum
- Support for Predominantly Undergraduate Schools
- Support for Continuing Education
- Encouragement of Women and Minorities to Participate in Engineering
- The Lack of Data Describing the Engineering Community
- Maintenance of Public Trust of Engineers and Engineering

Figure 2

order for the engineering profession to succeed at them, a number of actions need to be taken as regards:

- -The Continuing Faculty Shortage
- -The Need for More Graduate Students--Especially Those Who Are U.S. Residents
- -The Need to Restructure the Curriculum
- -Support for Predominantly Undergraduate Schools
- -Support for Continuing Education
- -Encouragement of Women and Minorities to Participate in Engineering
- -Lack of Data Describing the Engineering Community
- -Maintenance of Public Trust of Engineers and Engineering

THE FACULTY SHORTAGE

(FIGURE #3)

First and foremost, we must alleviate the present ills of engineering education in order to ensure quality education for the coming generations of student engineers. There are a number of problems; but perhaps the most

DIMENSIONS OF THE FACULTY SHORTAGE

FROM 1975 TO 1981:

Undergraduate Enrollment Increased by 65%

The Number of Faculty Grew By Only 10%

A 1983 SURVEY OF ENGINEERING DEANS SHOWED:

1,567 *Budgeted Positions* Unfilled (8.5% of total)

TO RESTORE THE 1975-76 STUDENT/FACULTY RATIO (ABOUT 17.5 TO 1)

Would Require Some 6,700 Additional Faculty

OTHER CONSIDERATIONS

Need to Replace Retiring Faculty

Career in Industry Is Generally More Attractive

Figure 3

serious and persistent one is the faculty shortage. Faculty careers these days are just not attracting the outstanding engineering graduates in sufficient numbers. Rather, careers in industry and government are much more attractive from the standpoints of compensation, availability of state-of-the-art capital equipment, and aggressive R&D programs.

(FIGURE #4)

Faculty salaries, starting as well as mid-career, must be improved. The committee recognizes the complexity of accomplishing this. University administrations and state legislatures must be convinced, as the committee was, that the present situation cannot continue without seriously compromising the quality of engineering education. At present, we are operating on the momentum of the past and not, as many believe operating at a new high of academic efficiency.

Better research and instructional equipment must be made available in more adequate space. The committee

OVERCOMING THE FACULTY SHORTAGE

- Improve Faculty Salaries
- Provide More Up-to-date Research/Teaching Equipment and More Space
- More Substantial Faculty-Development Programs Must Be Put In Place
- Reduce Student/Faculty Ratios By Various Means

Figure 4

recommends that a program of federal government and industry matching grants address this problem. Faculty development programs must be put in place that go beyond the traditional sabbatical every seven years.

Student/faculty ratios must be reduced. Greater use must be made of non-tenure-track faculty without necessarily requiring the PhD. The source of this faculty can be early retirees from industry, government, and the military. Until graduate students are more readily available, undergraduate students can be used to help with the workload associated with underclass students. Educational technologies such as the computer and satellite transmission also have a large untapped potential.

NEED FOR MORE U.S.-RESIDENT GRADUATE STUDENTS

(FIGURE #5)

If engineering academic careers are made attractive, then we will still need to make graduate study more attractive compared to beginning an industry career with a

MEETING THE NEED FOR MORE GRADUATE STUDENTS

- Making An Academic Career More Attractive Is Not Enough
- Graduate Study Itself Needs To Be Made More Attractive

> The Committee recommends that "doctoral fellowships should carry stipends equal to at least half the starting salary of a new B.S. graduate."

- It Would Be Beneficial If More <u>U.S. Residents</u> Pursued the PhD

Figure 5

BS degree. Graduate study is the feeder for academic careers as well as research careers in government and industry. Certainly there will be an increase in the number of graduate students when academic careers become more attractive. However, graduate students studying for the PhD face four to six years of severe financial austerity, compared to what they would be enjoying in industry. This in itself is a big disincentive. Therefore, the committee has recommended that stipends for engineering doctoral study be no less than half the industrial starting salary for a BS.

Up until now, the serious lack of U.S. residents in graduate schools has been offset by the presence of large numbers of foreigners on educational visas. Should this source of graduate students dry up to any significant degree, in addition to a faculty shortage we will be faced with a shortage of teaching assistants and research assistants. Clearly, we need to attract more domestic students to the PhD programs and to faculty positions after that.

It is well to note that there does not seem to be any shortage of PhD graduates as far as industry is concerned. Salary comparisons bear out that impression. The starting and cumulative subsequent salaries of PhDs in industry, while higher each year than those of the BS or MS, do not catch up with the cumulative BS salary for about twenty years. Any shortage perceived by industry would cause a bidding up that would make the PhD much more financially attractive.

RESTRUCTURING THE CURRICULUM

(FIGURE #6)

Since the end of World War II, we have restructured the engineering curriculum to include significantly more science, mathematics, and general education. This has been done not only at the expense of courses in shop practice and design, but also at the expense of technical courses that are marginally outside the engineering specialty. Additionally, there have arisen pressures to

RESTRUCTURING THE CURRICULUM

The Present Situation

Since World War II, the engineering curriculum has contained:

- more specialization
- more science and mathematics
- more analysis and theory
- more general education

and

- less emphasis on design
- less hands-on shop practice
- fewer technical courses outside the specialty

Figure 6

include other types of study which I will describe. Each of these thrusts is unimpeachable in its own rights. However, no more courses can be accommodated in a four-year curriculum without causing the root curriculum to suffer. The question is: How can we ensure that engineering education contains the best possible balance among these different elements.

These additions that are urged fall into four general categories:

(FIGURE #7)

1) More liberal arts, humanities, and social sciences.

The U.S. economy increasingly is global in character. Even if a company is only interested in domestic business, it must compete with imports. Engineers must be aware of cultural difference in order to design products and services that will find a broad market. The day is past when an American product will find a ready market abroad without the designer being acutely aware of the preferences and foibles of the foreign customer.

RESTRUCTURING THE CURRICULUM

New Thrust #1: More Liberal Arts, Humanities, and Social Sciences

IMPARTS:

- Greater awareness of cultural diversity
- More well-rounded professionalism
- Better facility for communication (both oral and written)

Figure 7

Non-technical studies are becoming a requirement for the well rounded engineer who hopes to be something more than a high-level technician.

It is also a fact that many engineers perceive that they are not accorded the degree of respect shown to other professionals. While this is a highly individual thing, it is also fair to acknowledge that engineering is the only profession that does not require a general education prior to a professional-school education. That a college-level liberal arts education makes for a better-rounded individual capable of leading a fuller life is almost a truism.

Lastly, industrial employers have been complaining that engineering graduates are sadly lacking in the ability to communicate well either orally or in writing. The ability to be persuasive is an absolute essential for success regardless of profession. The engineer's ability to communicate convincingly and fluently with other engineers, with superiors, with subordinates, with customers, with the general public -- to say nothing of governmental officials, domestic and foreign -- is as essential as the ability to perform elegant design. A good command of the language is just as necessary as first year calculus.

(FIGURE #8)

2) More technical breadth.

Because the four-year curriculum has dropped technical courses that are marginally related to the particular specialty being studied, we are creating mechanical engineers who can't talk to civil engineers; etc. Also, due to the rapid development of technology, we now have more engineering specialties than ever. A few decades ago, there were the five basic engineering disciplines of civil, mechanical, electrical, chemical, and mining. Today, we have better than thirty technical professional societies, and many of these have sub-disciplines of their own.

Technical progress has caused the creation of whole new industries, and the demise of others. The result has

RESTRUCTURING THE CURRICULUM

New Thrust #2: More Technical Breadth

- New Technologies Create New Industries and New Engineering Specialties
- There Are Now More Than 30 Recognized Engineering Disciplines
- Today's Specialized Education Prevents Cross-communication and Cross-fertilization
- Engineers Should Be Able To Make the Transition Into Adjacent Fields

The curriculum should provide more breadth across the disciplines and within each discipline. In-depth specialization should be postponed to the graduate level.

Figure 8

been to create new engineering specialties and to kill others. There is little question that this will continue and cause many engineers to shift disciplines or specialties in the course of their careers.

Thus, an engineering education must have as a prime goal giving the student enough of a technical academic base so that that person is capable of self-education and continuing education over the course of a forty-year career. Engineers of the future must have the ability to "slide" into an adjacent discipline should the need develop. Also, it will help the competitiveness of American industry if engineers on interdisciplinary projects have some basic knowledge of each other's fields. We must re-insert the technical generality into the curriculum and even seek to increase it. If this means less specialization in the undergraduate experience, then so be it. The committee recommended that deep specialization be postponed to graduate work.

(FIGURE #9)

3) More depth in more disciplines.

The converse of the previous point also holds true, even though it is clearly in direct conflict with it. Because there are now so many engineering specialties, and because technology has made--and is continuing to make --remarkable progress, it has become necessary for schools to offer more specialties and to go into greater depth in each one in order to produce engineers who are reasonably proficient in their fields. Industrial employers who are large and wealthy don't mind the task of further educating a new employee. Smaller employers who can't afford this complain that engineering graduates are not really useful for the first six months to a year. It is a significant expense to them to provide the needed on-the-job training.

These small to medium-sized companies ask that the graduate have some knowledge that is industry-specific in addition to the basic engineering science and mathematics. They are concerned about the risk of giving an expensive apprenticeship only to have the employee leave just as he

RESTRUCTURING THE CURRICULUM

New Thrust #3: More Depth in More Disciplines

- Technological Advances Demand Greater Specialization of Graduates and the Curriculum
- Industry-Specific Knowledge Is Also Expected
- Company-Provided Training Is Not Always the Answer

Figure 9

or she is becoming useful. As costs become a bigger factor, they tend to turn away from recruiting directly from college and to start hiring only experienced engineers.

(FIGURE #10)

4) Another complaint that both graduates and employers have is the low level of "business" knowledge that is contained in the standard four-year curriculum.

Although it may sound like a push for MBA education, this really is not so. What is lacking is rudimentary training in basic business practices that any engineer must know in order to do a good engineering job. Such things as cost estimating, simple accounting, depreciation pratices, career management, patent practices, international currency considerations, etc., should be capable of being injected into the curriculum without requiring a separate course for each topic.

Another area that could use some elaboration is how a typical company is structured and how the various

RESTRUCTURING THE CURRICULUM

New Thrust #4: Business Practices

- Basic Business Practices (Not MBA-style Education)
- Needed Educational Elements:
  - cost estimating
  - simple accounting
  - depreciation practices
  - patent practices
  - corporate organization
  - career planning and management

Figure 10

engineering jobs relate to each other and to the non-engineering jobs and functions. A new engineering graduate without industrial experience should not simply take pot luck in accepting a job offer. He or she should have some idea as to the various opportunities for engineers, so that some enlightened career planning can take place.

(FIGURE #11)

The committee was unable to reach consensus on any single best way to handle the engineering curriculum restructuring. However, there was agreement on several points that are quite important. They are as follows:

-The four-year program as now constituted satisfies industry's requirement for entry-level engineering jobs in many, if not most, instances. Even if a change were desired, there is no mechanism for imposing a new entry level standard (for instance, an MS).

-In order to accommodate the greatest amount of both broad technical and non-technical education in the undergraduate programs, the committee recommends that deep specialization be postponed to the graduate programs.

POINTS OF CONSENSUS

- The Current 4-Year Curriculum Generally Satisfies Industry's Requirements for Entry-Level Positions
- The Diversity in the U.S. Engineering Educational System Is One of Its Great Strengths
- Engineering Educational Programs Must Be Able to Challenge the Top Students Now Enrolling
- Deep Specialization Should Be Postponed to Graduate Study
- Career Flexibility Is Essential for Engineers; Technical Breadth Must Be a Top Priority in Education

Figure 11

-Any change in the undergraduate curriculum should keep breadth of technical education as a top priority. The need for engineers to be capable of re-educating themselves over the course of a forty-year career should be a major forming influence on the undergraduate curriculum.

(FIGURE #12)

-Almost as important is the requirement for addressing the humanities, social sciences, and liberal arts. Communication skills -- both written and oral -- are a high priority. In the context of an increasingly global economy, sensitivity to cultural and regional differences will be an important quality for the engineer to acquire. Engineers will also need to appreciate the financial, political, and security forces at play internationally.

-The computer has become pervasive in modern engineering practice both as a tool for performing the engineering job itself, and for carrying out other necessary activities such as record keeping, communications, and reporting. Since engineering itself has changed so fundamentally due to the computer, it follows that engineering education must accommodate that change. Computer techniques must become second nature to the graduating engineer, and, thus need to be woven into the subject matter of all studies. Access to computer resources has become a prime necessity for a good engineering education.

-The effect of high performance, low cost, small physical size semiconductor electronic circuits on each of the engineering disciplines has been profound. Instrumentation has changed. Tradeoffs in cost, function, and reliability among various engineering techniques that have stood for years, are now different. In short, the textbooks need to be

POINTS OF CONSENSUS

- The Humanities, Social Sciences, and Liberal Arts Provide Many Necessary Perspectives for the Engineer
- Hands-On Familiarity With Computers Is Essential
- Textbooks in All Disciplines Should Be Rewritten to Reflect Advances in Computer Technology and Their Implications
- Work-Study or Cooperative Education Provides a Valuable Form of "Internship" Experience
- A Range of Challenging Programs Should Be Offered

Figure 12

rewritten for all the engineering disciplines. The curriculum that does not take this into account is hopelessly outdated.

-Although committee members expressed dissatisfaction with some aspects of cooperative education, there was clear support for acquiring some sort of industrial experience during the undergraduate years. The committee felt that interning in one form or another not only provides some financial relief, but also introduces a motivational component to the undergraduate experience. The interning experience also enriches and focuses the classroom experience. It gives the student a chance to observe the practice of engineering, an aspect that has been given less emphasis in contemporary engineering curricula.

-One point was not brought out in the report, although several members of the committee would agree with it. That is, as engineering increasingly attracts the top students in the entering college cohort, engineering schools need to develop programs that will challenge the best of these. Today, the best challenge to the outstanding student is the PhD program. However, if the student is not interested in this duration or extent of technical specialization, then equally challenging but different programs should be developed.

While the committee agreed on these points, there was no consensus on how to incorporate new educational elements into the curriculum, or, indeed, on the degree to which they were necessary. Clearly, the implication was that taken together they would require more than the nominal four years to accommodate. But it was felt that industrial employers would not give greater compensation for a longer program. Thus, any institutions moving in this direction would probably fail to attract students in competition with those schools that chose to stay with the four-year programs. We failed to solve this vexing problem. Our hope is that, having illuminated it, more thinking on the part of the engineering community as a whole will result in a creative solution.

THE SUPPORT FOR PREDOMINANTLY UNDERGRADUATE SCHOOLS

(FIGURE #13)

Since World War II, federal government support has tended to create a set of about fifty research institutions in science and engineering. These institutions focus heavily on graduate studies. They attract world class faculties due to their superior, sophisticated laboratories and the top graduate students seeking to learn in that environment. They are a valuable

SUPPORTING PREDOMINANTLY UNDER-GRADUATE SCHOOLS

– THE "SECOND TIER" –

- A Relatively Small Group of Well-Funded Research Institutions Focus on Graduate Study
- More Than 200 Predominantly Undergraduate Schools Supply Half the Nation's B.S. Engineering Graduates
- These Latter Schools Lack:
  - World-class faculty
  - Advanced laboratory facilities and equipment
  - Extensive computer resources
  - Extensive technical and research libraries
- The Schools of the "Second Tier" Must Be Better Supported

Figure 13

asset to the nation in terms of the research results and in terms of the PhD scholars they create. Also very important is the fact that they produce about half of the undergraduate degrees in the country.

However, there are more than two hundred other accredited engineering schools that have opted to remain predominantly undergraduate. They also are of great value to the nation. In addition to supplying the country with half of its BS engineering graduates, they also supply a goodly fraction of the PhD candidates for the research institutions. These mainly undergraduate schools operate under severe disadvantage due to their inability to attract world class faculty and the lack of supporting structure that goes with the big research grants. Such things as cutting-edge laboratory equipment, machine shops, big computers, and extensive library holdings are lacking and thereby decrease the quality of instruction available for both graduate and undergraduate students.

Creative ideas for supporting these undergraduate schools are being considered. Clearly, we cannot make them all into research schools, nor do we want to. However, relief can be given in a number of ways that will lead to less workload for the faculty, better faculty development programs, access to state-of-the-art equipment for faculty and students, student exposure to the world's leading researchers at the other schools, etc. The National Science Foundation has become acutely aware of the situation and is dedicated to addressing this problem. Industry and state government also need to support these schools in order to maximize the country's stock of well educated engineers.

THE SUPPORT OF CONTINUING EDUCATION

(FIGURE #14)

After the academic years and during an engineer's career of up to forty years, further education is obtained by a generally haphazard process of on-the-job learning, company training programs, seminars, conferences, and professional reading. It is estimated that only about 5% of this continuing education consists of formal classes or training programs. However, there is growing emphasis on

DRIVERS FOR CONTINUING EDUCATION OF ENGINEERS

- New Technologies and New Industries Change the Nature of Engineering Work
- Engineering Is Becoming More Interdisciplinary
- The Computer Is Bringing Rapid and Enormous Change
- International Competition Requires Better Performance

Adaptability Will Be An Essential Characteristic of the Engineer

Figure 14

continuing education on the part of both engineers and higher management. The rapidity of technical change in every field of engineering, the increasingly interdisciplinary nature of engineering work, and the widespread effects of the computer and cheap integrated circuits are the principal technical reasons for the increased emphasis on continuing education. Another contributing reason is increased world competition requiring greater engineering performance.

None of these reasons will disappear or diminish in the future. Our national goals require a strong engineering work force, so that continuing education will continue to play a vital role. If they have access to continuing education, engineers can be effective over a longer time, thus expanding the work force and increasing its capability. Employers play an extremely important role as regards continuing education. Management support, "moral" as well as financial, can determine the extent to which engineers will invest their precious personal effort and time in continuing education. The availabliity of tuition refund may not encourage many to participate but the lack of tuition refund will certainly discourage those who might otherwise participate.

It has been estimated that in 1983, 30 billion dollars was spent by industry on all training and education. Likewise, government spent an estimated 10 billion dollars. While only a fraction of this amount was spent on engineering continuing education, it shows the tremendous value being put on more effectiveness and less obsolescence.

Not only academe, but industrial and government employers, technical societies, and private vendors are responding to the engineers' need for continuing education. The greatest demand is for highly targeted short courses that focus on new and emerging technologies and engineering practices.

ENCOURAGEMENT OF WOMEN AND MINORITIES

(FIGURE #15)

Women and minorities continue to be underrepresented

ENCOURAGING WOMEN TO PARTICIPATE IN ENGINEERING

- Women Comprise 5.8% of the Engineering Work Force
- About 15% of Undergraduate Engineering Students, and 17% of First-Year Students, Are Women
- These Percentages Are Markedly Lower Than in Other Science and Technology Fields

Figure 15

in engineering. The first part of this conclusion is based on the committee's finding that the percentage of women is markedly lower in engineering than in other science and technical fields. While some 20% of chemists and 29% of computer specialists are women, for example, only 5.8% of engineers are women. Yet the percentage of women in engineering practice more than tripled between 1979 and 1983; and the percentage of women in engineering freshman classes nationwide is about 17%. Thus, while things are improving, they are not yet improving well enough on a comparative basis. Also, the data indicated a leveling off of women entrants to engineer school in the most recent years.

On the positive side, we had no reports that women were receiving undue resistance in hiring or on-the-job discrimination in industry. The scarcity of women in middle and upper-level management was felt to be more of a pipeline phenomenon. The increased numbers in engineering schools have not yet had a chance to build to a large number in the field, especially in management.

We did not collect data on women in engineering academe in an organized manner. Anecdotal evidence would seem to indicate that tenure is not granted to women faculty members in the same proportion as men. Also, there is a perception that there is discrimination against women in assignment of teaching responsibilities and in the selection of research teams. Such perceptions, whether justified or not, discourage women from choosing graduate study and tenure track careers. The committee recommended that college administrators make candid assessments of the negative aspects of life for women on their campus and, if they exist, take firm steps to correct them.

(FIGURE #16)

With the exception of Asians, the situation as regards minorities seems quite discouraging. While significant progress has been made in terms of percentage participation, the forward progress has slowed, and the total numbers are not very high. In the case of Asians, the representation is 3.9% in engineering school, while

ENCOURAGING MINORITIES TO PARTICIPATE IN ENGINEERING

- Minorities Overall Constitute About 5% of the Engineering Work Force
- Asians Comprise 2.8% of the Engineering Work Force and 3.9% of the Undergraduate Population
- Blacks Comprise 1.4% of the Engineering Work Force and 4.4% of the Undergraduate Population
- Hispanics Comprise About 0.3% of the Engineering Work Force

Figure 16

they make up only 1% of the general population. Asians also are 4.6% at the master's level and 4.3% in doctoral programs.

With regard to blacks, the situation is that, although they make up 12% of the general population, they are only 4.4% of the engineering students and only 1.4% of the engineering workforce. There is much speculation concerning the reasons for this. One factor is the relative lack of secondary school quality in preparing inner-city and rural blacks for entry to engineering studies. Another is the lack of role models in academe and industry that the young black can relate to. Still another is the fact that engineering cannot be practiced in a way that directly serves the black community, as can law or medicine or accounting or primary and secondary education. Lastly, as in the case of women, the pipeline has been in operation for such a short time that the effect of larger overall numbers has not yet had a chance to become significant. Whatever the reasons, the committee felt that efforts to change the situation for the better should continue and increase. The nation is not reaping the benefit of talent that these minorities represent, to say nothing of the social injustice that the present situation represents.

The presence of Native Americans and Hispanics in the profession and in engineering schools has also remained low in comparison to their numbers in the overall population, perhaps for much the same reasons. The social inequity and loss is no less greater.

THE LACK OF DATA DESCRIBING THE ENGINEERING COMMUNITY

The committee's study was a serious attempt to characterize and structure the entire engineering community. A clear understanding of the profession is necessary as a basis for national policymaking, for fiscal and economic planning, and, in general, for gaining a better understanding of how the technology development process works.

(FIGURE #17)

Thus, we formed a panel (Panel on Infrastructure

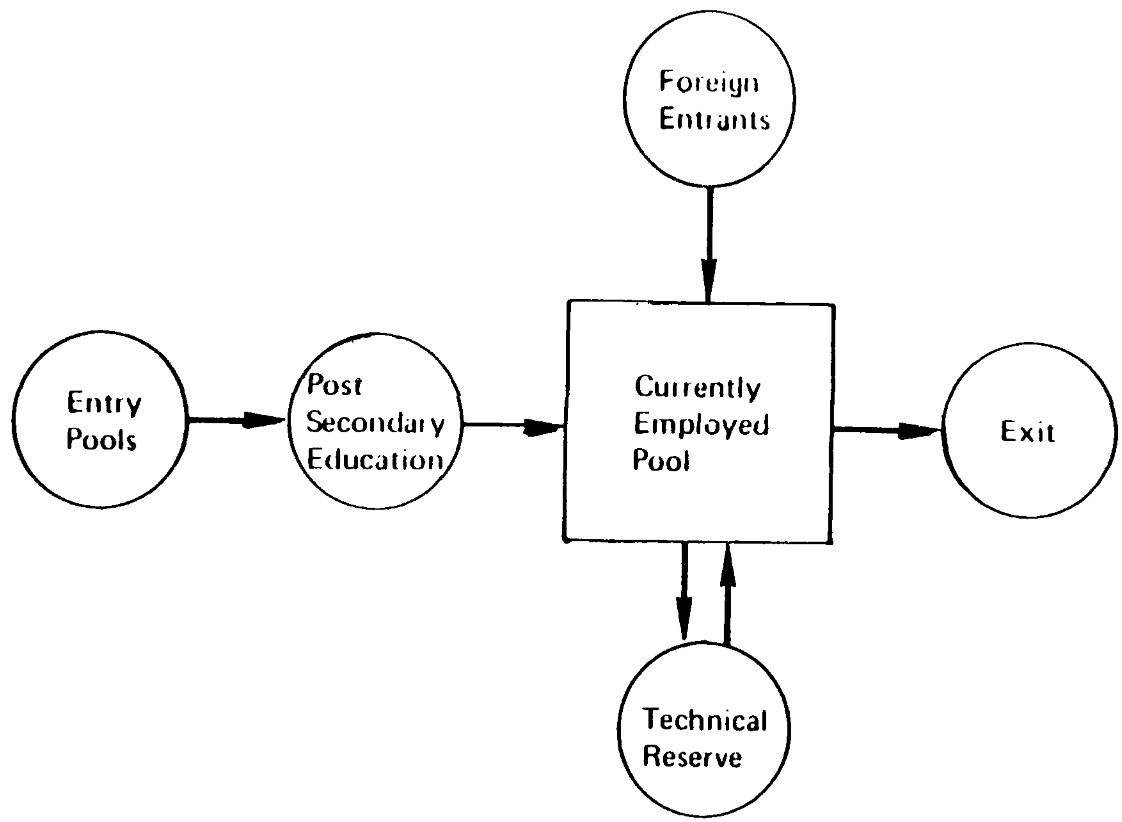


Figure 17. Dynamics of the Engineering System

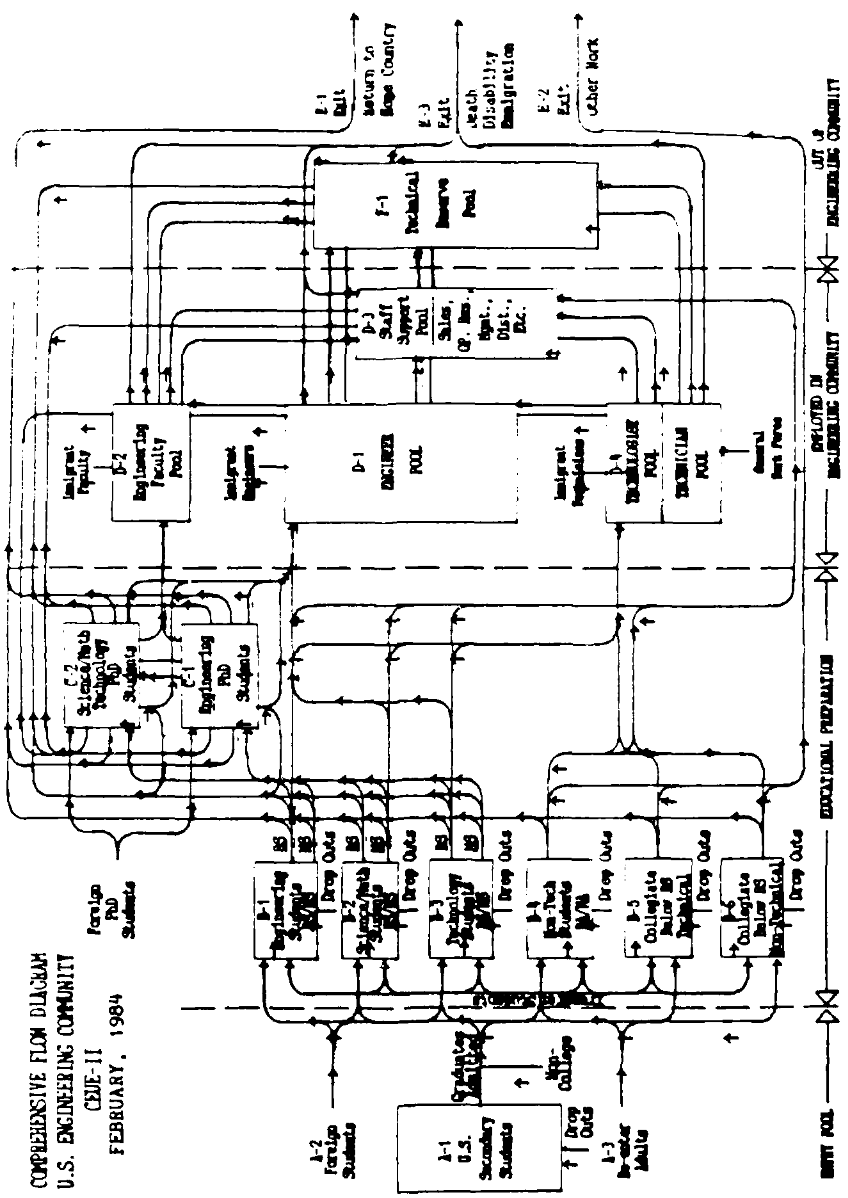
Diagramming and Modeling) to determine the components of the engineering system and how they operate and interrelate. Further, the panel was asked to develop a set of flow diagrams that would provide, at varying levels of detail, a representational basis for understanding and quantifying the dynamics of the engineering system. They

(FIGURE #18)

did this, and we believe that the results represent a major contribution toward achieving these goals.

(FIGURE #19)

After developing the flow diagrams, the panel next attempted to fill the diagrams with data for different years. In the process, it found that the existing data bases relating to engineering manpower, although numerous and extensive, are inadequate for the purpose. In all, fourteen significant data bases were used to obtain data and estimates on the education and employment of groups making up the engineering community. These data bases had



COMPREHENSIVE FLOW DIAGRAM
U.S. ENGINEERING COMMUNITY
CEUE-II
FEBRUARY, 1984
A-2 Foreign Students
A-1 U.S. Secondary Students
A-3 Re-enter Adults
Drop Outs
Non-College
Foreign PhD Students
C-2 Science/Math Technology PhD Students
C-1 Engineering PhD Students
D-2 Engineering Faculty Pool
Immigrant Faculty
Immigrant Engineers
D-1 ENGINEER POOL
Immigrant Technologists
TECHNICIAN POOL
General Work Force
F-1 Technical Reserve Pool
E-1 Exit
Return to Home Country
E-3 Exit
Death Disability Emigration
E-2 Exit
Other Work
ENTRY POOL
EDUCATIONAL PREPARATION
EMPLOYED IN ENGINEERING COMMUNITY
OUT OF ENGINEERING COMMUNITY

Figure 18

DESCRIBING THE ENGINEERING COMMUNITY: PROBLEMS WITH THE DATA

Lack of Compatibility

Differences in:

- Definitions
- Focus
- Measurement Criteria
- Choice of Respondent
- Frequency of Updating

Figure 19

been compiled by a variety of national organizations and agencies concerned with technical personnel. While an enormous amount of information was available, a number of difficulties were encountered in using the existing data bases to derive numerical values for the flow diagrams.

Because they were derived for a multiplicity of purposes, there was a lack of compatibility among data bases. Lack of consistency in the definitions used by the various compilers was also a problem. Because of the differing needs of data base managers, there are differences in the focus of data bases (for example, how scientists and engineers are employed versus where they are employed). As a result, there are marked differences in measurement criteria from one data base to another. There are also differences in the choice of respondent (for example, individuals or households or establishments) and in the frequency of updating (varying from 1 month to 10 years). These differences result in significant discrepancies in personnel estimates.

(FIGURE #20)

From the standpoint of the flow diagrams, these data bases also had certain shortcomings. For example, overall, the data bases fail to provide data on non-degree engineers or associate-degree engineers and computer specialists. Coverage of gender, racial and ethnic background, citizenship, and income is uneven across the various data bases. There are only limited data on the flows of students between engineering and other courses of study or across various engineering disciplines. Additionally, the data bases often fail to distinguish between masters and doctoral students or to identify their disciplines. Data on the mobility of students between two- and four-year colleges are lacking. These shortcomings are at least partly a function of the prevailing narrow definition of the engineering community. While they could be compensated for to some extent, the net effect on the flow diagrams developed by the panel is that data elements tend to underestimate the size of the various constituencies that make up the engineering

DESCRIBING THE ENGINEERING COMMUNITY: PROBLEMS WITH THE DATA

Shortcomings:

- No Data on Non-degreed or Associate-degree Engineers or Computer Specialists
- Uneven Coverage of Demographic Factors
- Limited Data on Cross-disciplinary Movement By Students
- Poor Discrimination at the Graduate Levels
- No Data on Movement Between Two- and Four-Year Colleges

Figure 20

community.

(FIGURE #21)

The main data base sources were the Engineering Manpower Commission (EMC) and the Bureau of the Census - primary data collectors only - and the National Science Foundation, the National Research Council, the Bureau of Labor Statistics, and the National Center for Education Statistics - all interpreters as well as collectors of data.

The unavailability of comprehensive, compatible data bases is made more disturbing by the fact that important data are not being used. An example is the Higher Education General Information Survey data, which are collected and filed by each state but not subjected to subsequent analysis until copies of the raw handwritten data are received by the National Center for Educational Statistics. This puts a lag of months and years to their profitable use. These data could be put to more immediate use at minimal cost if they were digitized at the state

PRIMARY DATA SOURCES

- Engineering Manpower Commission (EMC) of the American Association of Engineering Societies
- Bureau of the Census
- National Science Foundation
- National Research Council
- Bureau of Labor Statistics
- National Center for Education Statistics

Figure 21

level (perhaps with federal funding).

In short, the currently available data bases provide only a very limited understanding of the engineering community. One cannot make historical comparisons or construct consistent portraits of the engineering community, past or present. As a result, the committee has strongly recommended that the National Academy of Engineering take the initiative to call together the various public and private data-collecting organizations to see how best to arrive at common definitions, survey methodologies, and diagramming methodologies. The purpose would be to ensure to the greatest degree possible that data collection efforts result in accurate and compatible data bases that describe the engineering community and its various components in totality and at the lowest possible cost.

(FIGURE #22)

Despite the shortcomings, available data did point out various characteristics of engineering employment that

ENGINEERING EMPLOYMENT CHARACTERISTICS

- In 1983, the 1.6 Million Engineers Comprised 1.4% of the Work Force
- About 75% of U.S. Engineers Work in Business and Industry
- The Federal Government Employs 6% of U.S. Engineers Directly (About 30% Indirectly)
- Less Than 5% of Engineers Are in Research (Less than 1% in Basic Research)
- Only 2.7% of Engineers Are in Teaching
- The Disciplines of Electrical/Electronic, Mechanical, and Civil Engineering Together Comprise About Half of All Engineers

Figure 22

were quite informative. The fact is that the 1.6 million engineers employed in 1983 represented only 1.4% of the total U.S. work force. While 1.4% is not exactly trivial, it is substantially less than the fraction of engineers in some other countries. Japan, for instance, produces about the same number of engineers on less than half the population base. We consider that we have technology-based economy here in the U.S., so one would normally expect a greater fraction of engineers.

An interesting finding is that, although about 75% of U.S. engineers work in business and industry, a surprising number of these are actually working for the government in one way or another. While the federal government employs directly only about 6% of U.S. engineers, if you take into account those who work for companies whose revenue essentially derives from prime government contracts, the fraction swells from 6% to 30%. Taking into account those who work for companies whose income is derived primarily from serving as subcontractors to the primary contractors, the fraction grows to 38%.

The available data also show that less than 5% of employed engineers are engaged in research, and only 2.7% are in teaching. We also know that three engineering disciplines (electrical, mechanical, and civil) taken together comprise about half of all engineers.

MAINTENANCE OF PUBLIC TRUST IN ENGINEERING

Along with the enormous increase in engineering activity in the post World War II era has come an increase in the awareness and critical scrutiny of that activity by the public. Especially since the early 60's, antitechnology attitudes have become prevalent as public attention has focused on the growing capacity of technology for doing harm to individuals, the environment, and society itself. There have been many concerns: air and water pollution, product safety as in automobiles and baby cribs, the use of advanced technology in wars, and fears regarding nuclear power, to say nothing about nuclear war. These have led to an atmosphere of mistrust regarding the objectives of technology development and the morality of its purveyor, the engineer.

Since the mid 1970's, the public attitude seems to have shifted in the other direction. Views of engineering and technology are much more positive than they were. However, the time of blind and naive public acceptance of engineering and technology wonders are now forever past. There is a residue of antitechnology attitude that means that engineers have new social responsibilities in addition to their technical ones. While the engineer cannot be solely responsible for the social consequences of engineering work, the engineer cannot be absolved of responsibility either.

(FIGURE #23)

Thus, we must conclude that the public's perception of engineers and engineering has become an important factor in the country's decision-making process. Neither business, industry, government, nor the engineering profession can ignore the public's perception of the effects of technology or the fruits of engineering work. This places upon all these constituencies the burden of helping to keep the public informed. However, the mass

THE NEED TO KEEP THE PUBLIC INFORMED

- Public Perceptions of Technology Have A Major Impact
- Public Perceptions Are Shaped by the Media
- The Engineering Community Can Help To Improve Mass Media Coverage
- Mutual Cooperation and Trust Are Required

The Committee recommends that the National Academy of Engineering take the initiative in creating a "media institute" that would provide centralized coordination of a nationwide network of technological information sources to respond to media requests for information.

Figure 23

media are what the public depends on most for its information and understanding. Therefore, any effort to improve public understanding of engineering must focus on helping to improve mass media coverage. The engineering community must help the media in this regard.

Mechanisms for improving media coverage are, for the most part, already in place. They need to be strengthened and expanded. Even more importantly, the engineering community needs to shed its reluctance to discuss often controversial and complex (as well as proprietary) technical matters with the media. Often, engineers mistrust the motives of reporters. But this kind of attitude, however understandable, is self-defeating. The media must learn to trust the engineer, and the engineer must learn to trust the media in spite of individual and occasional lapses of good faith. The committee has recommended that the National Academy of Engineering take the initiative to create a media institute that would allow coordination of a nationwide network of technological information sources. Sources of this nature already exist, as for example, the Media Resource Service of the Scientist's Institute for Public Information. The problem with this service is that it is not universally used, and is primarily focused on science and scientists with minimum activity regarding engineers and engineering.

(FIGURE #24)

This has been a very abbreviated summation of the most important elements of the report of the Committee on the Education and Utilization of the Engineer. In addition, nine panel reports will be published in the next few weeks and months which are much more focused and contain extensive supporting information. We hope that, taken together, these reports serve to inform the policymakers in this country, both within and without government. As a group, the committee felt strongly that the engineering profession is healthy -- although it has some problems and could be better. We feel that it is resilient and competent, and that it is important to the nation and getting more so all the time.

REPORTS OF THE CEUE AND ITS PANELS

- Engineering Education and Practice in the United States: Foundations of Our Techno-Economic Future
- Engineering Infrastructure Diagramming and Modeling
- Engineering Employment Characteristics
- Engineering Graduate Education and Research
- Engineering Undergraduate Education
- Engineering Technology Education
- Continuing Education of Engineers
- Engineering in Society
- Support Organizations for the Engineering Community

Figure 24

THE THEORETICAL MODELING OF PIEZOELECTRIC TRANSDUCERS

by

Dr. Gordan Hayward*

Good afternoon Gentlemen and Lady:

I'm going to talk this afternoon about modeling a specific type of Piezoelectric Transducer. These relate to long, tall, thin bar elements, which are utilized in ultrasonic phased-arrays.

The basis of my talk is the necessity to model such structures in order that we can utilize such phased-arrays for nondestructive evaluation.

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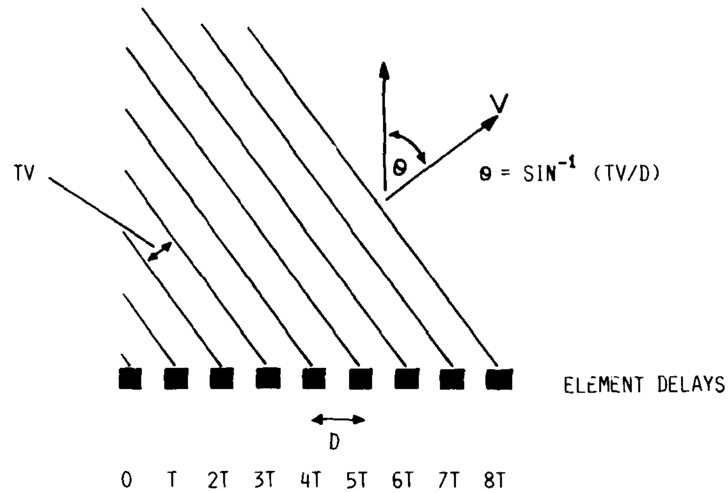
*Dr. Hayward received his Bachelor of Science degree in electrical engineering from the University of Glasgow and his Master's and Ph.D. degrees from the University of Strathclyde. After receiving his Ph.D. degree, he worked with a research/development firm engaged in laser applications to low level optical detection systems. Following that he was appointed Research Assistant in the Department of Electrical Engineering at the University of Strathclyde. He is presently a lecturer in that department at University of Strathclyde. His research interests include transducer modeling and applications of ultrasound to medical diagnosis and non-destructive testing.

Editorial assistance for this paper was provided by Professor A. A. Sarkady and Professor H. M. Neustadt, U.S. Naval Academy Electrical Engineering Department.

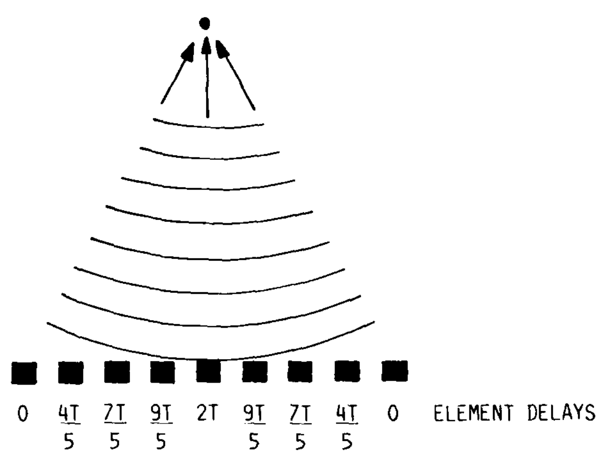
Before I go into the actual modeling details, I want to discuss first of all what I mean by a phased-array element. In the top diagram, Figure 1, we have a number of little elements which I would like to call, for the moment, Piezoelectric Transducers. These can be excited under electronic control at different time intervals, and we can steer the resultant beam in much the same way as we do in a sonar system, or much the same way as we do in a radar system.

For an ideal array and ideal wave propagation, the angle of steer is given by this expression here, where D is the separation distance of the elements in the array, and V the acoustic wave velocity. As well as steering the beam, we can similarly focus the beam at any point in the field, and again under electronic control. So with a system like this, in theory, you have the capability of manipulating an acoustic beam either at a focal point or around in space in a specific direction.

The types of array configuration, Figure 2, are pretty numerous. This type of beam-switched linear array indicates a line of so-called transducers, which are switched or



(A) STEERING



(B) FOCUSSING

PHASED ARRAY STEERING AND FOCUSSING Figure 1

ARRAY CONFIGURATIONS

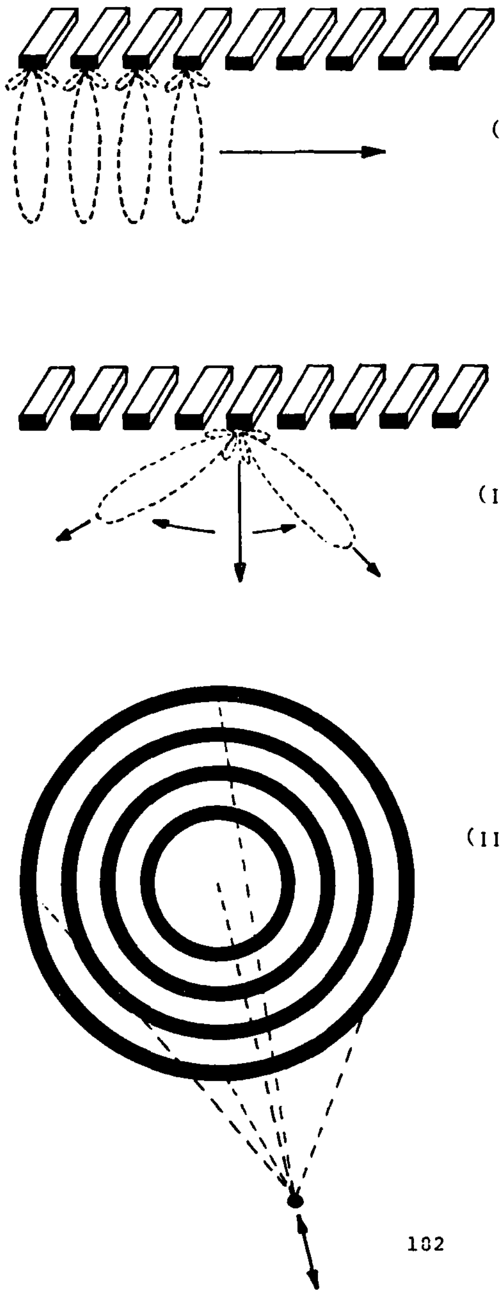


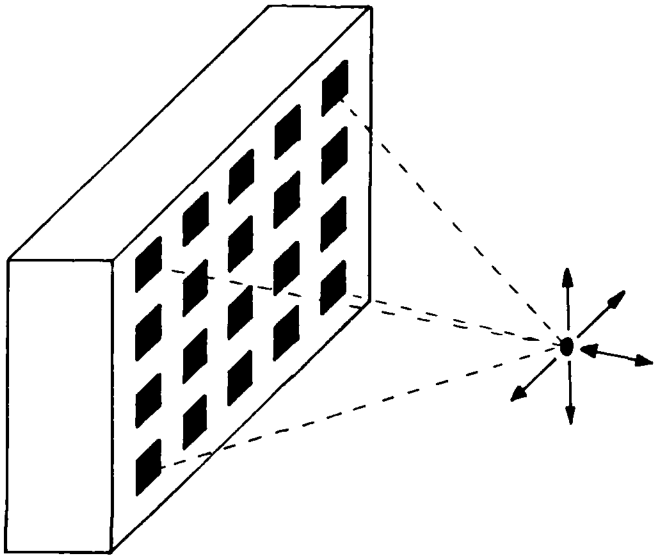
Figure 2

excited, and in turn may receive on the same element or on a different element. From structure like this, we can constitute an image. Linear arrays of this nature are used widely in biomedical imaging and in some cases in non-destructive evaluation. In an alternative structure we can use the same array configuration, but we can steer and focus the array, again under electronic control, and manipulate the beam in different directions. In this case it's a straightforward linear excitation function across the array. In this case we can steer the beam as well as focus.

An alternative array structure is an annular system which we can focus at different points along the axis of the probe, and this again has application in biomedical imaging and in non-destructive evaluation. Another possible array structure is a two-dimensional one, which does give rise to the possibility for holography or three-dimensional imaging, Figure 3, if one can, in fact, design the elements in a suitable fashion, and that electronic hardware is available.

This is another example of a possible array structure. If I can briefly outline potential advantages for the array systems, Figure 4, in non-destructive evaluation. Firstly,

2-D ARRAY STRUCTURE



- STEERING AND FOCUSSING IN 3 DIMENSIONS
- 3-D IMAGING
- HOLOGRAPHY

Figure 3

POTENTIAL ADVANTAGES FOR PHASED ARRAY SYSTEMS IN NDT

- VARIABLE PROBE ANGLE FROM A FIXED POSITION
- FOCUSSING TO MINIMISE BEAM SPREAD
- DEFECTS MAY BE INSONIFIED FROM DIFFERENT DIRECTIONS
- LARGE AREA COVERAGE
- IMAGING OF TEST SPECIMEN
- NEW TECHNIQUES BECOME AVAILABLE

Figure 4

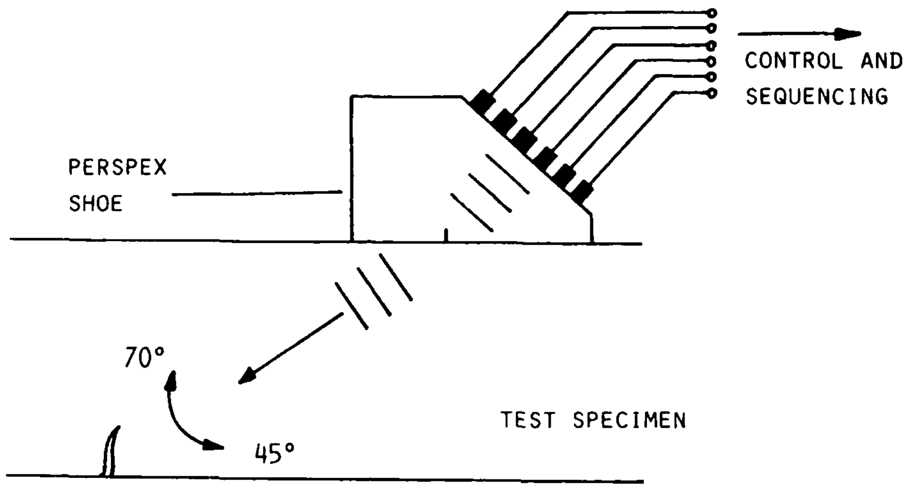
we have the possibility of varying the probe angle from a given fixed probe position. In theory that's possible, although one must certainly consider the array beam characteristics, especially in solid materials, and also possible variation of beam characteristics as the steering angle is varied. These factors must be considered in array design. But in theory we do have this possibility, we can electronically focus to minimize the effect of beam spread. This ought to improve defect detectibility and also defect sizing, if it can be implemented in the proper fashion.

We can identify defects from different directions without moving the probe again by steering the beam under electronic control. And this ought to provide enhanced information on the nature of the defect, and nature of the scattering mechanism. So, by using an array in this fashion, it is theoretically possible to obtain enhanced information into the nature of the reflecting object. It's again possible without moving the probe to cover larger areas of the inspection site. It is also possible to have banks of arrays comparing two or three hundred elements to provide larger areas of blanket coverage. It is possible to provide in situ monitoring from fixed positions. It is possible to image the test specimen and from the image obtain information on orientation and flaw size. Finally, arrays also introduce the possibility of improved signal processing strategies, and the use of modern image processing techniques.

So, when using array transducers, the system designer has more flexibility in designing the processing system, in order to enhance the information from the array. So as far as non-destructive testing is concerned, phased-arrays definitely do have a lot of potential in NDE. And one of the areas I want to cover in my talk this afternoon is what we're doing at Strathclyde to try and ensure that one day phased-arrays will actually fulfill that potential. There are, in fact, some technical difficulties which must be overcome as practical phased-arrays mature. Before doing so, however, I would like to cover some applications of phased-arrays, Figure 5, which we are currently investigating at Strathclyde. The first of these is, in fact, a variable angle probe, which would be suitable in a fixed monitoring position. This will, in fact, cover the

APPLICATIONS OF PHASED ARRAYS IN NDT

THE VARIABLE ANGLE PROBE (GENERAL PURPOSE)



. MANUAL SCANNING (A - SCAN DISPLAY MODE)

. REMOTE MONITORING (FIXED POSITION MODE)

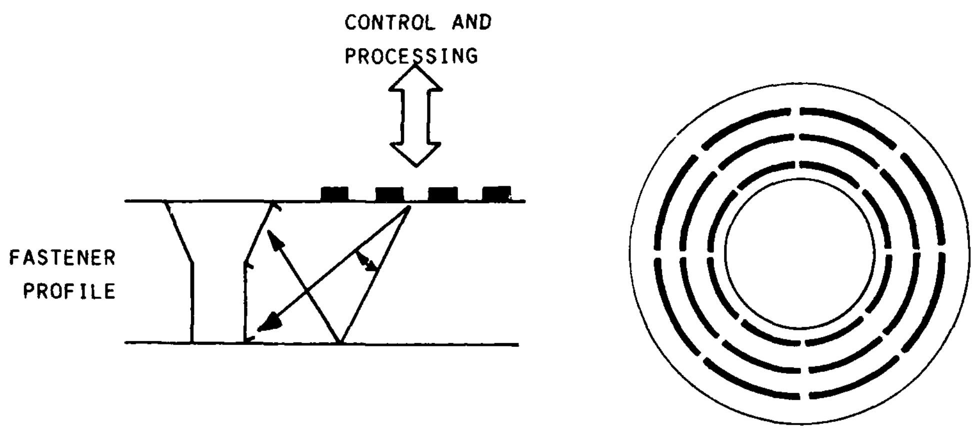
Figure 5

shear wave angles from 70 degrees to 45 degrees in steel or aluminum at the inspection site. In other words, the beam is actually steered in the test specimen, from the array elements here, and is formed by the fraction in the test specimen, and some of the work we are investigating in this area involves the evaluation and pulse shape of the beam profile and pulse shape at different angles in solid materials. So that is one possibility for phased-array and NDT.

Another project which we have on the way within our group is the investigation of annular arrays for inspection of aircraft fasteners in aluminum. In this case we have an array structure which is essentially a segmental circular array structure, Figure 6. We can sequence the elements in this direction, which will allow us to vary the angle in the test specimen, and we can transmit in a rotating sequence. We can transmit on any bunch and we can receive on any other bunch. So the thrust of this research was to try to develop a pseudo three-dimensional imaging strategy for inspecting circular fasteners in aircraft skins.

APPLICATIONS OF PHASED ARRAYS IN NDT

CIRCULAR ARRAYS FOR AIRCRAFT INSPECTION



- MONOLITHIC PHASED/SWITCHED STRUCTURE
- RAPID SCANNING AND AUTOMATIC CENTERING
- POTENTIAL FOR IMAGING AND IMPROVED PROCESSING

Figure 6

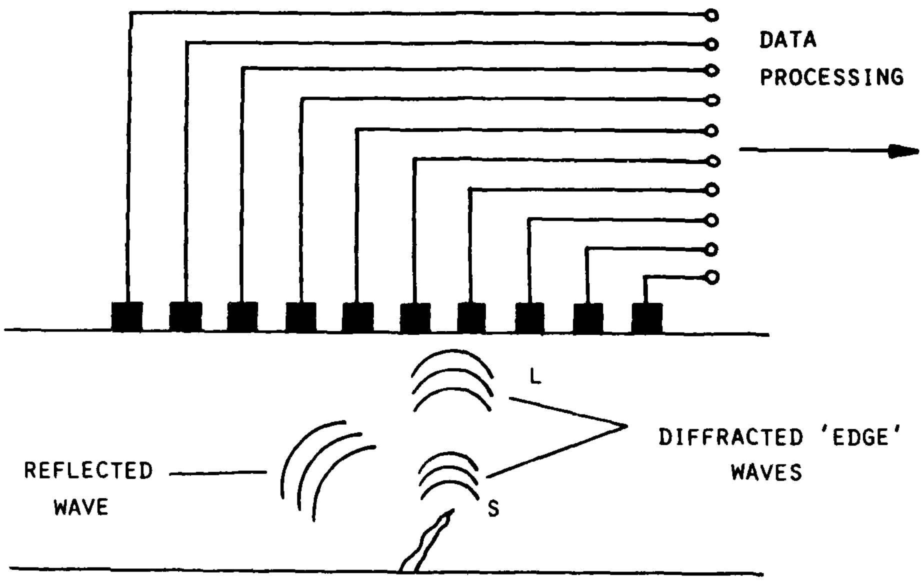
Another area which we're investigating is using the array as a static spatial sampler, in which case you're not particularly trying to transmit at different angles with the array, but instead, the array is used as a spatial sampler, Figure 7, to sample reflected information from a flaw in a particular position, and by physical array processing, it is possible to identify the longitudinal and shear wave component. We can also measure the wavefront curvature and there is some potential for utilizing phased-array in this fashion for improved defect identification.

I don't think it is too difficult for us to see these applications and to see the possibility of implementing these applications. But the truth, in fact, is a bit different. The arrays themselves tend to be very difficult to manufacture.

One of the main philosophies of the phased-array is that we do not have coupling between individual elements in the array. They are independent and in practice that is very difficult to achieve. So what I want to discuss today is the behavior of the individual elements and to get through some of the theoretical background of these devices.

APPLICATIONS OF PHASED ARRAYS IN NDT

SPATIAL SAMPLING FOR FLAW CHARACTERISATION



- IDENTIFICATION OF SHEAR, SURFACE AND LONGITUDINAL WAVE COMPONENTS
- MEASUREMENT OF WAVEFRONT CURVATURE
- WAVEPATH IDENTIFICATION POSSIBLE

Figure 7

I am trying to come up with a modeling strategy which will predict the behavior of an element in a phased-array, in accurate fashion, in order that we can, in fact, design a reliable and repeatable array structure for non-destructive evaluation. If I can summarize some of the practical considerations before one goes off and utilizes a phased-array for NDE. The individual array elements themselves have fairly complex mechanical behavior. I gave a talk here last week to some folks on the behavior of uni-dimensional structures, typified by probes used in non-destructive testing.

The typical phase-array element does not behave in a uni-dimensional fashion. The electrical-mechanical interaction is fairly complex, Figure 8, and before we can start to design the array, we have to understand this process, because the interaction within the array element determines the center frequency of the array. For physical steering and processing, the center frequency is going to determine the element spacing. There are minimum constraints on the element spacing. So this center frequency has to be known and, unfortunately, this is a

PRACTICAL CONSIDERATIONS FOR PHASED ARRAY IMPLEMENTATION IN NDT

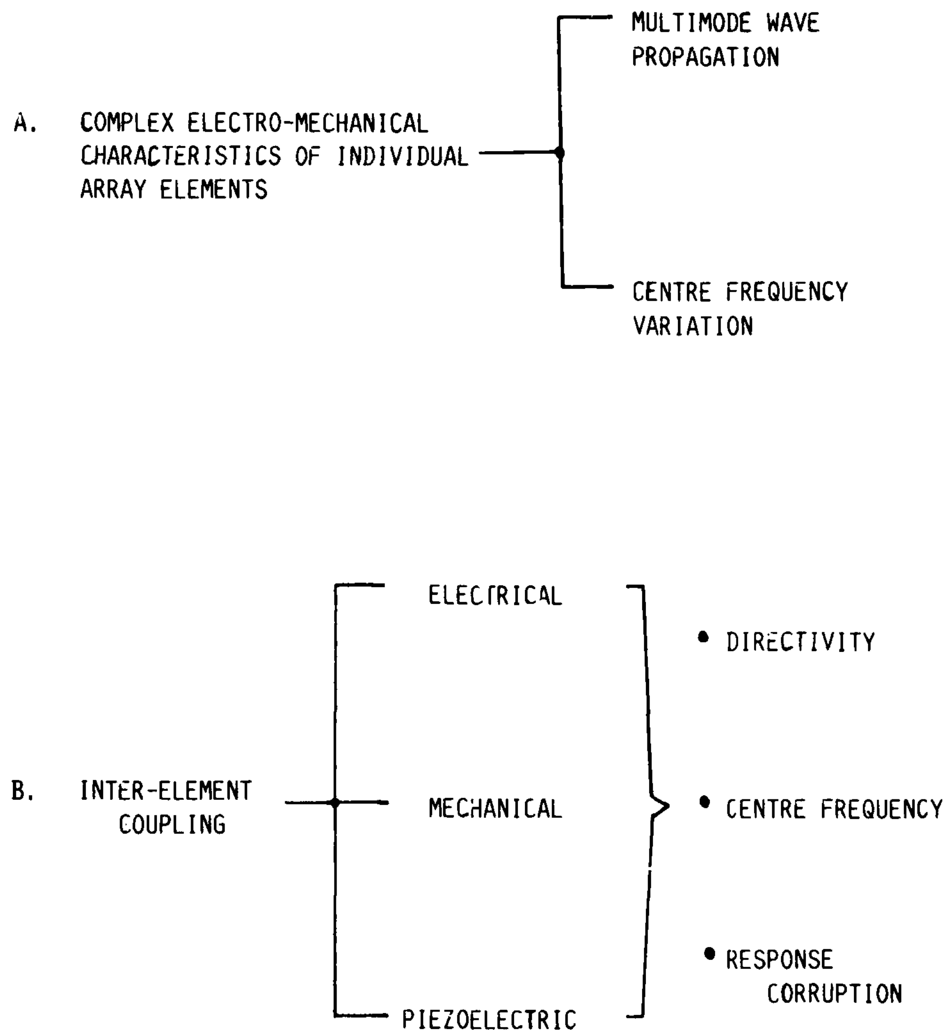


Figure 8

direct function of the individual reverberations within the array elements themselves. So before we can hope to design the array this process here has to be understood. Once the element is taken and mounted in the array assembly, you have another problem. And that is the problem of inter-element/coupling--how one element couples to its nearest neighbor. If we can find out an element and its nearest neighbor are in some form excited simultaneously, then the directivity is going to be affected and the result of data is most definitely going to be affected. So we have to consider the influences of inter-element coupling. What happens in an array structure when one has coupling between elements? If we can understand this process, then it may be possible by applying suitable processing techniques, or even those of typical array manufacturing techniques, then we may minimize or perhaps even eliminate the effects of coupling between elements.

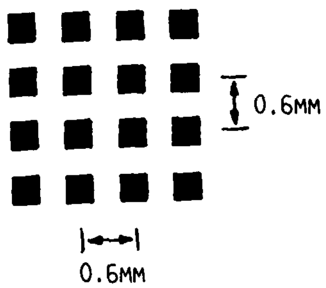
But these two facts are, by and large, fixed by the system. One of the reasons for our investigating this area of work is to try to find out more about the inherent mechanisms behind the behavior.

Now another circumstance has to be considered in phased-array design. We must ask ourselves, since this type of array structure has been known for several years, why hasn't it taken off in any major fashion? Perhaps because of the complexities of these arrays I discussed earlier. One thing that one has to consider is the cost/benefits of manufacturing an array, Figure 9.

A two-dimensional array structure like this 5 megahertz terminal array radiating direct to steel will have typical spacing between elements of 0.6mm. Each of these elements has to be excited independently and hopefully, also, you process the data independently from each one. So the choice and complexity of the electronic hardware is going to increase. The ability to manufacture an array like this, with such small elements and the electrodes and, indeed, to get the structure to operate in a satisfactory fashion has tended to inhibit the progress of phased-array technology. It's true to say that recently the technology behind this has been tied in with the semiconductor industry. Some of the Japanese medical companies have, in fact, produced very good two-dimensional arrays for biomedical imaging, and it

PRACTICAL CONSIDERATIONS (CONT.)

C. MANUFACTURING COMPLEXITY AND COST



5MHz LONGITUDINAL ARRAY
RADIATING DIRECTLY INTO STEEL

D. COST AND COMPLEXITY OF ELECTRONIC HARDWARE

E. PROBLEMS ASSOCIATED WITH RADIATION INTO SOLID MEDIA
- SURFACE WAVE GENERATION
- SHEAR WAVE GENERATION

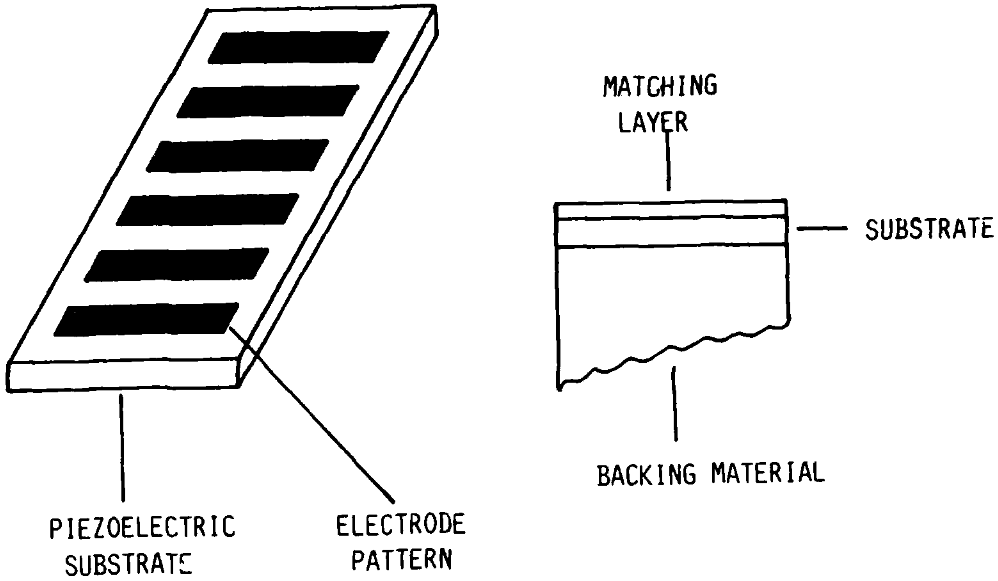
Figure [illegible]

may well be that these structures will see their way into NDT. But at present in NDT they really are limited to a single line array for practical implementation. Furthermore, I touched on this earlier, in NDT there are specific problems associated with small area elements radiating into solid materials.

In biomedical arrays, I'm sure you've all seen some of the images obtained in fetal scanning and cardiac scanning using ultrasonic array systems. In this case the medium is essentially a liquid medium capable of supporting one main mode of propagation, that is, the longitudinal component.

When you're radiating into solid materials from essentially narrow strip radiators you generate shear components, very strong shear components, and also under some conditions very strong surface wave components. So application to NDT has to take these factors into account, and you have to understand the mechanisms before an NDT system, Figure 10, can be properly utilized. For NDT, there are essentially two methods of manufacturing the phased-array. One is to take a substrate of piezoelectric material and lay down the electric pattern of the array in a

ARRAY STRUCTURES



- RELATIVE EASE OF MANUFACTURE
- STRONG INTER-ELEMENT COUPLING

(A) THE MONOLITHIC ARRAY

Figure 10

photolithographic fashion. So we deposit the electric pattern on a substrate, and we then attach perhaps a front face matching layer and a backing layer on to the back of the array board. We then have a phased-array. The advantage of this process is that the manufacturing process is fairly straight forward. The major disadvantage is that the electric elements themselves are coupled very strongly via the mechanical coupling along the length of the array. They are also coupled very strongly electrically through the capacitance of the substrate material. So in this type of array it's extremely difficult to escape from very strong inter-element coupling, and at Strathclyde we're looking at this type and also discrete element structure. But the problems associated with this form of array are complex and it is extremely difficult at the moment to get suitable data back for interpretation. But we have had some reasonable results in this case. The big problem for this array, is strong coupling between elements, although it is fairly cheap and relatively easy to manufacture.

The alternative method for manufacturing the array is to take a number of independent piezoelectric rods, each radiating perpendicularly to the electrodes (dark surface in Figure 11a), and place them in a system like that shown in Figure 11(b). The standard technique of doing it is to attach a slab of material on a backing block and cut right through. The intermediate layer is filled up with a lossy filler, a typical lossy filler that we used was gas microballoons in an epoxy resin base. The microballoons tend to scatter the ultrasound which will try to propagate between the elements. So this technique of array manufacturing is more cumbersome and more difficult to implement, but we get around some of the problems associated with strong coupling along the array. In practice it's very difficult to completely eliminate mechanical coupling. There are always some means by which stress waves can propagate from one element to another. But this technique tends to minimize the influence of these particular waves.

So in the talk today, I'm going to discuss the modeling of elements in an array as shown in Figure 11(b), and discuss a modeling strategy to predict the behavior of a typical element which one would use in an array of this nature. Now we can structure an element like this as shown

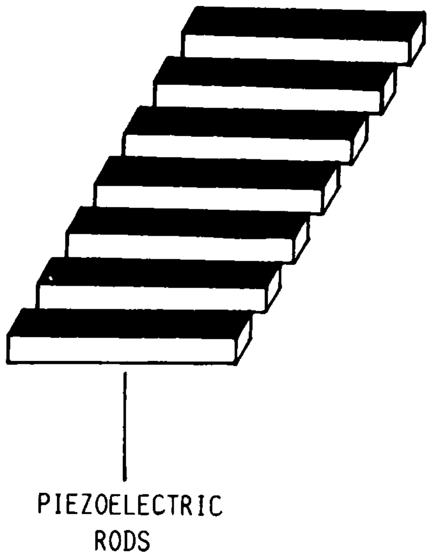


Figure 11(a)

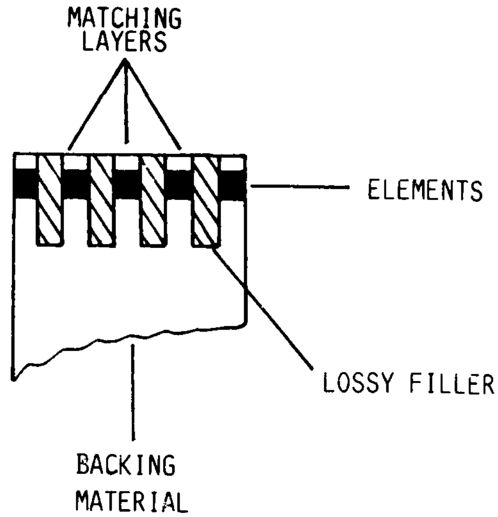


Figure 11(b)

- COMPLEX MANUFACTURE
- MINIMUM CROSS COUPLING

(B) THE DISCRETE ELEMENT ARRAY

Figure 11

in Figure 12. This is the basic piezoelectric slab, and in an isolated fashion for completeness, we're driving the slab via some form of electrical force that may be a matching network of a lumped electrical load involved. We represent the electrical load on the piezoelectric slab by this function Z_E.

We're interested in mechanical wave propagation and reception in the Z (or 3) direction. But because of the shape of this particular material, we also have strong mechanical coupling to the left here, and to the right (X direction, or number 1), and also, to some extent, over the end faces (Y direction, or number 2). So we have a two or three dimensional system and it's the modeling of this two-three dimensional system that I am going to go into now. So I am going to call the major component, this component here, in the Z direction, the thickness component of vibration, and that's the main one of interest in the array design. These components here will be referred to as lateral modes of vibration.

Now the governing relationship between the various dimensions in this system are given by the coupled

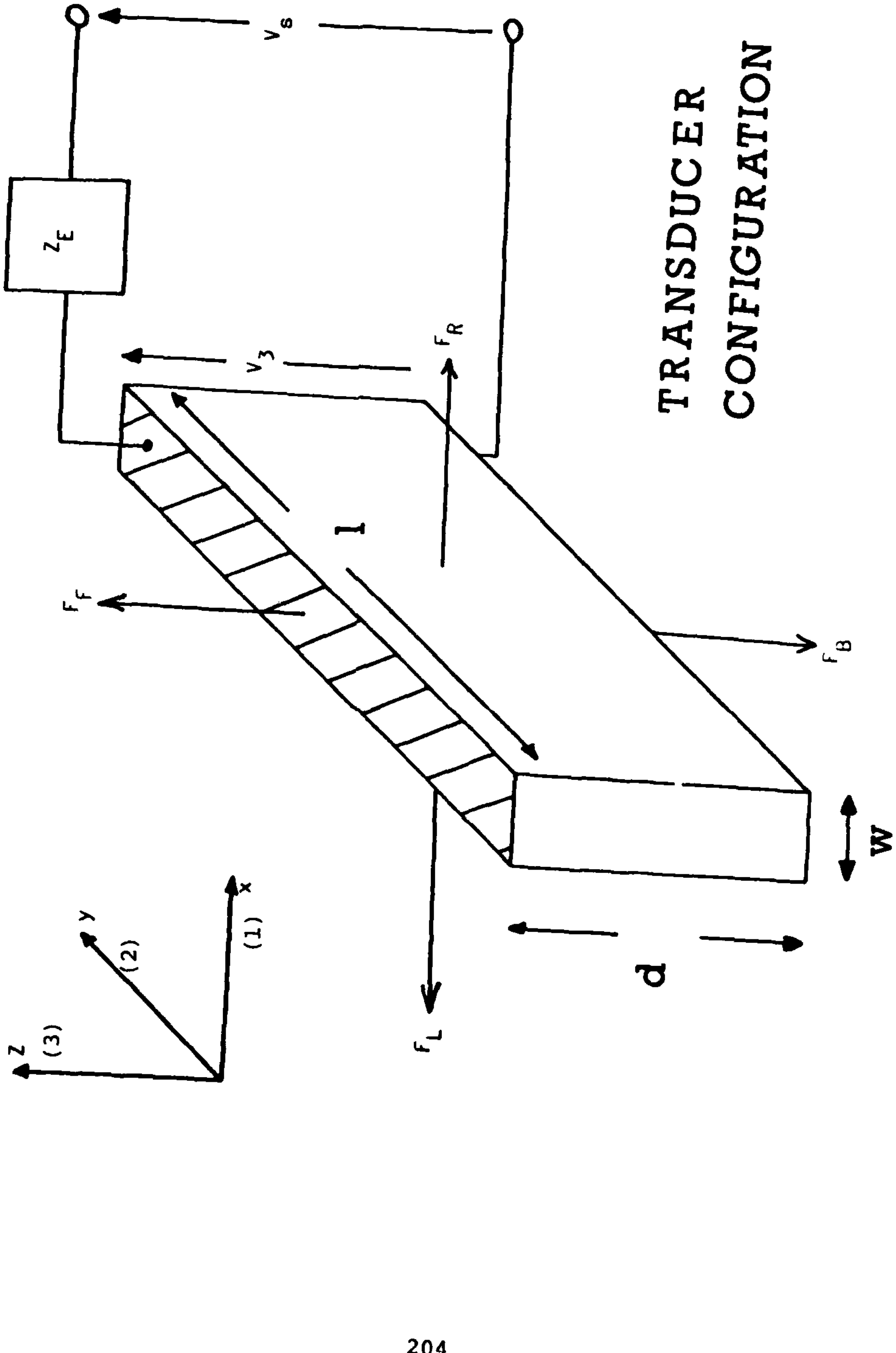


Figure 12

piezoelectric relationships here, Figure 13. This is the stress in the lateral direction (Γ_1), this is the stress in the thickness direction (Γ_3), this is the electric field in the thickness direction (E_3), and these are the stiffness co-efficients (Y_{11}, Y_{13}, Y_{33}) and the piezoelectric charge constants (h_{13} and h_{33}). Epsilon is the dielectric constant of the material, S is the strain, and D is the electric flux density. So the electro-mechanical system of such a radiator is governed by this matrix expression, and by solving the boundary conditions (the mechanical boundary conditions of continuity of stress and particle placement). What I want to end up with is a suitable model which will describe the wave performance in the material.

Now if I can go back, it is worth reiterating this point. If I can go back to the transducer element which we have here, Figure 12, and briefly go over the operation of such an element.

In transmission, we apply a voltage (V_s) here and we deposit a quantity of charge on the electrodes of the device. This quantity of charge will initiate stress waves primarily in the Z direction, to some extent in the X direction and to a lesser extent in the Y direction. These waves will reverberate back and forth, back and forth, and will couple to each other mechanically via Poisson's ratio, and they'll also cross couple via the piezoelectric coupling factor.

We have quite a strong coupling mechanism between the two main modes of vibration, and this, in fact, would influence the center frequency. So if we go on the assumptions that are inherent in this approach, in an element like that, we can approximate the mechanical reverberation in both directions by a plane wave equation. So from these equations, and from the standard equations of motion, we can get two coupled wave equations, Figure 13. This corresponds to the lateral mode which would be an equal sign in here. This is a particle displacement there, and this corresponds to a thickness mode. V_1 and V_3 are the stiffened velocities in the lateral and thickness directions, respectively.

Now the aim of this is on the assumption that we have two plane waves propagating in the principal vibrational directions. We want to couple them via the piezoelectric

THEORETICAL DEVELOPMENT

THE APPROPRIATE PIEZOELECTRIC RELATIONSHIPS ARE:

$$\begin{bmatrix} \Gamma_1 \\ \Gamma_3 \\ E_3 \end{bmatrix} = \begin{bmatrix} Y_{11}^D & Y_{13}^D & -h_{13} \\ Y_{13}^D & Y_{33}^D & -h_{33} \\ -h_{13} & -h_{33} & 1/\epsilon^S \end{bmatrix} \cdot \begin{bmatrix} S_1 \\ S_3 \\ D_3 \end{bmatrix}$$

THESE PROVIDE THE FOLLOWING PAIR OF WAVE EQUATIONS

$$\frac{\delta^2 \zeta_1}{\delta t^2} = \frac{v_1^2 \delta^2 \zeta_1}{\delta x^2}$$ LATERAL MODE

$$\frac{\delta^2 \zeta_3}{\delta t^2} = \frac{v_3^2 \delta^2 \zeta_3}{\delta z^2}$$ THICKNESS MODE

Figure 13

relationships given here. So we solve the wave equation using a Laplace transform, and the particle displacement in the lateral mode is given by this expression, particle displacement in the thickness mode is given by this expression, Figure 14. Terms involving A_1, B_1, A_3, and B_3 correspond to particle displacement in both directions, respectively, and these involve the cross-coupled factors, which we have yet to derive. Now, by implementing the piezoelectric equations, we can get expressions in A_1, B_1, A_3, and B_3 for the forces in the lateral direction and the forces in the thickness direction. You'll notice that we have the mechanical reverberation in the wave equation considered in here, Figure 14, we have a delay section in there and there, and other elements here, and we have various co-efficients which are starting to pop out in the equations.

Now I'd like to define some of these before I go any further. This expression here, Phi, Figure 15, I'm calling the lateral mode piezoelectric coupling factor. Now, essentially we apply a voltage to the electrodes and that voltage is converted to a force in the lateral direction.

TWO PLANE WAVE SOLUTIONS

$$\bar{\zeta}_1 = \bar{A}_1 e^{-sx/v_1} + \bar{B}_1 e^{sx/v_1}$$

$$\bar{\zeta}_3 = \bar{A}_3 e^{-sz/v_3} + \bar{B}_3 e^{sz/v_3}$$

THE FORCES GENERATED IN EACH DIMENSION MAY NOW BE OBTAINED.

$$\bar{F}_1 = sZc_1(-\bar{A}_1 e^{-sx/v_1} + \bar{B}_1 e^{sx/v_1})$$

$$+ \Psi_{31}\left[\bar{A}_3(e^{-sT_3} - 1) + \bar{B}_3(e^{sT_3} - 1)\right] - \phi\bar{V}_3$$

$$\bar{F}_3 = sZc_3(-\bar{A}_3 e^{-sz/v_3} + \bar{B}_3 e^{sz/v_3})$$

$$+ \Psi_{13}\left[\bar{A}_1(e^{-sT_1} - 1) + \bar{B}_1(e^{sT_1} - 1)\right] - h_{33}\bar{Q}$$

Figure 14

WHERE:

$$\phi = C_O d/w$$

PIEZOELECTRIC VOLTAGE CONSTANT RELATING VOLTAGE TO LATERAL FORCE

$$\Psi_{31} = \{Y_{13}^{D} - h_{13} h_{33} \epsilon^{S}\} l$$

MECHANICAL CONVERSION FACTOR RELATING THICKNESS DISPLACEMENT TO LATERAL FORCE

$$\Psi_{13} = Y_{13}^{D} l$$

MECHANICAL CONVERSION FACTOR RELATING LATERAL DISPLACEMENT TO THICKNESS FORCE

Figure 15

That is the coupling factor which I'm defining as the lateral piezoelectric coupling factor. You saw this factor Ψ_{31} here. Now that defines the relationships between thickness particle displacement to lateral forces. So that converts particle displacement in the thickness direction to force in the width direction, and that's a mechanical coupling factor. Similarly, particle displacement in the lateral direction is coupled to force in the thickness direction via this factor here. Now these are going to be cropping up again in the results of models, but they can be identified as a piezoelectric coupling factor, and mechanical coupling factors.

So continuing with the piezoelectric relationships, we already have the mechanical equations for the forces. We get a voltage equation here, again in the Laplace domain, which relates the voltage across the electrodes to mechanical reverberation, and to piezoelectric coupling in the lateral direction and the thickness direction. This is the charge on the electrodes here, and this quantity is the actual static capacitance of the transducer, Figure 16. The next stage in formulating a model, which we hope will get us

THEORETICAL DEVELOPMENT (CONT)

AN ADDITIONAL EXPRESSION RELATING VOLTAGE AND CHARGE TO MECHANICAL DISPLACEMENT MAY BE OBTAINED ALSO.

$$\bar{V}_3 = -\phi\left[\bar{A}_1\{\bar{e}^{sT_1} - 1\} + \bar{B}_1\{e^{sT_1} - 1\}\right]/Co$$

$$-h_{33}\left[\bar{A}_3\{\bar{e}^{sT_3} - 1\} + \bar{B}_3\{e^{sT_3} - 1\}\right] + \bar{Q}/Co$$

THE BOUNDARY CONDITIONS ARE NOW APPLIED TO OBTAIN SOLUTIONS FOR THE DISPLACEMENT FUNCTIONS A_1, B_1, A_3, B_3.

THE RESULTING EXPRESSIONS ARE THEN MANIPULATED TO PROVIDE A FEEDBACK REPRESENTATION OF THE TWO DIMENSIONAL SYSTEM.

Figure 16

a degree of insight into the behavior of this structure, is to solve the boundary conditions. Now at each face we must preserve continuity of stress, and preserve continuity of particle displacement. So the boundary conditions are so, to give a solution for A_1, B_1, A_3, and B_3, which are the particle displacement functions. So we end up with the following set of coupled equations, Figure 17, force out of the left hand face, force out of the right hand face, force out of the front face, and force at the back face. These key factors correspond to mechanical reverberation in the system. Here we have mechanical coupling, and here we have piezoelectric coupling in the thickness direction, piezoelectric coupling in the lateral direction.

Continuing! We can extract from these equations an expression for what I would call the operational impedance of such a radiator, and we define the operational impedance as the ratio of the voltage in the thickness direction, to any current in the thickness direction and that is given by a capacitance term modified by the effects of piezoelectric action in the individual directions, Figure 18. So these

THEORETICAL DEVELOPMENT (CONT)

TRANSMISSION

$$\begin{bmatrix}\bar{F}_L \\ \bar{F}_R\end{bmatrix} \begin{matrix} = \\ = \end{matrix} \begin{bmatrix} Z_L\bar{K}_L/\{Z_L+Zc_1\} \\ Z_R\bar{K}_R/\{Z_R+Zc_1\}\end{bmatrix}\left[\phi\bar{V}_3-\Psi_{31}\bar{K}_3h\bar{Q}/sZ_{C_3}\right]/\bar{M}$$

$$\begin{bmatrix}\bar{F}_F \\ \bar{F}_B\end{bmatrix} \begin{matrix} = \\ = \end{matrix} \begin{bmatrix} Z_F\bar{K}_F/\{Z_F+Zc_3\} \\ Z_B\bar{K}_B/\{Z_B+Zc_3\}\end{bmatrix}\left[h\bar{Q}-\Psi_{13}\bar{K}_1\phi\bar{V}_3/sZc_1\right]/\bar{M}$$

WHERE

$$\bar{M} = \{1-\Psi_{13}\Psi_{31}\bar{K}_1\bar{K}_3/s^2Zc_1Zc_3\}$$

$$\bar{K}_1 = \{T_L\bar{K}_L+T_R\bar{K}_R\}/2$$

$$K_3 = \{T_FK_F+T_BK_B\}/2$$

Figure 17

THEORETICAL DEVELOPMENT (CONT)

(A) OPERATIONAL IMPEDANCE MODEL

$$\bar{Z}_T = \frac{\bar{V}_3}{\bar{I}_3} = \frac{1}{sC_O} \cdot \left[\frac{1 - \bar{A}_T + \bar{A}_{31}}{1 + \bar{A}_W - \bar{A}_{13}} \right]$$

$$\bar{A}_W = \phi^2 \bar{K}_1 / s\, Zc_1 Co\, \bar{M}$$

$$\bar{A}_T = h^2\, Co \bar{K}_3 / s Zc_3 \bar{M}$$

$$\bar{A}_{13} = \Psi_{13} h \phi\, \bar{K}_1 \bar{K}_3 / s^2 Zc_1\, Zc_3 \bar{M}$$

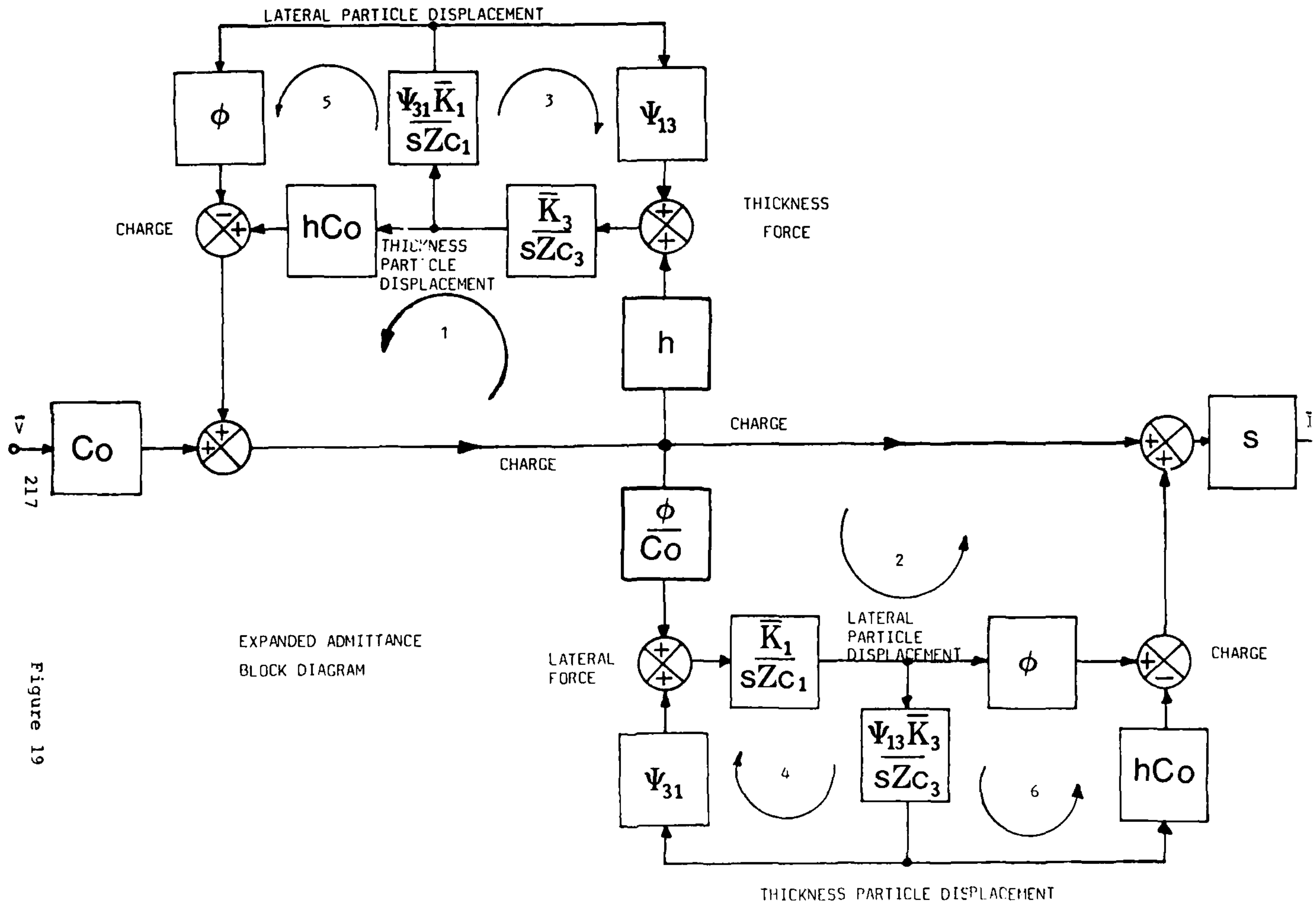
$$\bar{A}_{31} = \Psi_{31} h \phi\, \bar{K}_1\, \bar{K}_3 / s^2 Zc_1 Zc_3\, \bar{M}$$

Figure 18

factors here again relate to mechanical piezoelectric and electrical cross-coupling.

We can expand that equation and represent it in a system block diagram fashion for explaining the actual impedance in such a radiator. This is actually an admittance diagram, Figure 19. Now at one end here, you have a Laplace function of voltage. At the other end we have current. For the actual diagram, itself, relates current to voltage and represents the admittance of such a radiator. Now if you work your way through the diagram, we apply voltage here and we have the first block Co which is the static capacitance of the transducer. Therefore, at this point in the diagram, we have a deposit of charge on the electrode of the device. Note that charge is going to do two things. It is going to initiate waves traveling in the thickness direction, it's going to initiate force waves which travel in the lateral direction. These waves of force will interlink with each other through mechanical and piezoelectric cross-coupling.

So if we take the thickness direction first of all, we have charge here. That's converted via the piezoelectric charge constant, h, into thickness force. So we have a



EXPANDED ADMITTANCE
BLOCK DIAGRAM

Figure 19

function of force in the thickness direction which starts to reverberate back and forth. The reverberation is described by this function here, K3. The term $\frac{1}{SZC_3}$ converts the actual force to one particle displacement here. That particle displacement is converted via Co back to secondary charge, and in fact, what we have in this loop is a uni-dimensional section which would conform to strict uni-dimensional behavior. Further at this point here, the thickness particle displacement is converted here to a function of lateral force. So what this force describes is Poisson's ratio, effectively, with initiated waves traveling in the thickness direction, there coupled with waves traveling in the lateral direction. These are then recoupled back into thickness components via that block and recoupled back into charge via this block here, Figure 19. So we have the complete interaction, both piezoelectrically and mechanically, of the coupled waves in the system. However, at this point here, simultaneously to the initiation of a thickness mode component here, we also initiate a lateral component which couples in the lateral direction. Simultaneously, generation of thickness waves of force through here and being fed back as lateral forces in this section here.

So the block diagram when it is related in this fashion allows us to get an insight into any of the coupling mechanisms between the various wave modes in the system, and also, more importantly, how they interact and how important they are. We can analyze this block diagram, we can use different values for psi to assess how the lateral coupling is going to influence the radiator, and different values of h to show how thickness coupling is going to influence the radiator. We can change the stiffness coefficients here, the mechanical coefficients here and here, and evaluate how important mechanical cross-coupling is in influencing the behavior of a radiator like that. So, from this admittance diagram, we can get a lot of insight as to what's happening in a tall, thin structure like that, and that would give us some guidelines as to the mechanisms which are, in fact, important in determining it's overall properties, and that hopefully ought to lead to better design.

Similarly, we can develop a model for a receiver, where we have an incident wave of force in the thickness direction. How does the device respond? So these are the governing expressions here, Figure 20, and we can represent them in a systems block diagram like so, and the overall systems approach for a receiving transducer is given by this structure here, Figure 21, where we have incident forces on the front face, we can have one on the back face, one on the left hand face, one on the right hand face, and in general, at any one time, only one of these would be incident, Figure 22. The results of the voltage are developed at this point here. Now this is followed through by a wave of force on the front face only. This block here, represents the transmission coefficient. So some of our input force energy, Figure 22, is transmitted into the transducer. It reverberates back and forth in the thickness direction, according to this here, and it's converted to particle displacement by this block positioned here. That function of particle displacement, is then converted back into thickness particle displacement, coupling through the lateral displacement, coupling through here. So that we are coupling from one dimension into the other mechanically, and in this formulation of this diagram this represents the

THEORETICAL DEVELOPMENT (CONT)

(B) RECEPTION MODEL

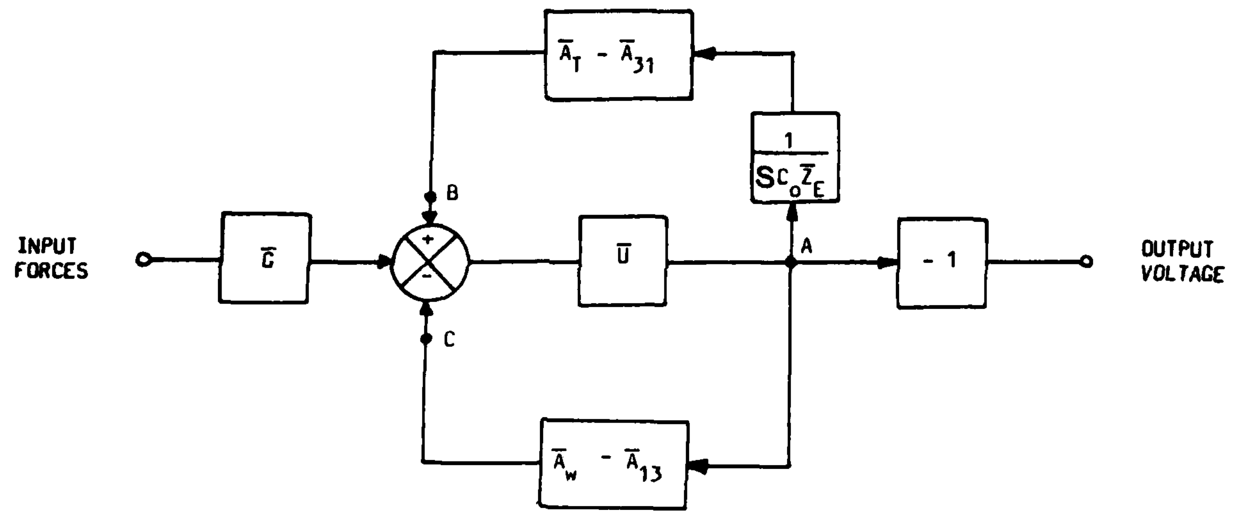
$$\bar{V}_3 = \bar{U}\bar{G}/\{1+\bar{U}\bar{H}\}$$

$$\bar{G} = \left[T_L\bar{K}_L\bar{F}_L + T_R\bar{K}_R\bar{F}_R\right]\left[\phi/Co - \Psi_{13}h\bar{K}_3/sZc_3\right]/sZc_1\bar{M}$$

$$+ \left[T_F\bar{K}_F\bar{F}_F + T_B\bar{K}_B\bar{F}_B\right]\left[h - \Psi_{31}\phi\bar{K}_1/sCoZc_1\right]/sZc_3\bar{M}$$

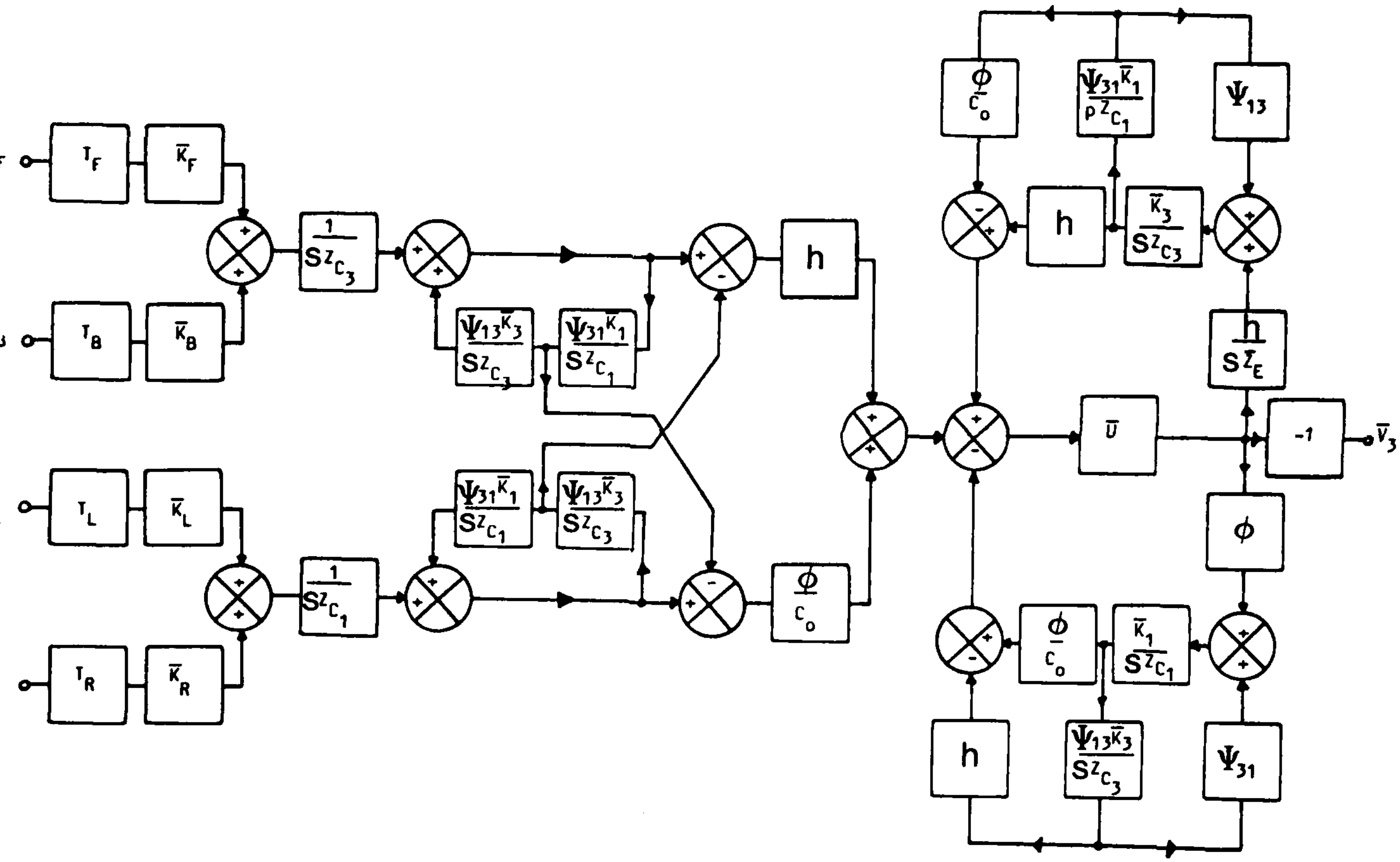
$$\bar{H} = \bar{A}_W - \bar{A}_{13} - \{\bar{A}_T - \bar{A}_{31}\}/sCo\bar{Z}_E$$

Figure 20



BLOCK DIAGRAM RECEIVING TRANSDUCER

Figure 21



BLOCK DIAGRAM RECEIVING TRANSDUCER

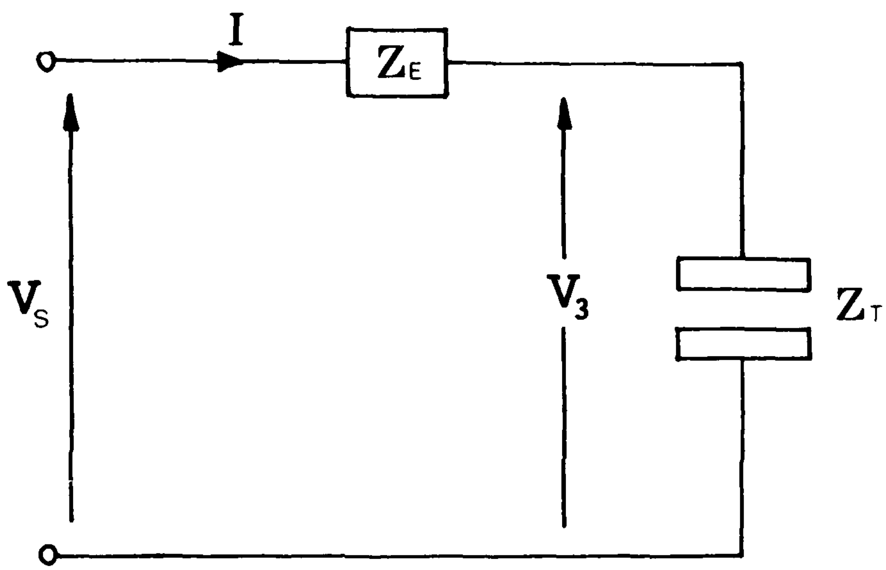
Figure 22

mechanical coupling section between the two principal wave modes. The forces are then converted to functions of charge by these components here and here. This site here represents the electrical interaction in the device. So, given that we can satisfy our system by approximating a plane wave solution, we have, in fact, everything in this model to allow us to predict what's going to happen when such a device is operating in the receiving mode.

Similarly we can define a model for transmission and represent that in terms of the operational impedance and the electrical load, Figure 23, and we achieve a block diagram along the same lines where we have an applied voltage to a system and we generate forces at each of the faces. So you see that if we have this element, Figure 24, as one element in an overall array, and we apply a voltage to it in general, we are going to generate a force from the front face, a force at the back face, and a force to the left and right which is going to couple several elements in the system, within such a transducer's structure, Figure 25.

The next thing to do before we can incorporate it to predict the performance of an ultrasonic array, is to couple

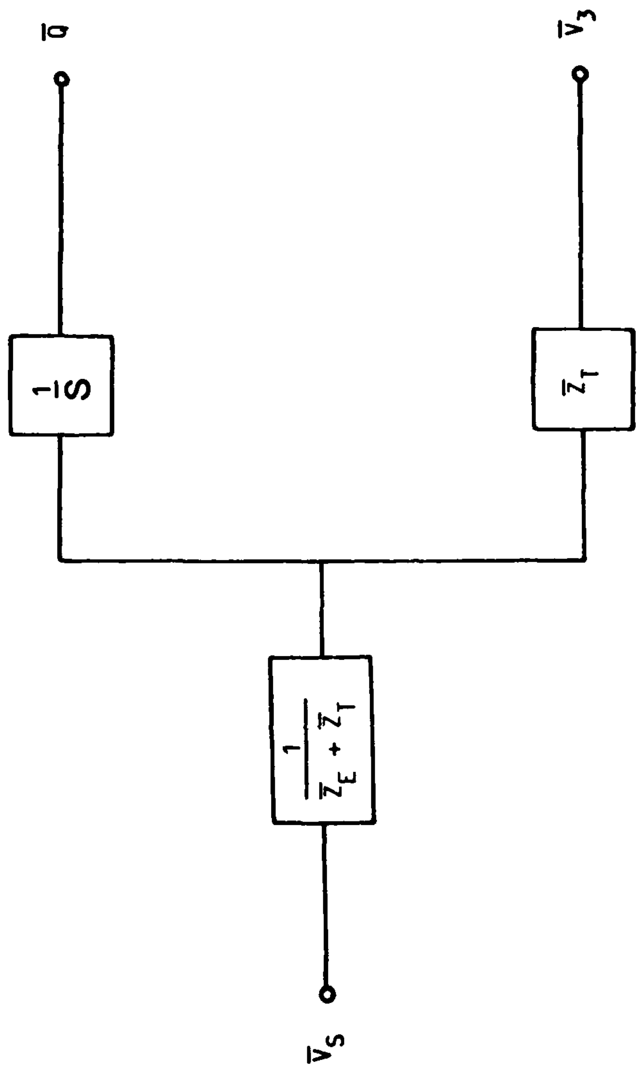
(c) THE TRANSMISSION MODEL



$$\bar{I} = \bar{V}_S / \{ \bar{Z}_E + \bar{Z}_T \}$$

$$\bar{V}_3 = \bar{V}_S \bar{Z}_T / \{ \bar{Z}_E + \bar{Z}_T \}$$

Figure 23



SINGLE ELEMENT OF AN ARRAY

Figure 24

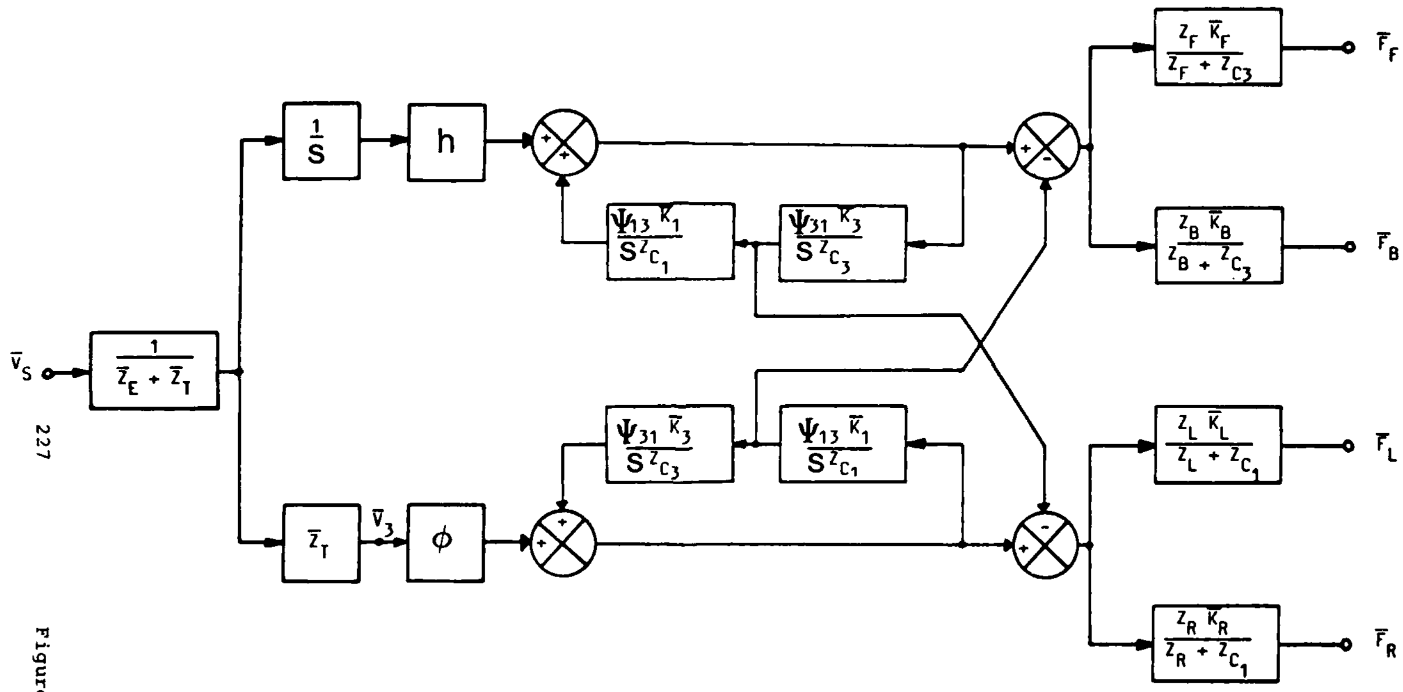
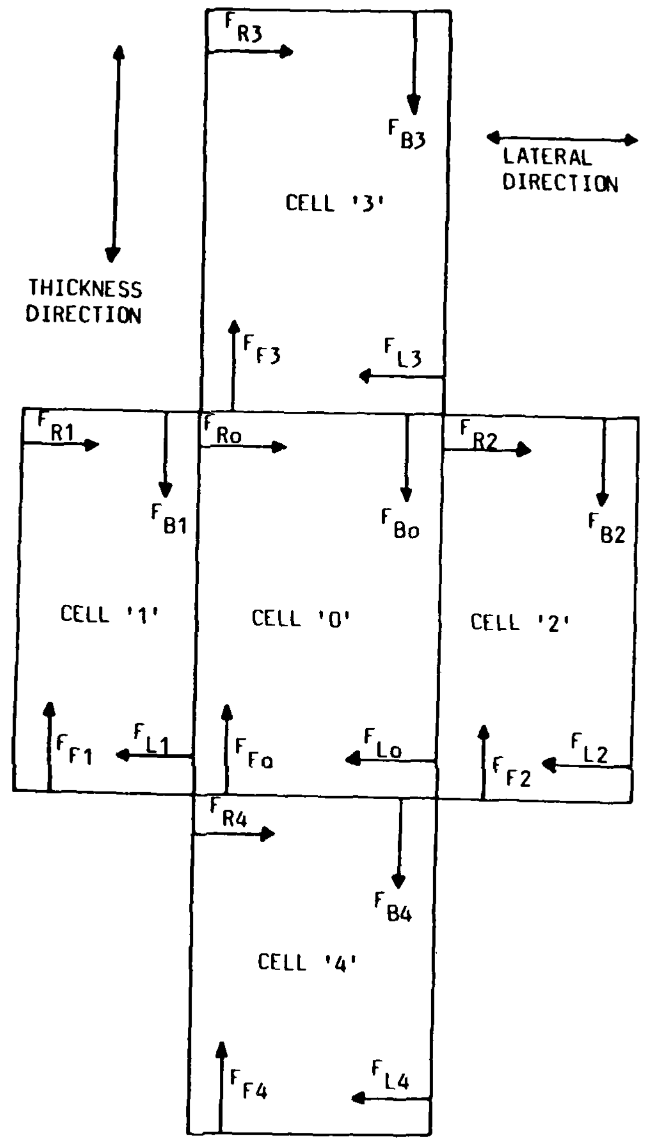


Figure 25

TRANSDUCER FORCE DEVELOPMENT

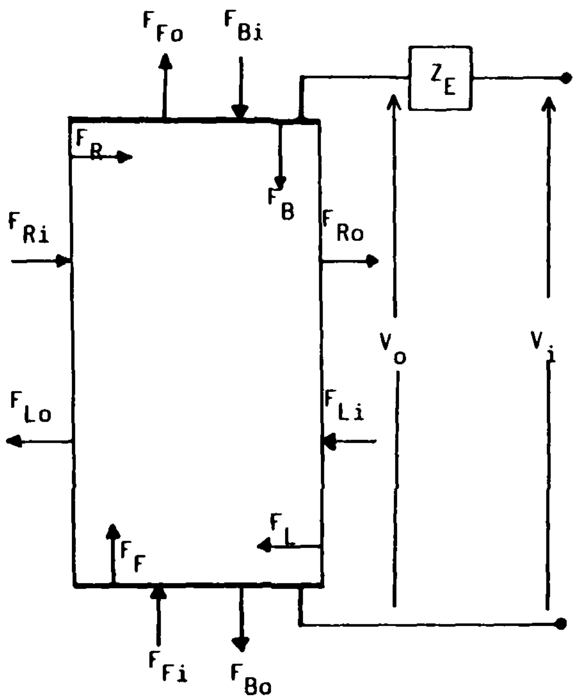
the element in a physically meaningful environment. So to do this, we adopt a cell-like structure in which we take that particular model and implement it in a physically meaningful array environment. So this central cell, Figure 26, is what I would call cell zero and that corresponds to the transducer material itself. This cell here is a front face layer which may be the matching layer for matching the array elements into the outside wall.

Cell four corresponding to some backing material on an additional layer in the system and cells 1 and 2 could be the inter-element filler, which separate the particular array element from it's nearest neighbor. So once we can define this basic structure, we've got everything in a phased-array structure. So, we formulate the elemental cell structure, Figure 27, in the following fashion, where we have forces leaving each face of the cell and forces incident on each face, and we want to implement the cell in the form of an acoustic lattice which will allow us to simulate this behavior of both incidence and reflection of individual faces of the elemental cell. We can represent the overall cell structure by a series of matrices, Figure



Cell Configuration

Figure 26



Elemental Structure

Figure 27

28, where I can define some of these as the internal vector, because it's a function of internal forces propagating in the cell, the input vector is a function of the applied voltage and external forces, the output vector, the output forces and the output voltage. The overall describing matrix, Figure 29, is given by this expression here.

So we take the model, implement in this fashion, and program it. Once we've got it in that stage, Figure 30, we are in the position to analyze a wide variety of phased-array configurations, and we then start looking for some insight into how we ought to design and construct these structures. So those are typical situations which we may have where the piezoelectric, or the active layers if you like, are indicated by these regions, non-piezoelectric or filler regions shown by these regions, Figure 31, and the system also includes the facility that we can excite elements in a different fashion. This is quite useful because in fact, we can suppress some wave propagation by exciting the nearest neighbor in a different fashion from the desired elements, or we can simulate a tall structure of this nature here, Figure 31, or we can simulate both pieces

$$[\bar{C}] = [I - \bar{A}]\,[\bar{B}][\bar{r}]$$

$$[\bar{d}] = [\bar{E}]\,[\bar{C}] + [\bar{G}]\,[\bar{r}]$$

$$[\bar{C}]^T = [\bar{F}_R \quad \bar{F}_L \quad \bar{F}_F \quad \bar{F}_B \quad \bar{V}_O]$$ internal vector

$$[\bar{r}]^T = [\bar{F}_{RI} \quad \bar{F}_{LI} \quad \bar{F}_{FI} \quad \bar{F}_{BI} \quad \bar{V}_I]$$ input vector

$$[\bar{d}]^T = [\bar{F}_{RO} \quad \bar{F}_{LO} \quad \bar{F}_{FO} \quad \bar{F}_{BO} \quad \bar{V}_O]$$ output vector

$$[\bar{d}] = \left[[\bar{E}] \cdot [I - \bar{A}]^{-1} \cdot [\bar{B}] + [\bar{G}]\right] \cdot [\bar{r}]$$

STRUCTURE MATRICES

Figure 28

$$[\bar{d}] = \begin{bmatrix} F_{Ro} \\ F_{Lo} \\ F_{Fo} \\ F_{Bo} \\ \nabla_o \end{bmatrix}$$ ....THE OUTPUT VECTOR

$[\bar{A}]$....THE SYSTEM INTERNAL MATRIX

$[\bar{B}]$....THE SYSTEM INPUT MATRIX

$$[\bar{d}] = \Big[[\bar{E}][I-\bar{A}][\bar{B}] + [\bar{G}]\Big] \cdot [\bar{r}]$$

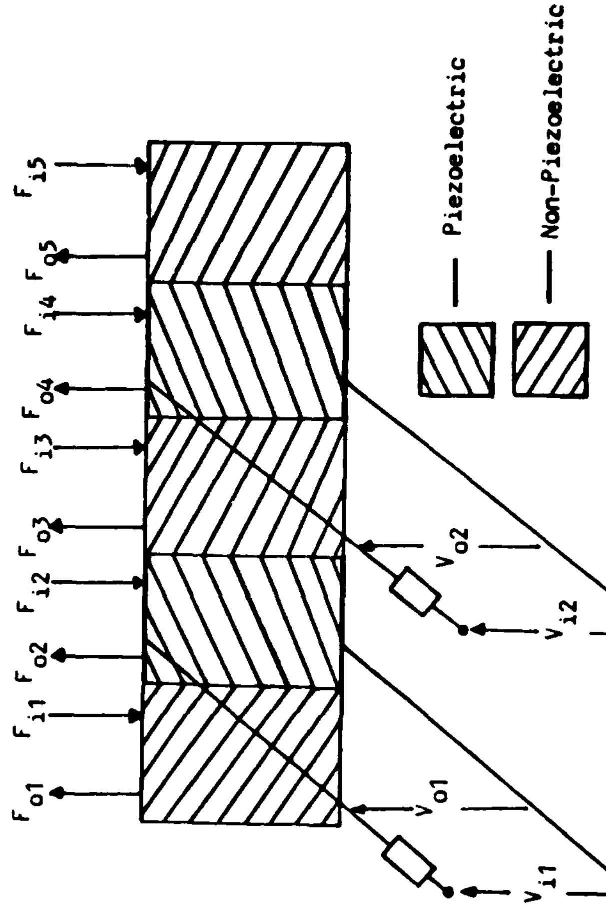
$$[\bar{r}] = \begin{bmatrix} F_{Ri} \\ F_{Li} \\ F_{Fi} \\ F_{Bi} \\ \nabla_i \end{bmatrix}$$ ....THE INPUT VECTOR

$[\bar{E}]$....THE SYSTEM INTERNAL OUTPUT MATRIX

$[\bar{G}]$....THE SYSTEM INPUT OUTPUT MATRIX

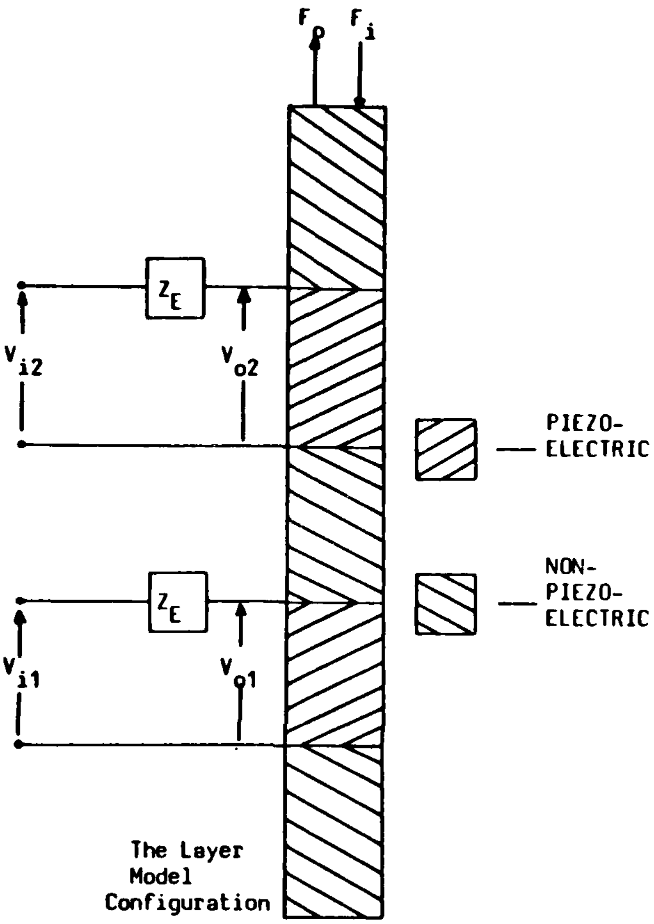
OVERALL DESCRIBING MATRIX

Figure 29



The Array Model Configuration

Figure 30

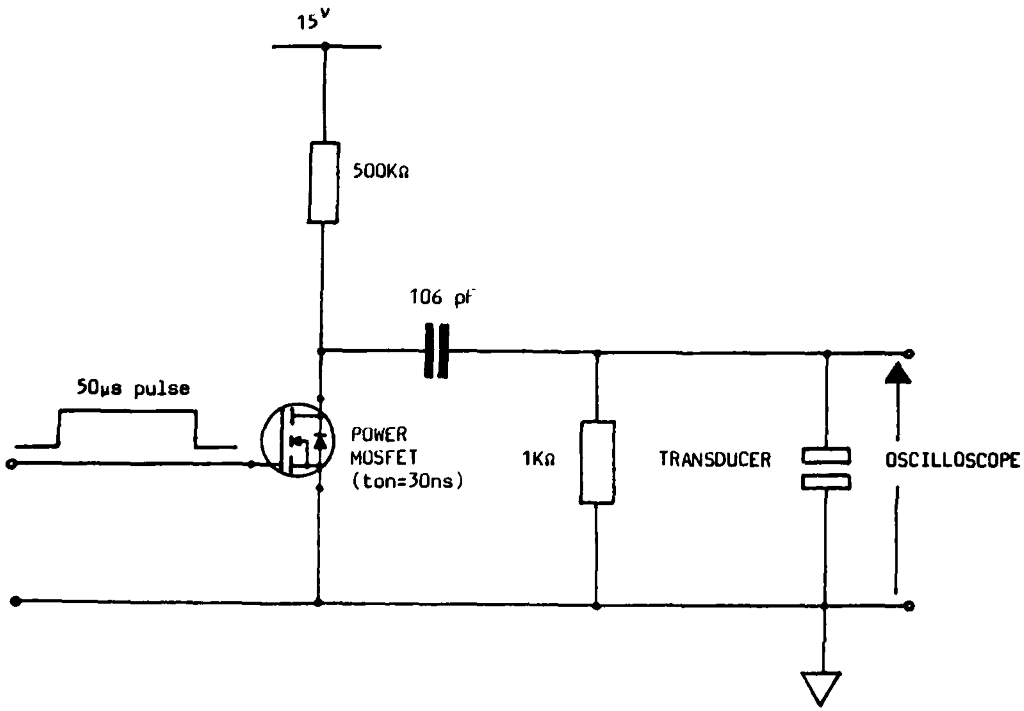


F_o
F_i
Z_E
V_{i2}
V_{o2}
Z_E
V_{i1}
V_{o1}
The Layer
Model
Configuration
PIEZO-
ELECTRIC
NON-
PIEZO-
ELECTRIC

Figure 31

put together to get some insight into the array itself. Now what I want to do is to go through some of the results we obtained using this model both for the transducer structures themselves, because we must understand that first, and laterally for actual elements housed in a complete phased-array.

Now in the initial set of results, I'm taking voltage measurements across the transducer, Figure 32. We use this as a calibration technique to test the model and also to get some information on the behavior of the device itself. Essentially what we do is charge a capacitor to some given voltage here and deposit that charge via a matching circuit which in this case is a kilo-ohm resistor, onto the transducer's electrode. We monitor the voltage at this point here in the system. So what I want to show you initially are some of the results I had by placing these tall thin element structures in a circuit like that, and we simulate the voltage we expect to get here, and measure it. I want to do a comparative assessment between the theoretical and practical results.



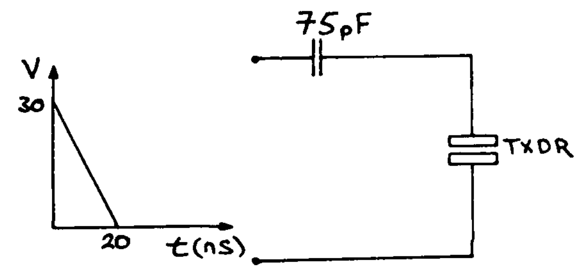
VOLTAGE MEASUREMENT ACROSS TRANSDUCER

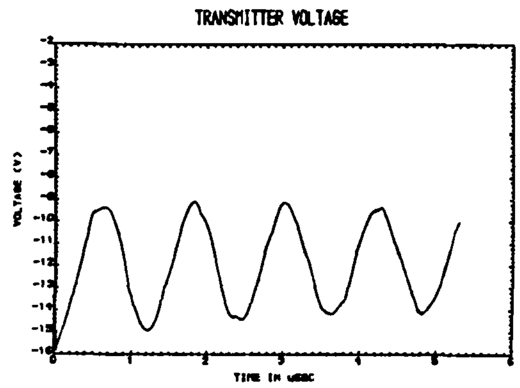
Figure 32

Now here you have a 75 pico-farad capacitor, the transducer here, and a 20 nanosecond MOSFET pulser, Figure 33. The dimensions of the transducer element are 1.9 mm x 0.86 mm x 20 mm, and this is the simulated response which we obtained from the model, the multi-dimensional model, and this is the measured response which we achieved on the oscilloscope. I think you can see that there is a fair degree of correlation between these two responses. Going on to another one, Figure 34, this time, same element, but changing the matching component of the resistor, putting a ten kilo-ohm resistor across the transducer. This is the theoretical voltage which we expect to measure and this, in fact, is the voltage which was obtained. So far so good. It does seem the array element model has, in fact, looked quite useful, has in fact, agreed fairly well.

This is a different array element, Figure 35, with a 20 micro-henry inductor in this case, and again the theoretical voltage response is given by the top trace here, and the measured response is given by the trace shown here, and certainly you can see quite clearly the dual frequency component in the particular system, and the model has in

SIMULATED AND OBSERVED TRANSMITTER VOLTAGE RESPONSE





CONFIGURATION PARAMETERS		
MATERIAL	:	PZT-5A
BACKING	:	AIR (all faces)
HEIGHT	:	1.9mm
WIDTH	:	0.86mm
LENGTH	:	20mm

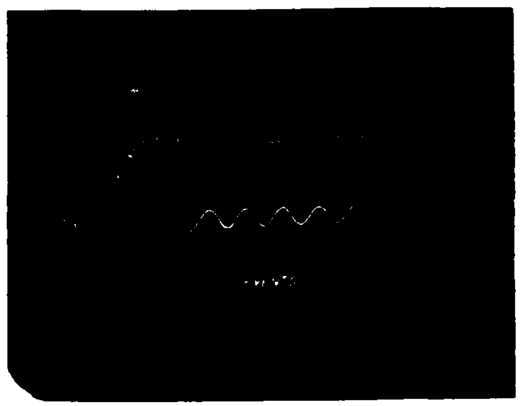
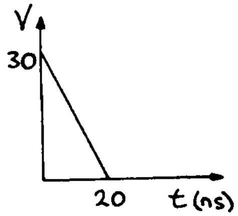
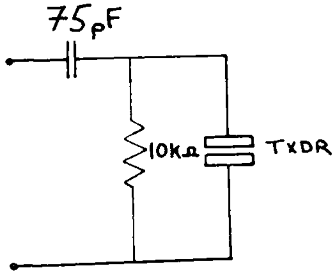
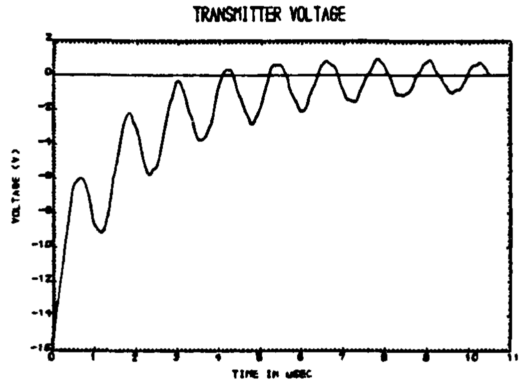


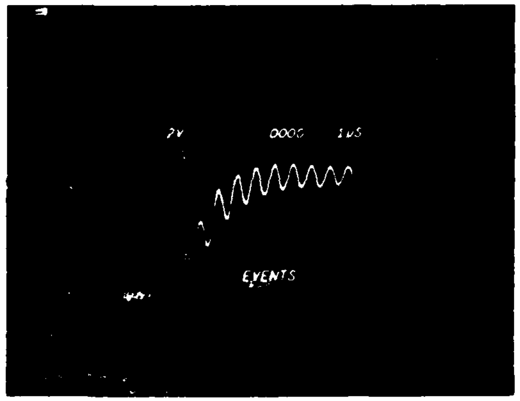
Figure 33

SIMULATED AND OBSERVED TRANSMITTER VOLTAGE RESPONSE





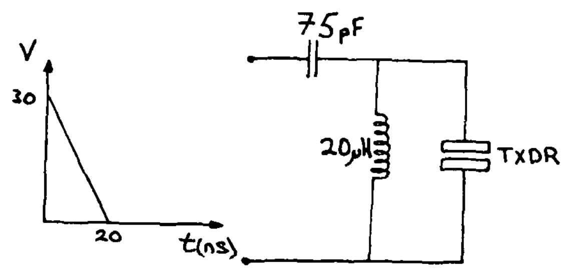


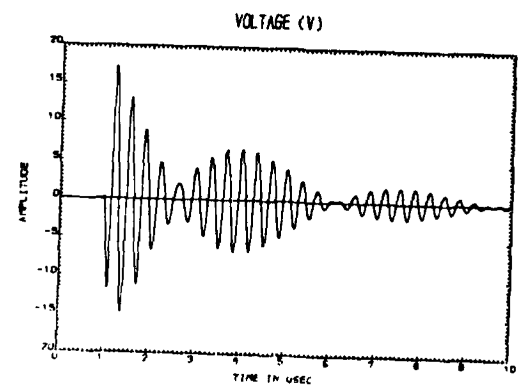


CONFIGURATION PARAMETERS		
MATERIAL	:	PZT-5A
BACKING	:	AIR (all faces)
HEIGHT	:	1.9mm
WIDTH	:	0.86mm
LENGTH	:	20mm

Figure 34

SIMULATED AND MEASURED TRANSMITTER VOLTAGE RESPONSE TO AN INDUCTIVELY TUNED FIRING CIRCUIT





CONFIGURATION PARAMETERS		
MATERIAL	:	PZT-5A
BACKING	:	AIR (all faces)
HEIGHT	:	1.9mm
WIDTH	:	0.86mm
LENGTH	:	20mm

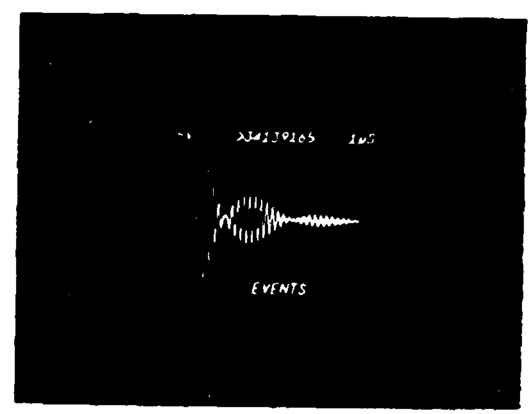
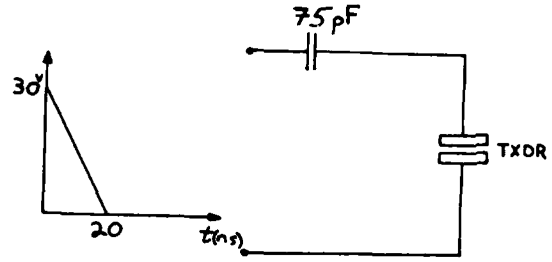
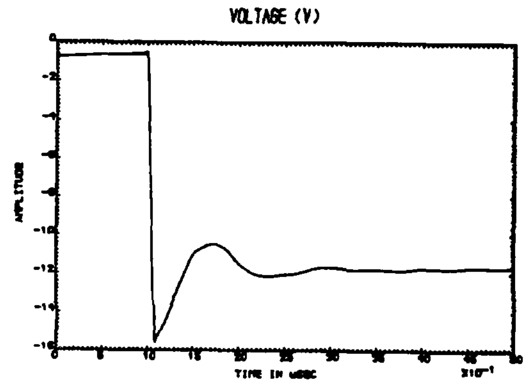


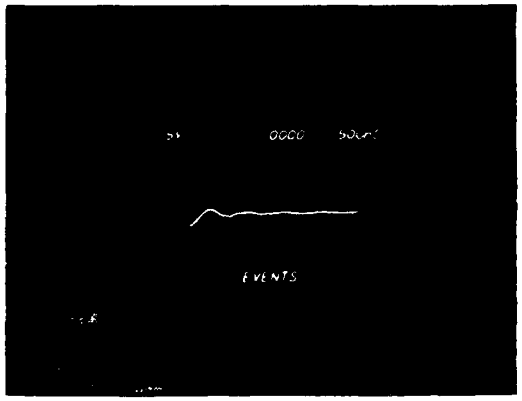
Figure 35

fact predicted these quite well. So what we did at that stage, after having developed the model and having performed several straightforward tests like this, we said, okay, it seems that we can characterize these array elements. It also seems possible that we can, in fact, simulate the behavior fairly accurately. So the next stage was to incorporate the elements in an array structure, and that means attaching layers to the front and back faces. It also means attaching some form of backing material to the elements. Now the first attempt for this was the voltage response with an element mounted on a lead backing block. Now the reason we used lead was that the acoustic properties of the lead are fairly quantifiable, and we've also modeled the lead backing block as a multi-dimensional system. So the parameters of the lead are known, and this bit here hasn't come out well, Figure 36, but it is, in fact, dropping down there and there is the rest of the response. So, in fact, we've got fairly good correlation when we mount one of these elements as it would be mounted in a practical system. Similar response, again using a lead backed element 10 kilo-ohm resistor across here, and this is the measured

SIMULATED AND OBSERVED TRANSMITTER VOLTAGE RESPONSE







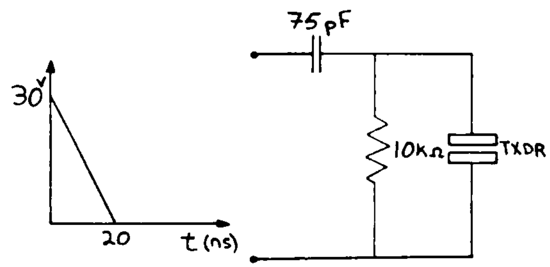
CONFIGURATION PARAMETERS		
MATERIAL	:	PZT-5A
BACKING	:	LEAD (rear face)
HEIGHT	:	1.9mm
WIDTH	:	0.86mm
LENGTH	:	20mm

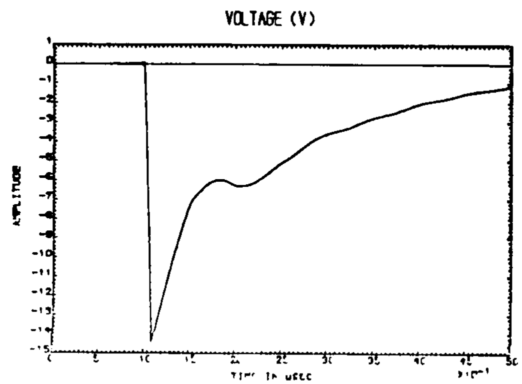
Figure 36

response, Figure 37, and this is the theoretical response that we get from a mounted element, and one of the difficulties, you have to understand, in mounting elements on the backing block, is that you can introduce extraneous resonances in the form of a mass-spring-mode where the element literally tries to tear itself off the backing mount, and you have to be careful that in the mounting procedure you did not incur resonances of this nature. In fact, we didn't see anything in these particular examples.

Now the next stage after this was to perform more meaningful impedance measurements on a variety of elements both contained in an array and also external to the array. On the left hand side, Figure 38, we have the theoretical amplitude and phase for an impedance measurement. So, we've got magnitude impedance, magnitude in this direction, frequency on this axis. On the right hand side we have the measured results. So for this particular element here it's quite interesting. What we have in this case is the mean thickness resonance of the transducer and here the lateral resonance coming in. Now, it's interesting to note here that the peak output of this device will occur at

SIMULATED AND OBSERVED TRANSMITTER VOLTAGE RESPONSE





CONFIGURATION PARAMETERS		
MATERIAL	:	PZT-5A
BACKING	:	LEAD (rear face)
HEIGHT	:	1.9mm
WIDTH	:	0.86mm
LENGTH	:	20mm

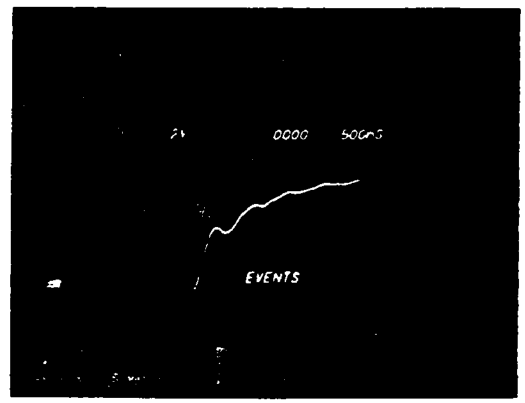


Figure 37

SIMULATED AND MEASURED OPERATIONAL IMPEDANCE SPECTRA

CONFIGURATION PARAMETERS		
MATERIAL	:	PZT-5A
BACKING	:	AIR (all faces)
HEIGHT	:	1.9mm
WIDTH	:	0.86mm
LENGTH	:	20mm

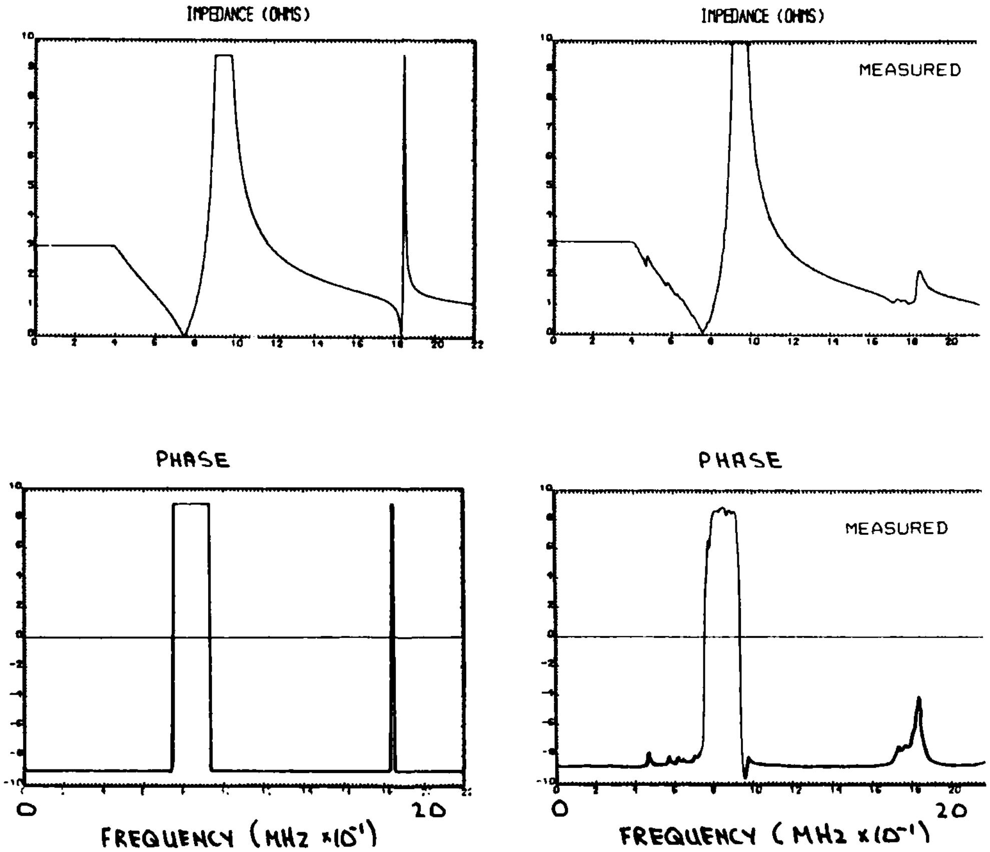


Figure 38

approximately seven-hundred and fifty kilo-hertz. This dip in the impedance characteristic is indicative of the point in the frequency spectrum at which the particular element will radiate most energy. Now the theoretical results again predicted seven-hundred and fifty kilo-hertz. But, this particular element was cut from a slab of ceramic with a fundamental resonance of one megahertz. So the fundamental resonance frequency of the device has dropped from one megahertz to seven-hundred and fifty kilo-hertz, as soon as it's cut into an element suitable for a phased-array. Now that's a very significant drop in that the main resonance frequency is the main criterion for determining the element spacing to avoid spatial aliasing and to minimize after-effect in the array structure.

This sort of result is important because it tells us right away that we should design an array, not for one megahertz operation, but for seven-hundred and fifty kilo-hertz. The phase results as well, are in fairly close agreement. Here's another element, Figure 39, slightly different dimensions, 1.96 mm high x 0.7 mm wide. The theoretical response here and the measured response here,

SIMULATED AND MEASURED OPERATIONAL IMPEDANCE SPECTRA

CONFIGURATION PARAMETERS		
MATERIAL	:	PZT-5A
BACKING	:	OIL (all faces)
HEIGHT	:	1.96mm
WIDTH	:	0.70mm
LENGTH	:	50mm

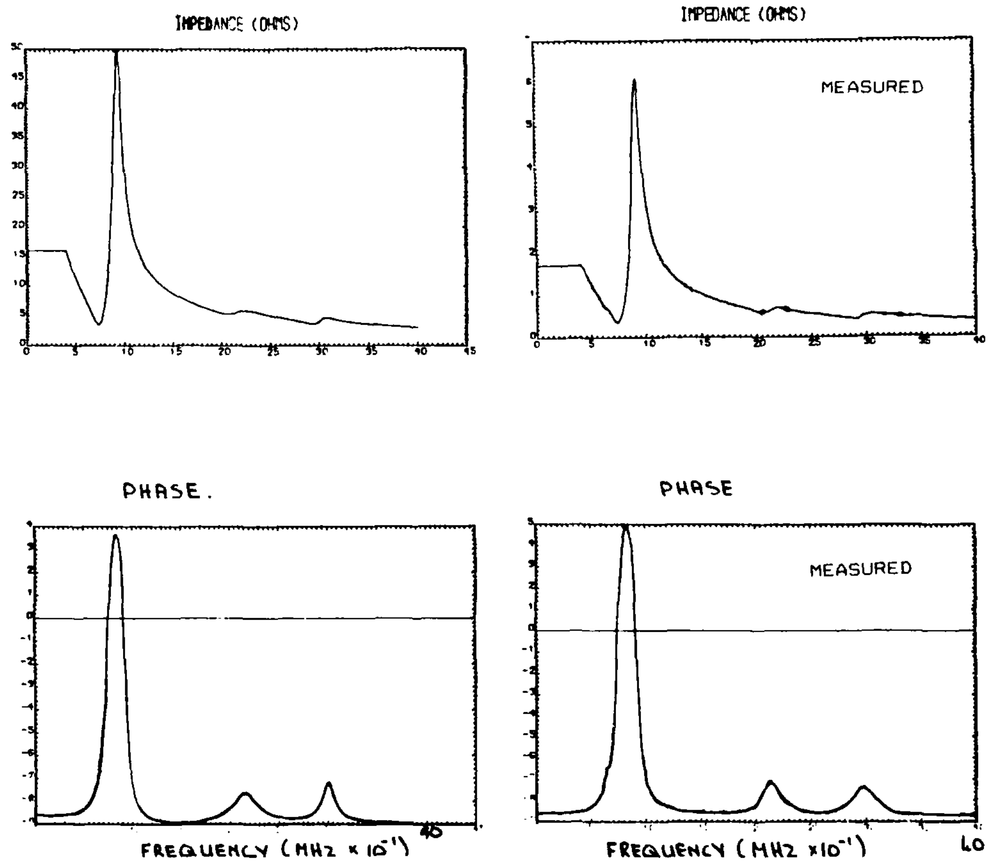


Figure 39

and what we have here is the electrical resonance again dropping down to about seven-hundred kilo-hertz. It's very close in this position.

This is an overtone resonance, Figure 40, of this one, a sub-harmonic, and here we have the lateral mode, the width mode showing in here. So from these again, this only verifies the model, but you get quite a considerable insight into how such an element is going to behave. This is the same device operating in oil. To place the device in an oil-bath--sorry, this is a different configuration, 1.96 x .45 mm wide radiating into oil. Again cut from a one megahertz slab. You see once more that the main resonance has fallen down to about seven-hundred kilo-hertz. Again in the theoretical prediction, and in fact, we do have an overtone on thickness mode resonance and we can just see in here the lateral resonance occurring at that point there, and in fact, that lateral resonance is a bit clearer on the phase characteristic, and you see it has picked up as well in the theoretical result. So, after literally having gone through hundreds of these tests to verify the model, the

SIMULATED AND MEASURED OPERATIONAL IMPEDANCE SPECTRA

CONFIGURATION PARAMETERS		
MATERIAL	:	PZT-5A
BACKING	:	OIL (all faces)
HEIGHT	:	1.96mm
WIDTH	:	0.45mm
LENGTH	:	50mm

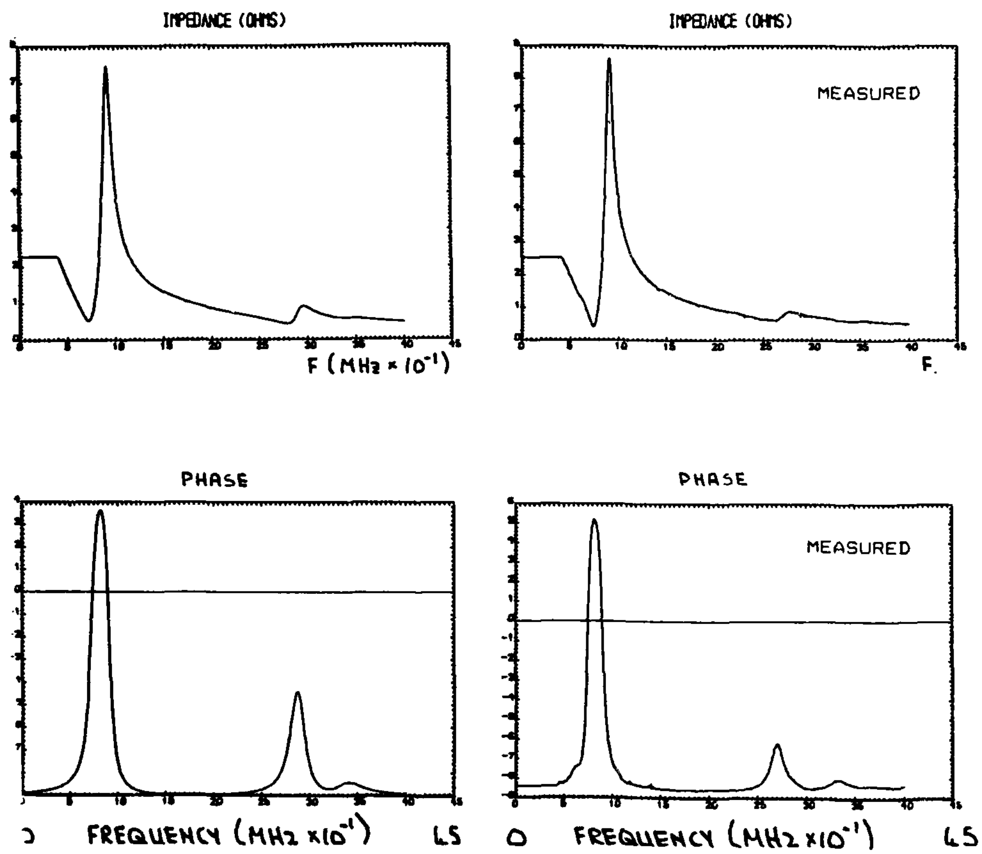


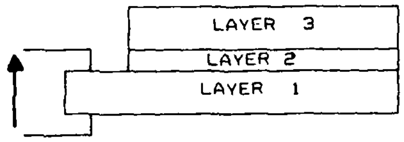
Figure 40

next stage is to use the model to design practical array configurations.

Here's a multi-layered response, Figure 41, in which we have the piezoelectric element, a bond line, and in this case a steel layer on the front face. This is cut from a one megahertz element. Addition of the steel layer reduces the main output to 500 kilo-hertz. So it's actually half. Similarly here, 500 kilo-hertz, and we get quite good agreement in other parts of the structure as well. Here we have lateral modes, here we have overtones of the thickness modes. Another multi-layered structure, Figure 42, changing the configuration occurring here, another very strong resonance occurring in here, and this is indicative of how careful one has to be in designing structures like this. The output of this is by no means a nice single-frequency output. There are 1-2-3 at least 4 main vibrational frequencies occurring in this system, useless using a probe structure like that for non-destructive evaluation, or any other interrogation. So the main thing is that we can, in fact, predict these when we want to design a layered system and to remove aspects like this. So the next stage in the

SIMULATED AND MEASURED OPERATIONAL IMPEDANCE SPECTRA FOR A THREE-LAYERED STRUCTURE IN THE THICKNESS DIRECTION

CONFIGURATION PARAMETERS		
LAYER 1		
MATERIAL	:	PZT-5A
HEIGHT	:	1.96mm
WIDTH	:	0.60mm
LENGTH	:	20mm
LAYER 2		
MATERIAL	:	EPOXY
HEIGHT	:	20µm
WIDTH	:	0.86mm
LENGTH	:	20mm
LAYER 3		
MATERIAL	:	STEEL
HEIGHT	:	0.80mm
WIDTH	:	0.60mm
LENGTH	:	30mm
BACKING	:	OIL (all faces)



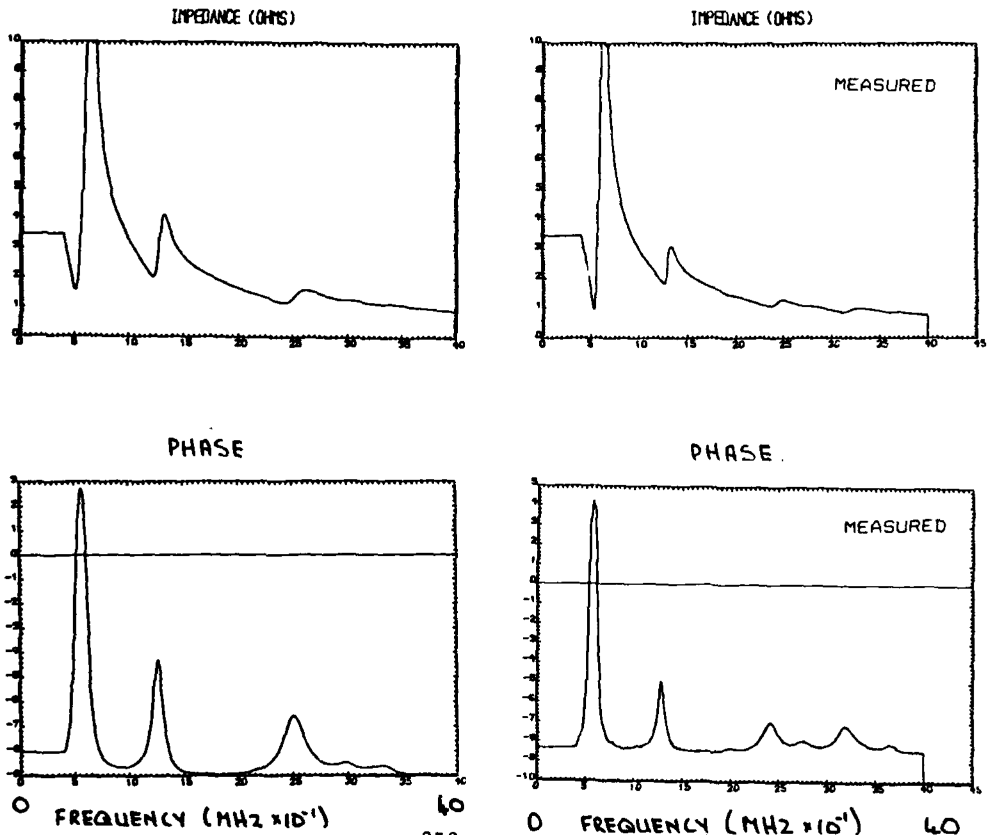
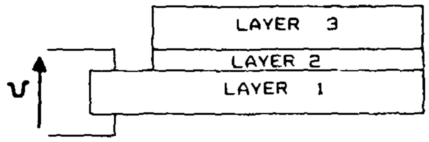


Figure 41

SIMULATED AND MEASURED OPERATIONAL IMPEDANCE SPECTRA FOR A THREE-LAYERED STRUCTURE IN THE THICKNESS DIRECTION

CONFIGURATION PARAMETERS		
LAYER 1		
MATERIAL	:	PZT-5A
HEIGHT	:	0.95mm
WIDTH	:	0.69mm
LENGTH	:	12mm
LAYER 2		
MATERIAL	:	EPOXY
HEIGHT	:	60μm
WIDTH	:	0.69mm
LENGTH	:	12mm
LAYER 3		
MATERIAL	:	PZT-5A
HEIGHT	:	1.54mm
WIDTH	:	0.69mm
LENGTH	:	10mm
BACKING	:	OIL (all faces)



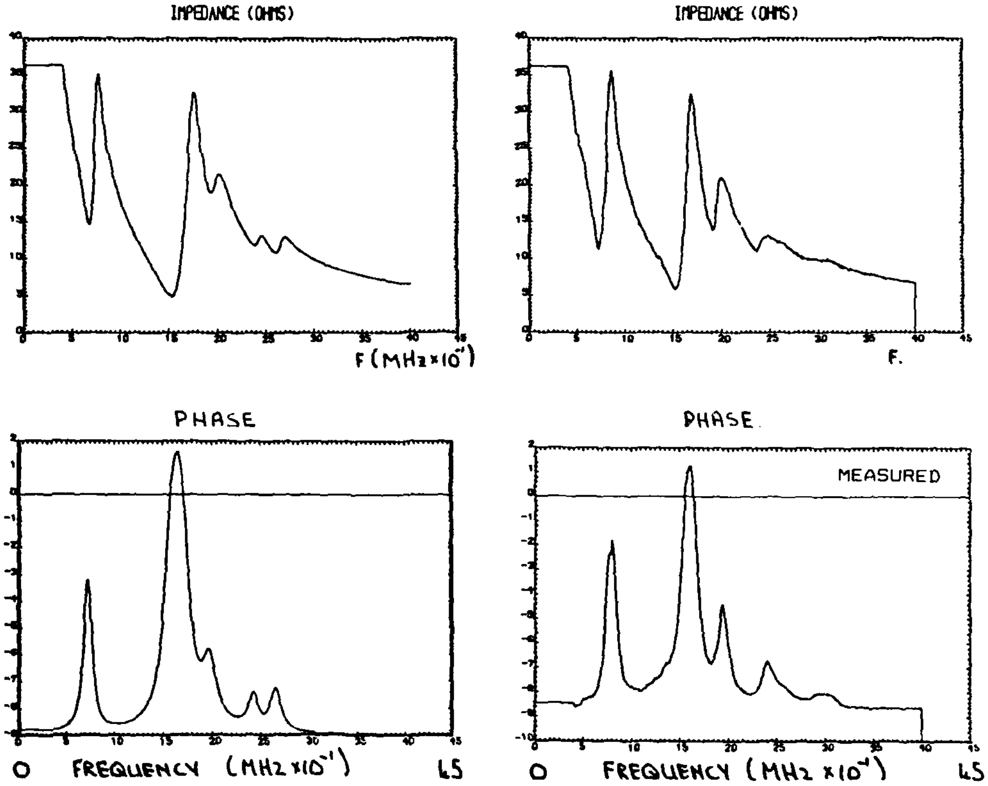


Figure 42

development was to say, okay, we can measure the impedances, they agree quite well, but it's not really impedance we're interested in. It's how the devices perform when they're radiating into the real world. So, here we have an element, Figure 43, an isolated element, in this case, radiating directly into water. This is the simulated response which we expect to get. That was the measured response, (Sorry, I've got these running the wrong way.) That was the simulated response, that was the measured response, and these are the frequency components associated with these kinds of data.

So that's the output spectrum, again theoretically and practically. Now you'll notice that there's not a great deal of difference in the actual spectrum. In fact, we haven't managed quite to pick out this higher frequency component here, and that has manifested itself in these components here being absent from the data in this position. Now the reason, I feel in this case, that we're not getting extremely close correlation is the method which we used to measure the output pressure profile. What we did was to place the element in a water tank and position a wideband

SIMULATED AND MEASURED FORCE OUTPUT FROM AN ISOLATED
TALL, THIN TRANSDUCER OPERATING INTO WATER

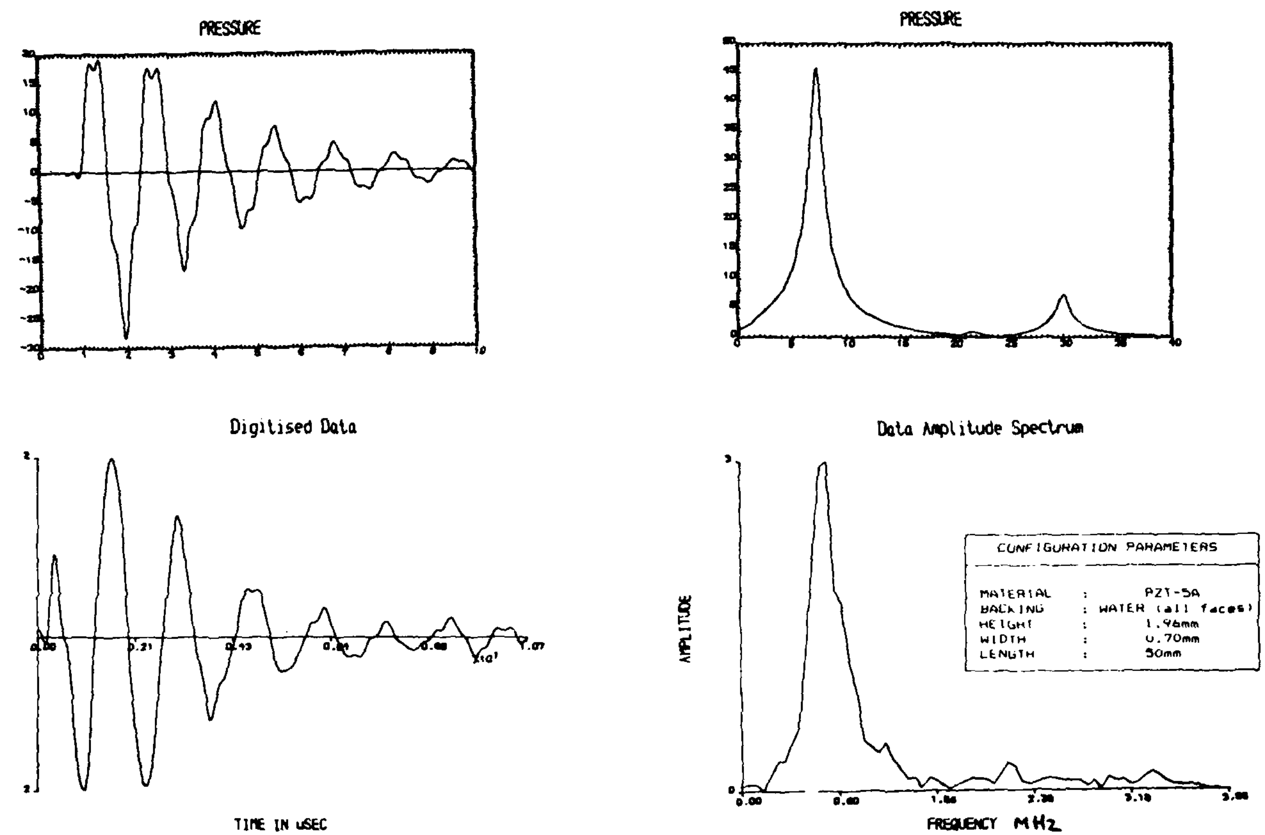


Figure 43

membrane hydrophone in front of the element, Figure 43, and I think that these artifacts were being introduced as a result of the behavior of the hydrophone not being truly omni-directional. A thin element like this has reasonably omni-directional response. I don't think the hydrophone was, in fact, picking up all of the components in the system. But we proceeded to take the pulse-echo response of this device, and here, Figure 44, are the simulated and practical results in the time and frequency domain of such an array element radiating into the water medium. So these are, in fact, quite close. We're very happy with responses like that if we can predict the behavior of the device to this accuracy. Then it should indicate that, in fact, we can design arrays on the model data as a basis.

Now here, Figure 45, we have the measured force response of an element mounted in an array and we include all the coupling mechanisms which I described earlier in the simulation. So this is the measured response which we obtained here. Sorry, this is the simulated response which is shown in top in the time domain and in the frequency domain, and this is the measured response we obtained from a

SIMULATED AND MEASURED FORCE OUTPUT FROM AN ISOLATED TALL, THIN TRANSDUCER OPERATING INTO WATER

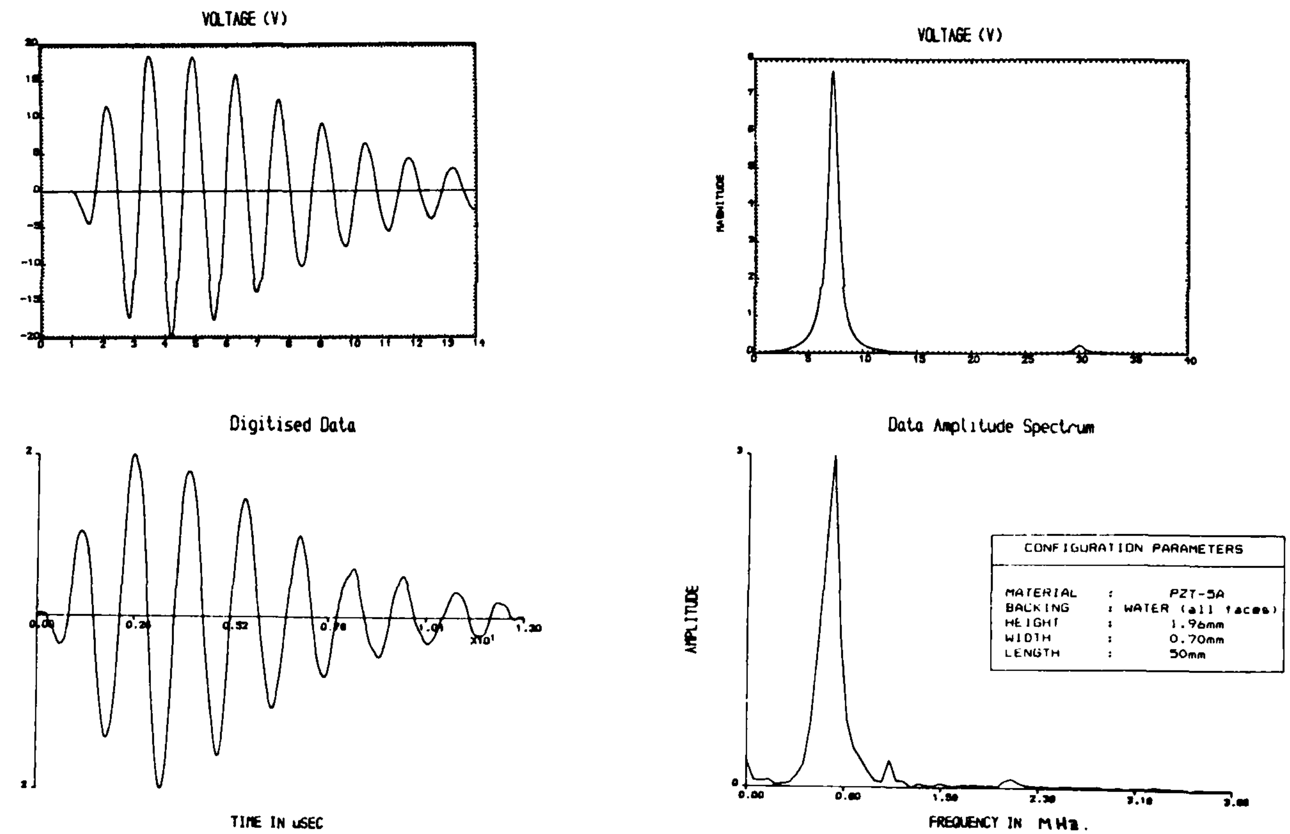


Figure 44

SIMULATED AND MEASURED FORCE OUTPUT FOR A MOUNTED ARRAY TRANSDUCER, OPERATING INTO WATER VIA A FRONT FACE LAYER

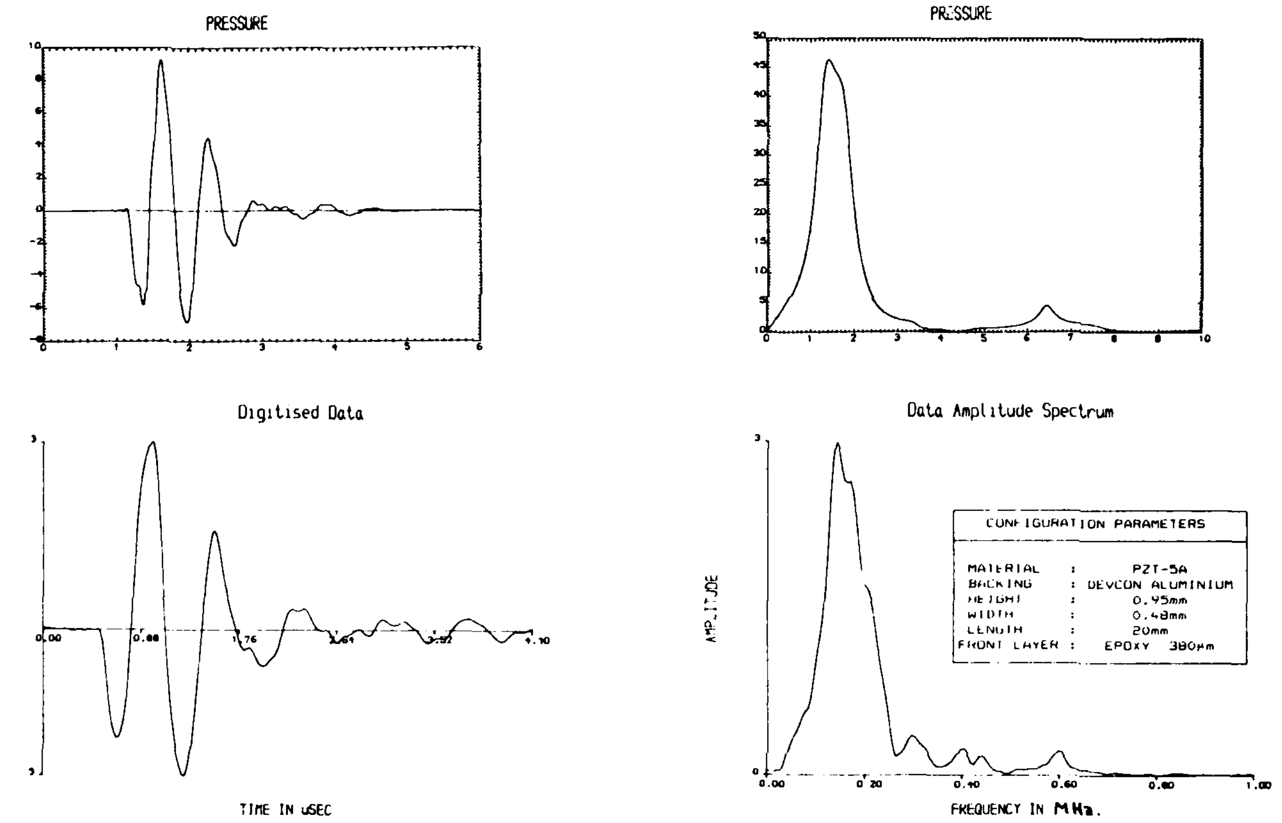


Figure 45

hydrophone in the time domain, and in the frequency domain. Now these are fairly close. This one tends to ring on for a little bit longer, and I believe this is because we did not take into account the full properties of the front face matching layer in the simulation. But they are, in fact, reasonably close. If I proceed to the transmit-receive response, or the pulse-echo response of the same array element operating into water via the front face layer, this is the simulated response, Figure 46, time domain, simulated response, frequency domain, and this is the measured frequency response. And this is the measured time domain response, and certainly this pit in here is a bit larger in amplitude than the trailing part here, but the main components are, in fact, preserved quite well, and this is a practical array radiating into a liquid medium.

So, to summarize, actually, where we've got in the modeling world--what we've done here--is to develop a multi-dimensional model, in this case mostly based on a 2- or 3-dimensional approximation of mechanical wave behavior in an array structure. To develop from this a model, which would give us physical insight into the behavior of such an array

SIMULATED AND MEASURED PULSE ECHO RESPONSE FOR A MOUNTED ARRAY TRANSDUCER, OPERATING INTO WATER VIA A FRONT FACE LAYER

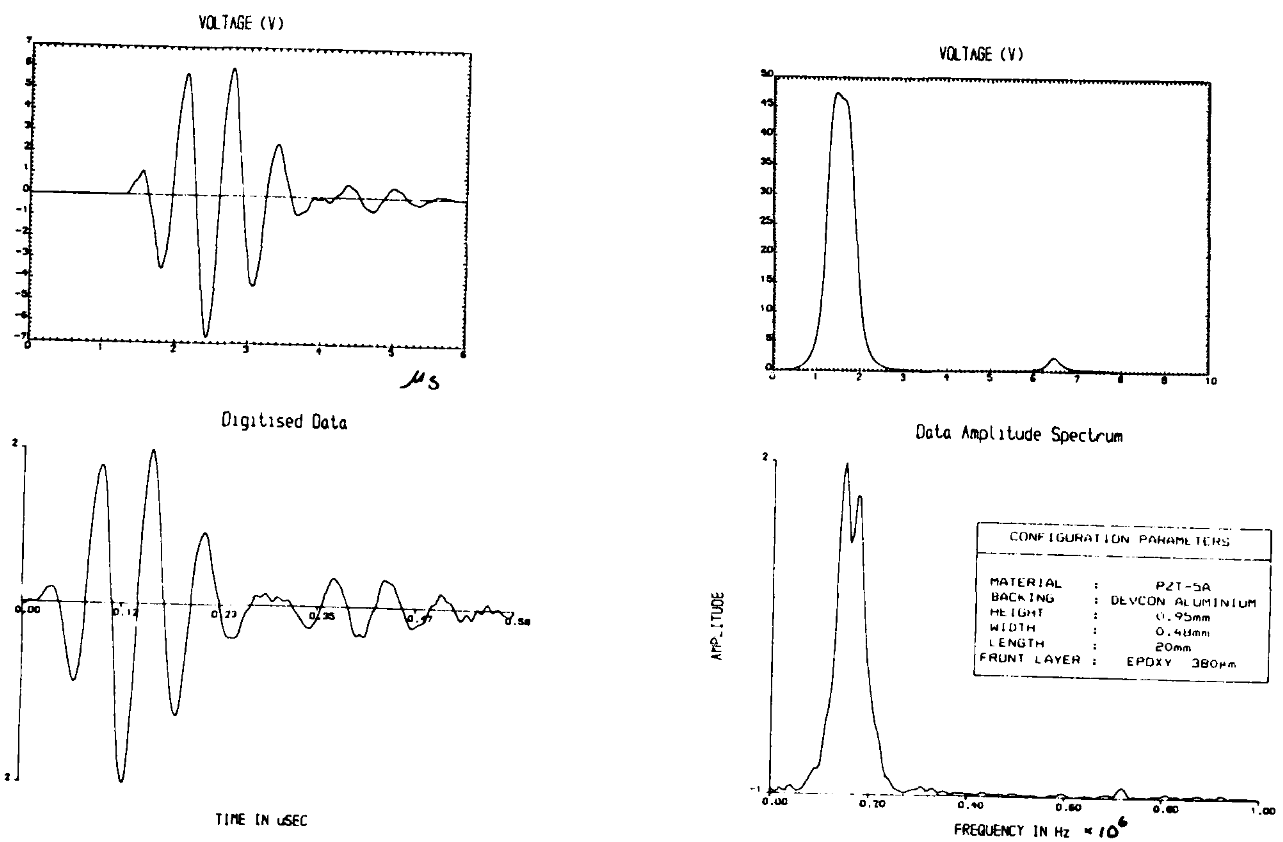


Figure 46

element, to understand the main factors pertaining to it's operation, and to design array systems according to the predicted results from a theoretical basis, so that we can, in fact, construct arrays for beam steering and beam switching using the model data.

I would like to add that so far we have published none of this work, so I don't have any copies of papers to hand out, but we have submitted it for publication, and it should be appearing in the scientific press in due course.

So thank you for your attention.

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THE UNITED STATES NAVY - NATIONAL ACADEMY OF SCIENCES CONNECTION

by

Lee M. Hunt*

The connection between the United States Navy and the National Academy of Sciences is now 123 years old. Over that long history the strength of the connection has, of course waxed and waned, but it has never been broken. Today it is stronger than ever.

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*Mr. Hunt did undergraduate work in geology and chemistry at George Washington and American Universities and his graduate work in oceanography at Texas A & M University. Early in his career he founded and was president of Southern Iron Corporation and Glennjack Mining Co. In 1960 he joined the staff of the National Academy of Sciences and served as Executive Secretary of the Mine Advisory Committee and the Committee on Undersea Warfare. Since 1974 he has been Executive Director of the Naval Studies Board. He is the author of two books on Oceanography and has been instrumental in launching National Academy of Sciences investigations into the questions of nuclear winter, inertial confinement fusion and the role of comet and asteroid impacts in earth history.

The duration and the continuity of that connection stand in testimony to the Navy's enlightened approach to the support of science, and to the American scientific community's continuing willingness to contribute time and talent, at no financial compensation, to an ever improving naval capability.

The Naval Academy and its faculty are the repository of all that is useful to know about the Navy's past, present, and -- to the degree that it is knowable -- its future. However, I would be very surprised -- albeit very gratified -- if you have an equal understanding of the National Academy of Sciences. Therefore, I would like to spend the first few minutes giving you a thumbnail sketch of the National Academy of Sciences -- its origin, its mission, the major evolutionary highlights, and the present organizational structure. Then I would like to take a quick trip through 123 years of Academy-Navy cooperative effort. And, finally, I would like to spend the remainder of the time discussing the results of a few recent efforts by the Naval Studies Board. So, let's begin with the origin of the National Academy of Sciences.

Late on the last day of business for the Thirty-Seventh Congress -- March 3, 1863 -- Senator Henry Wilson, Republican of Massachusetts, rose to the floor to introduce a bill calling for the establishment of a National Academy of Sciences. With the reading of but two short paragraphs, Senator Wilson called for an institution which would:

"....whenever called upon by any department of government, investigate, examine, experiment, and report upon any subject of science or art, the actual expense of such investigations, examinations, experiments, and reports to be paid from appropriations which may be made for the purpose, but the Acadmey shall receive no compensation whatever for any service to the government of the United States."

The Bill was passed by voice vote in the Senate, passed without comment in the House several hours later, and was signed into law before midnight by President Abraham Lincoln.

I don't know whether the speedy passage of the Academy Bill was due to the usual rush before adjournment, to the crisis atmosphere created by the Civil War, or to a particular enlightenment on the part of that Congress. Before passing judgement, however, we should recall that the Thirty-Seventh Congress -- which operated from July 4, 1861 to March 3, 1863 -- also passed into law:

1. The Emancipation Act abolishing slavery first in the District of Columbia, and then in the Territories

2. The establishment of the Department of Agriculture

3. The Homestead Act, opening the public domain in the west to all who would settle there

4. The National Banking Act, authorizing a truly national currency

5. The Pacific Railroad Act, authorizing construction of a railroad to connect the Atlantic and Pacific coasts

6. And, the Morrill Land Grant Act, providing for the establishment of agricultural colleges in the states and territories, including the Massachusetts Institute of Technology

It is difficult to imagine an alternative set of legislation that could have more profoundly influenced the moral, economic, and intellectual growth of the United States over the past century and a quarter.

Behind the passage of the Academy Bill, of course, there were years of work by six dedicated scientists whose vision reached well beyond the immediate requirements of the Civil War. They were:

1. Rear Admiral Charles H. Davis
2. Louis Agassiz
3. Alexander Dallas Bache
4. Joseph Henry
5. Benjamin Pierce
6. Augustus A. Gould

The Charles H. Davis Lecture Series -- operated by the Naval Studies Board and the Office of Naval Research, and presented twice annually to the students and faculty of the Naval Postgraduate School and the Naval War College -- was named in honor of Admiral Davis' contribution to the establishment of the Academy.

The new Academy can best be described as a private, non-profit, membership organization whose response to government requests for technical advice was carried out by select members without compensation. Election to membership, then as now, was considered the highlight of a scientific career reserved only to the best in their field.

By the time of World War I, with its increased demands on the scientific community, it was recognized that the Academy's strict membership requirements did not afford sufficient manpower to respond to emergency demands. As a result, President Woodrow Wilson authorized the establishment of the National Research Council (NRC) in 1916. The NRC quickly became the working arm of the Academy. Its strength lay in the fact that it allowed the Academy to maintain its strict membership requirements, and to draw on qualified non-members to meet demands which exceeded the ability of members to respond.

Under this arrangement it was inevitable that the engineers and the members of the medical profession would come to feel that they were not properly recognized under the title National Academy of Sciences. Therefore, in 1964, the Governing Board of the Academy authorized the establishment of a National Academy of Engineering and an Institute of Medicine. The National Academy of Sciences remains the corporate body, and the National Research Council serves as the working arm for all three.

The present organizational structure of the institution is shown in Figure 1. The bottom tier, made up of commissions, offices, and boards, houses the standing and ad hoc advisory groups responding to one or another government agency. The Naval Studies Board resides under the Commission on Physical Sciences, Mathematics, and Resources.

As shown in Figure 2, the current membership of the NAS is 1,584; NAE, 1,376; and IOM, 708; for a total of 3,668. The permanent staff totals 987, with 528 professionals and 459 support. This year there are 9,500 scientists and engineers contributing their services to some 979 committees requested by various government agencies.

The headquarters building for the National Academy of Sciences, shown in Figure 3, is located at 2101 Constitution Avenue. The building was constructed in 1928, with one wing and a 675-seat auditorium added in the

Figure 1. National Research Council Organization

MEMBERSHIP, STAFF, COMMITTEE MEMBERS

MEMBERS

NAS	NAE	IOM	TOTAL
1584	1376	708	3668

STAFF

PROFESSIONAL	SUPPORT	TOTAL
528	459	987

COMMITTEE MEMBERS

COMMITTEES	TOTAL MEMBERS
979	9,500

Figure 2. Current Membership

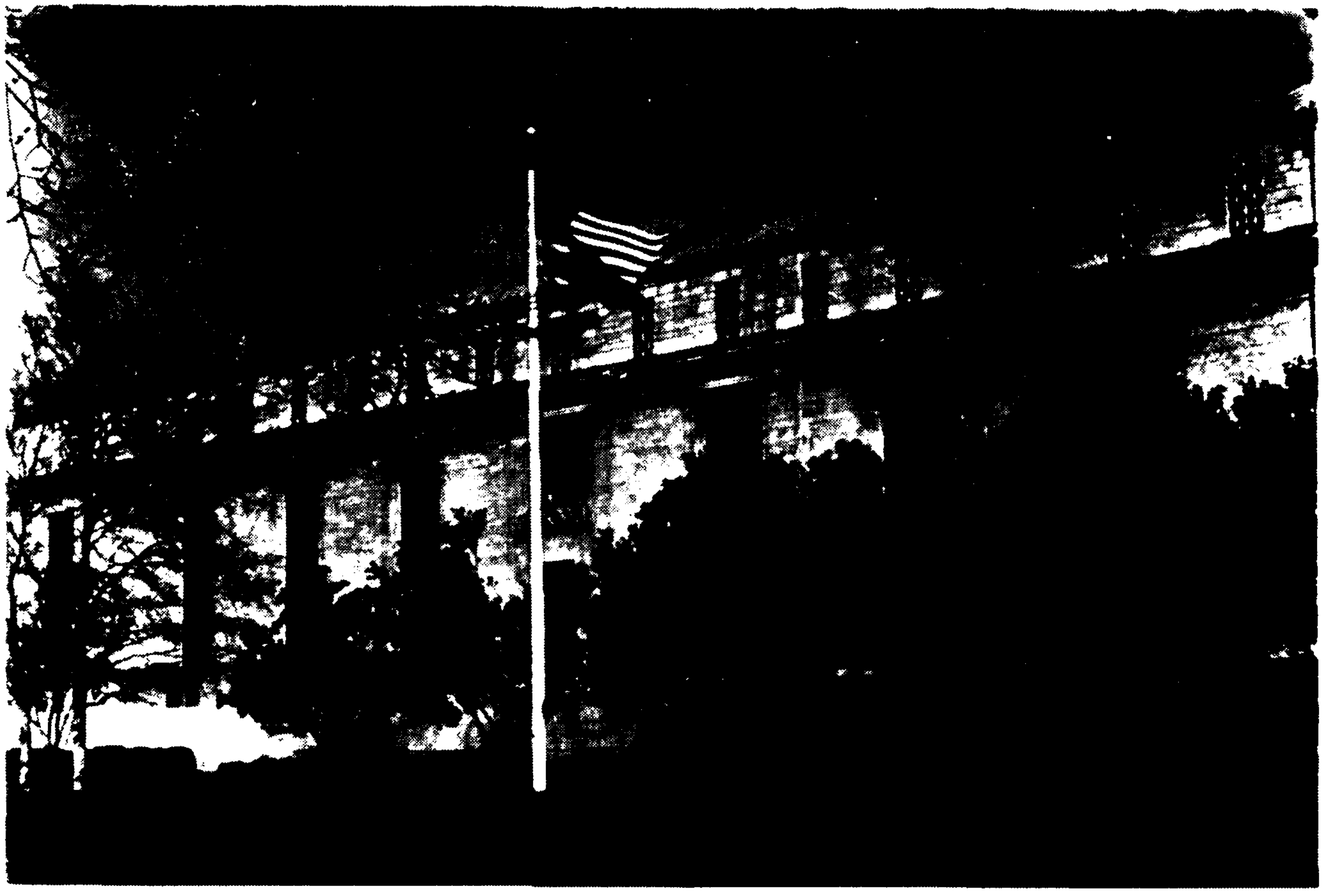

Figure 3. Headquarters Building of the National Academy of Sciences

late 1960s. Prior to 1928 the NAS was housed in the Smithsonian Museum. Not shown is the Joseph Henry Building at 21st Street and Pennsylvania Avenue where most of the NRC committees are housed. This building is leased from the George Washington University.

In 1956, the Academy inaugurated the so-called summer study; in other words, a study mechanism designed to move study teams away from the distractions of the large cities, and to an environment conducive to concentration and creativity. Woods Hole, Massachusetts was selected as the site because it offered a quiet, relaxed community and it was close to the Ivy League universities. The Study Center, leased for years and later purchased, is shown in Figure 4. Over the years, of course, the center of gravity for university excellence has shifted west and slightly south. In recognition of this the Academy -- using a grant from the Beckman Foundation -- is now building a Study Center on the West Coast. Figure 5 shows the architect's model of the Beckman Center, which will be located on the edge of the

Figure 4. Woods Hole Study Center

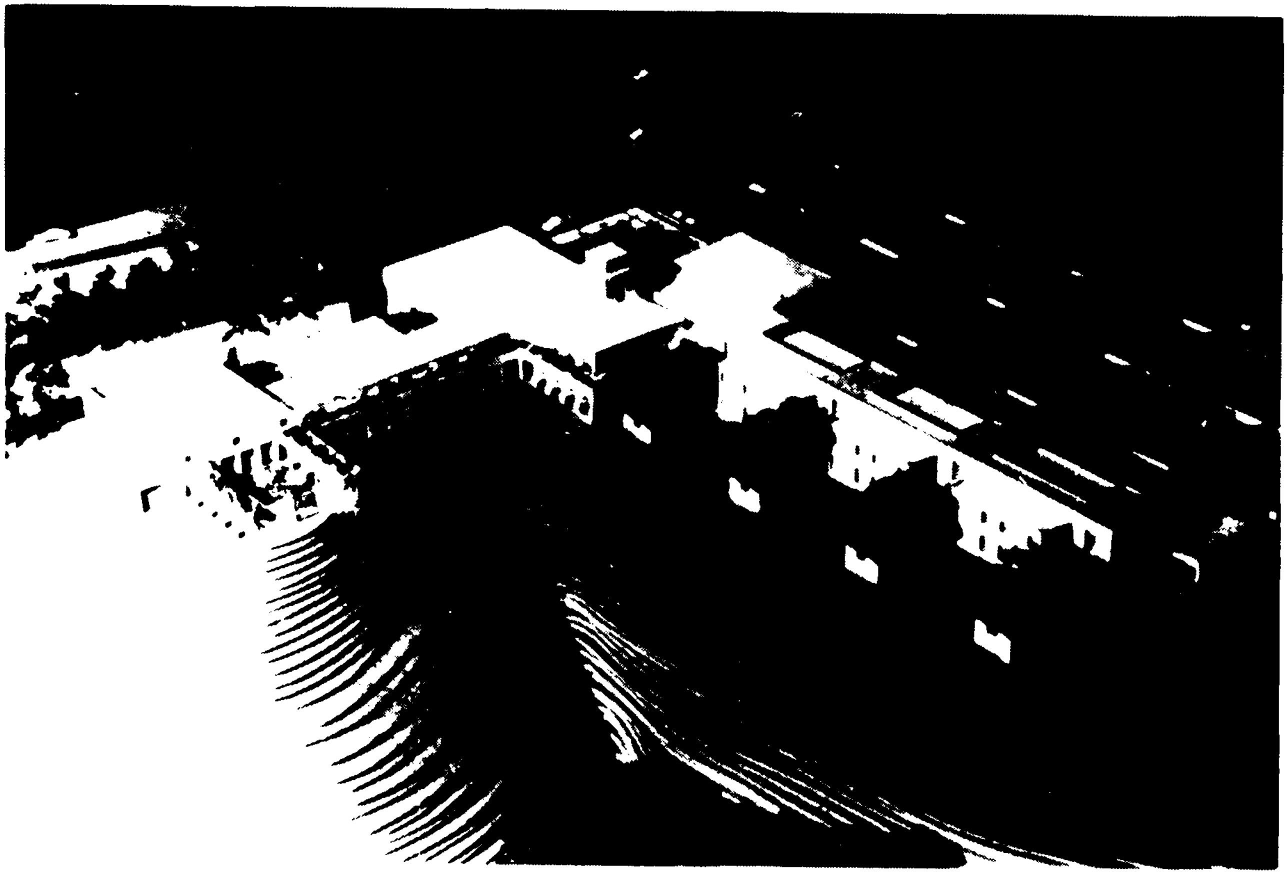

Figure 5. Model of the Beckman Center

Irvine Campus of the University of California. Completion is expected in October 1987.

Now let me drop back to year one and give you a quick summary of the Academy-Navy connection between 1863 and the present. Figure 6 shows the major studies done for the Navy between the years 1863 and 1885. During the period 1886 to 1916 the dialogue and the cooperation between the Academy and the Navy continued, but there were no major studies. I point this out because I want to refer to it again later, and because it demonstrates that all-too-human condition that I call the Tommy Syndrome. You will recall Rudyard Kipling's poem "Tommy" in which he so poignantly captured the peacetime plight of the military:

"For it's Tommy this, and Tommy that, and Tommy how's your soul?
But it's 'thin red line of 'eroes' when the drums begin to roll."

In other words, during periods of prolonged peace the civilians become preoccupied with trying to achieve the good life; the scientists return to the comfort of their ivory towers; and the military turns to another kind

USN-NAS COOPERATION - 1863 - 1946

<u>1863 - 1885</u>

ON MAGNETIC DEVIATION IN IRON SHIPS

ON PROTECTING THE BOTTOMS OF IRON VESSELS

ON WIND AND CURRENT CHARTS AND SAILING DIRECTIONS

ON THE EXPLOSION OF THE U.S. STEAMER CHENANGO

ON EXPERIMENTS ON THE EXPANSION OF STEAM

ON PROPOSED CHANGES IN THE AMERICAN EPHEMERIS

ON THE TRANSIT OF VENUS

ON THE ASTRONOMICAL DAY, THE SOLAR ECLIPSE OF 1886, AND THE ERECTION OF A NEW NAVAL OBSERVATORY

Figure 6. Major Studies

of war -- the Battle for Survival.

The result, of course, is a frantic game of catch-up-ball when the next emergency arises, as shown in Figure 7: literally an explosion of technical activity.

Then, in the 1919-1929 period the Tommy Syndrome sets in once again. We had won "the war to end all wars," the stock market was booming, and "happy days [were] here again."

In the period 1930-1941, as shown in Figure 8, you can sense the national preoccupation with the Great Depression which distracted us from the increasing alarm in the voices of those who saw war clouds gathering on both the eastern and western horizons. You can almost feel the struggle of those few who saw the technological advances in Germany and Japan, and tried to force our system into high gear -- without much success.

The 1941-1945 period, of course, saw a level of participation by the American scientific community which far surpassed anything in our past. The Academy became a part of the triad composed of the Office of Scientific Research

USN-NAS COOPERATION - 1863 - 1946 (CONTINUED)

1916 - 1918

SUBMARINE WARFARE

SEARCH LIGHT FOR SUBMARINE DETECTION; SUBMARINE DETECTION; SUBMARINE VISIBILITY; PERISCOPES; SUBMARINE CHASERS

AIR WARFARE

LOCATION OF INVISIBLE AIRCRAFT; PREVENTION OF STATIC CHARGES ON AIRSHIPS; HELIUM PRODUCTION

SURFACE WARFARE

NAUTICAL INSTRUMENTS; OPTICAL INSTRUMENTS; GUN MANUFACTURE; NAVY RANGE FINDER; SOUND RANGING; BINOCULARS VERSUS MONOCULARS; CONCEALMENT OF SHIPS WITH WATER SPRAY; STANDARDIZATION OF BATTLESHIP GREY PAINT;

OTHER

EXPLOSIVES; GAS IN WARFARE; NOXIOUS GASES; CARTRIDGE PRIMERS; PSYCHOLOGICAL EXAMINATION OF RECRUITS; VISUAL PROBLEMS

Figure 7. Major Studies Continued

1930-1941

1930	ON DIFFERENT METHODS OF LONG-RANGE WEATHER FORECASTING AND THE SCIENTIFIC BASES FOR THESE METHODS
1934-1936	COMMITTEE ON NAVAL RESEARCH
1934-1935	COMMITTEE ON WAR AND NAVY DEPARTMENTS
1935	ON IMPROVING MEANS FOR SIGNALING FOR SAFETY AT SEA
1936	SHIP STABILIZATION
1936-1939	COMMITTEE ON RELATIONSHIPS WITH WAR & NAVY DEPARTMENTS
1935-1940	ON THE DESIGN AND CONSTRUCTION OF AIRSHIP
1938	INTERNAL COMBUSTION ENGINES
1939	COMMITTEE ON AIRPLANE INSTRUMENT LANDING EQUIPMENT
1939	COMMITTEE ADVISORY TO NAVAL BUREAU OF ENGINEERING
1939-1940	ON PROBLEMS IN METALS AND LAMINATED GLASS
1939-1940	ON MARINE AND RADIO ENGINEERING PROBLEMS
1939-1940	ON THE POSSIBILITIES OF NEW AND RADICAL MEANS FOR MARINE PROPULSION
1940-1941	REPORT OF THE SUBCOMMITTEE ON THE SUBMARINE PROBLEM

Figure 8. 1930-1941 Studies

and Development under Vannevar Bush, the National Defense Research Committee under James Conant, and the National Academy of Sciences under Frank Jewett. OSRD provided the policy, organization, and top-level management; NDRC carried out the R&D through a vast network of university and industrial laboratories, and the Academy located and supplied the trained scientists and engineers. It was, as Jewett said, "the most powerful industrial research organization the world had ever known."

In the context of our discussion, the period since the close of World War II is unique in that it does not show the steep decline in the Academy-Navy connection: the Tommy Syndrome was held at bay. There are three principal reasons for this:

1. First, key civilian and military leaders emerged from the trauma of World War II with the strong conviction that never again should the military and the civilian scientific community be allowed to drift apart during peacetime as they had during the period between the two world wars.

2. Second, the same leaders were equally convinced that government support of scientific research had proven to be so valuable, so powerful that it should be retained in the postwar years.

3. And, finally, peace never came. It was replaced by a global condition known as the Cold War, or, as Admiral James Watkins termed it, a Period of Violent Peace.

Armed with the first two convictions, the Navy established the Office of Naval Research in 1946, and simultaneously, asked the Academy to assume the responsibilities of the Subsurface Warfare Division of the wartime NDRC. The ONR rapidly established a model for enlightened government support of science, and the Academy's Committee on Undersea Warfare became the authoritative technical voice in submarine and anti-submarine warfare.

The Navy's identification of the Soviet submarine fleet as the major conventional threat in the years immediately following World War II was exactly right. However, in all too characteristic fashion, it neglected what I call the Sleeper Threat -- mine warfare. Although an American invention of 1776 vintage, we have made every effort to ignore mine warfare until our enemies have rubbed our noses in it. In years immediately preceding Pearl Harbor we began essentially from scratch and a section of magnetic sweep tail brought from England by Commander Hyman Rickover. By war's end we peaked at 37,000 men and 560 ships devoted to mine warfare. By the time of the Korean Conflict we were back down to 37 ships with only 7 available in the Western Pacific. And then the Sleeper Threat reared up to bite us once again.

In anticipation of our amphibious assault against Wonson, scheduled for October 19, 1950, 32 Soviet mine specialists, using untrained North Korean labor and 15 sampans, assembled 3,000 moored contact and magnetic influence bottom mines and planted a defense field covering 400 square miles. Seven minesweepers went in to clear the field on October 10 expecting the job to require five days. Before it was over we reactivated eight additional sweepers, employed all of the small South Korean mine countermeasures force, bombed the field with carrier air, used helicopters and swimmers as mine spotters, and, in desperation, talked the Japanese into operating 20 of their sweepers under contract. On the 19th, as scheduled, 250 ships and 50,000 assault troops began to orbit off the coast. Seven days later, on the 26th, they stormed ashore through narrow swept channels to be met by the Bob Hope Entertainment Troop. The South Korean Army, meeting less resistance than anticipated, had driven north of Wonson.

As a result of this embarrassment ONR asked the Academy to establish the Mine Advisory Committee to serve as the Navy's hair shirt in mine warfare. These two sister committees, one concentrating on submarine warfare and the other on mine warfare, served continuously until 1974 when they were replaced by the Naval Studies Board. In turn, the Naval Studies Board was established at the request of the Chief of Naval Operations who called for "a committee to which the Navy could turn for independent and outside counsel on any area of its responsibilities involving the interplay of science and technology with other national issues." In other words, the Navy asked the Academy to establish a technical advisory body which broadened the scope of the two long-standing committees to cover any technical area of interest to the Navy.

At this point let me pause for a moment and try to answer a question which must be on your minds: namely, "So the Navy has had this long association with the National Academy of Sciences. Probably hasn't hurt us any to be so visibly and formally connected with the scientific community. But, over the past 123 years, using 1986 dollars, that association has cost us the equivalent of, maybe, three RH-53 helicopters. Besides PR, what did we get for our money?"

Well, that is a perfectly legitimate question. Unfortunately, since there is no formal audit mechanism there is no straightforward answer. Even with an audit mechanism the connection between recommendation and implementation would be imperfect at best. Example: In 1973 the Committee on Undersea Warfare strongly recommended that the Navy reconsider its position on the fate of the four IOWA class battleships. Question: Were those now credited with the recommissioning of those ships influenced by that recommendation. Answer: Probably not. More likely, they weren't even aware of its existence.

To answer the original question one should consider both tangible and intangible benefits. On the intangible side there is the high percentage of world class scientists brought to bear on each problem; there is the objectivity of the study findings reflected in the statement, "If you are afraid of the answer, don't pose the question to the National Academy of Sciences"; and there is, of course, the ever-growing number of top-flight scientists and engineers made familiar with the unique problems of the Navy through the study process who can be called upon in a crisis -- they are already trained and an identity with the Navy already established.

On the tangible side let me just mention a few representative developments growing out of close Navy NAS cooperation:

1. The Naval Ocean Systems Center and the Navy Underwater Sound Laboratory. The last study shown on Figure 8 (Report of the Subcommittee on the Submarine Problem) found that the physics of underwater sound was imperfectly understood and recommended the establishment of a dedicated laboratory at San Diego and New London to correct this problem, and to build a continuing base of scientific knowledge in support of ASW. I should caveat the first of these laboratories. The historical record is not clear as to whether

NOSC or NUC (Bayside-Point Loma) is the present version of the original response to the recommendation.

2. The ALBACORE submarine hull grew directly from a cooperative effort between the old Bureau of Ships and a team of hydrodynamicists and naval architects assembled by the Committee on Undersea Warfare.

3. The Polaris submarine program resulted directly from the Project NOBSKA study requested of the Committee on Undersea Warfare by Admiral Arleigh Burke.

4. And, the Captor mine development program was launched as a direct result of the findings of the Deep Sea Mine Study conducted by the Mine Advisory Committee.

Incidentally, the fact that the first Polaris submarine was launched within two years of the NOBSKA study, and the first Captor mine reached the fleet twenty years after the Deep Sea Mine Study makes yet another telling statement about the relative importance of mines.

I would like to close with a brief discussion of three studies conducted during the 1980s at the request of the CNO. The study topics are mine warfare, sea-based aviation, and the Navy's role in space. Two of the three studies were highly classified and produced a total of thirty-three volumes. For both these reasons I will limit my remarks to an unclassified statement representing the most important findings of each study.

Mine Warefare

I have mentioned that the mine is an American invention, that we have largely ignored it until we are forced to do otherwise, and that 37,000 men and 560 ships were ultimately required to deal with the problem during World War II. Today we have about 17 RH-53 helicopter minesweepers, 3 active duty and 22 reserve MSOs (all about 30 years old), and 7 MSBs. In turn, this token force faces the largest peacetime mine stockpile in history, and an adversary who takes mine warfare very seriously.

This condition led to what I consider the four most important findings in the entire study. These were as follows:

* We can never hope to afford in peacetime nor have the time to build in wartime the number of mine countermeasures ships and craft required to meet an all-out conventional challenge -- even with the help of our allies. Therefore, along with our conventional shipbuilding program we believe that emphasis should be placed on MCM packages

that can be quickly deployed aboard a wide range of ships and craft of opportunity.

* Using the SWATH hull form built to commercial standards, a 33-ton inshore minesweeper-mine-hunter, fully equipped and capable of operating through Sea State 3, can be built for approximately $1 million.

* In the past, 90 percent of all mine countermeasures operations have been conducted in waters that held no mines. Clearly, a remote reconnaissance capability is needed to bring efficiency to this most inefficient of naval operations.

* During the foreseeable future one of the most important developments in mine countermeasures will be the successful completion of the Global Positioning System (GPS). The resulting navigational accuracy -- available to all ships and craft -- will permit an efficiency of channel clearance and channel following that will reduce the time and force levels required to breach mined areas.

Naval Aviation Study

The objective of the Naval Aviation Study was to look about 30 years downstream to explore the impact of emerging technology on Naval Aviation. The study group quickly determined that advanced engines and airframes are not the problem -- existing technology will fully support the follow-on to the F-14 and the FA-18. Rather, the more important problems facing the Navy in the years ahead emerge from the system in which naval aircraft are imbedded. This conclusion led to a number of findings, the three most important of which are as follows:

* Required for the future is a global information net capable of passing all-source data through fusion centers and providing it, properly formatted and in near real time, to all levels of command.

* Consistent with emerging wide-area surveillance and over-the-horizon targeting capabilities is the need for a family of long-range, smart missiles adapted to the Forward Pass concept.

* To relieve pressure on the big-deck carriers, to increase their offensive capability, and to increase the range of support aircraft, a V/STOL-capable SWATH destroyer, operating on the periphery of the Battle Group and capable of keeping pace with the big-deck carriers in heavy seas is required.

At this point I would like to take a small detour, just for the fun of it. We all know that at some indefinite point in the future the aircraft carrier will be replaced by a more capable platform just as the carrier replaced the battleship. But, I have never seen any serious discussion as to what that platform will look like, or what its capabilities will be. Today, for the first time anywhere, I would like to give you an indication of what I believe the successor to the carrier -- at some point in time -- will be like.

It is not uncommon to find that the long-awaited answer to a question is simply a variant of something quite familiar. I think the earliest prototype of the carrier's successor was quite visible in World War II as shown in Figure 9. Most of you will recognize it as an amphibious assault ship known as an LSMR. These ships were altered LSMs in which the open well deck was decked over and fitted out with several hundred launch rails for assault rockets having a range of about 1,100 yards. The rockets were used to soften up a landing beach and its obstructions and other defenses.

Through many evolutions, beginning with the LSMR, the platform that first competes with and then replaces the present big-deck carrier will, itself, carry perhaps 1,000 aircraft into battle. The major difference, other than numbers, will be the absence of aviators. The "aircraft" will be long-range, precision-guided, and essentially zero CEP, missiles.

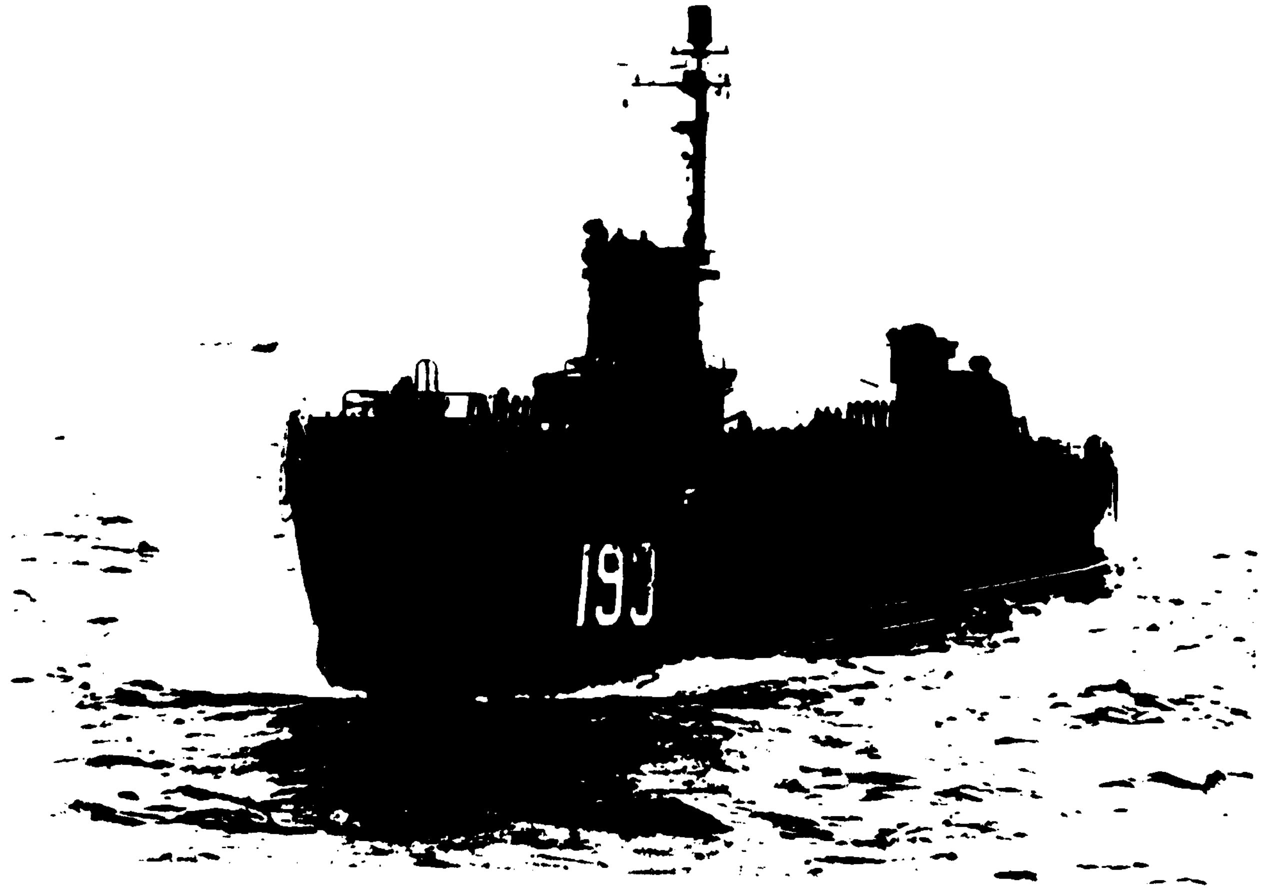

Figure 9. Land Ship Mechanism (Rocket)--LSMR

Now you will probably say that if this is so, then at least a more recent prototype than the LSMR should now be visible. A valid point, and I suggest that the Soviet SLAVA class cruiser is just such a prototype.

Navy Space Program

In 1978, responding to a request from Admiral James Holloway, the Board established the Panel on the Implications of Future Space Systems for the U. S. Navy. To date that panel has issued some 25 reports, and joined with the Navy to sponsor two major navy space symposia. Rather than try to summarize the rather sensitive results of the panel's efforts, I would like to try to corral the essence of the entire history of Navy space in three sets of comments as follows:

1. Just after 6:00 p.m. on the evening of October 4, 1957, an announcement was made in Washington which forever altered the world in which we live, and the way in which the Navy carries out its missions. Former Commander Lloyd Berkner, attending a reception for scientists involved in the International Geophysical Year on the second floor of the Soviet Embassy, clapped his hands for silence and said, "I wish to make an announcement. I've just been informed by the New York Times that a Russian satellite is in

orbit at an elevation of 900 kilometers. I wish to congratulate our Soviet colleagues on their achievements.

2. On the morning of October 14, 1981, another announcement was made which clearly articulated the long-range significance of the first announcement to the Navy. Dr. Eberhard Rechtin, Chairman of the Naval Studies Board, and Dr. Vincent McRae, Chairman of the Board's Panel on the Implications of Future Space Systems for the U.S. Navy, made the following statements to the audience attending the first Navy Space Symposium then being held at the Naval Postgraduate School:

* Space technology, within 5 to 15 years, will permit tactically useful real-time, all-weather, day-night and global identification, tracing, and targeting of most surface ships and aircraft.

* Within the lifetime of the fleet we are now building, such real-time information will greatly change strategies, tactics, and weapon systems; it will drive the development of a family of long-range, precision-guided missiles.

* The submarine and the satellite will become natural allies.

* Sea control will depend on space control.

* The impact on the surface fleet will be revolutionary, not evolutionary.

I would like to close with a personal statement made here for the first time.

3. Today the United States Navy, with the liquid three-quarters of the earth's surface under command of its fleet, and most of the potentially contested land areas of the earth under command of its SSBNs, its Strike Aircraft, and its Marine Corps, is on the very brink of abrogating its responsibility for the design, development, acquisition, and operation of those space-based assets upon which its very survival -- in peace as well as in war -- will ultimately depend.

FIBER OPTICS

by

James H. Davis*

Good afternoon.

For the next 35 to 40 minutes I'm going to take you from the macro-world that you live in today into the micro-world of the photon and fiber optics.

In the Navy, fiber optics is an emerging technology, but glass fibers had their beginnings about 3000 B.C., Figure 1. The Egyptians were the first to make and use glass fiber. They would melt sand and pull fiber by dipping the end of a stick into the molten liquid and then

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*Mr. James H. Davis is the director of the Naval Sea Systems Command Fiber Optics Program Office, Code SEA 56ZC. His primary responsibility is to accelerate the acceptance and use of fiber optics in the Navy. Additional responsibilities include: lead syscom manager for fiber optics standardization, and represents the Navy as the single point of contact for fiber optics on the newly established joint service fiber optics management panel. Mr. Davis was selected to head the Navy's first fiber optics standardization office, established in 1984. He has taught fiber optics at the George Washington University and is planning to teach an undergraduate fiber optics course for the NAVSEA Institute. Mr. Davis is a graduate of the University of Southern Mississippi, where he majored in Physics and Mathematics.

HISTORY

- 3000 BC – EGYPTIANS
- 1870 – JOHN TYNDALL
- 1880 – ALEXANDER GRAHAM BELL
- 1966 – CHARLES KAO & GEORGE HOCKHAM
- 1970 – CORNING 20 dB FIBER

Figure 1

run with the stick, producing a long fiber. They used this fiber for decorative purposes only.

John Tyndall in the 1870's demonstrated how light could be captured in a stream of water flowing from a jar. This was a significant but unrecognized event in the development of fiber optics as we know it today.

In the early 1880's Alexander Graham Bell demonstrated the transmission of speech using light. His photophone modulated sunlight and was able to transmit voice over a distance of about 750 feet.

It wasn't until 1966 that Kao and Hockham came up with a material that was clear enough to send optical signals through without high losses--high losses being up around 1,000 dB/km. Corning in the early '70's developed a fiber which had a 20 dB/km loss and by the mid-'70's losses had been reduced to below 5 dB/km.

Figure 2 shows what has taken place in terms of decreases in signal loss since the mid-'60's. Remember, for every 3 dB decrease in attenuation, available power is doubled. In other words, you lose half your energy or you double your energy for every 3 dB loss or gain. So you can

PROGRESS IN LOW-LOSS FIBER FABRICATION

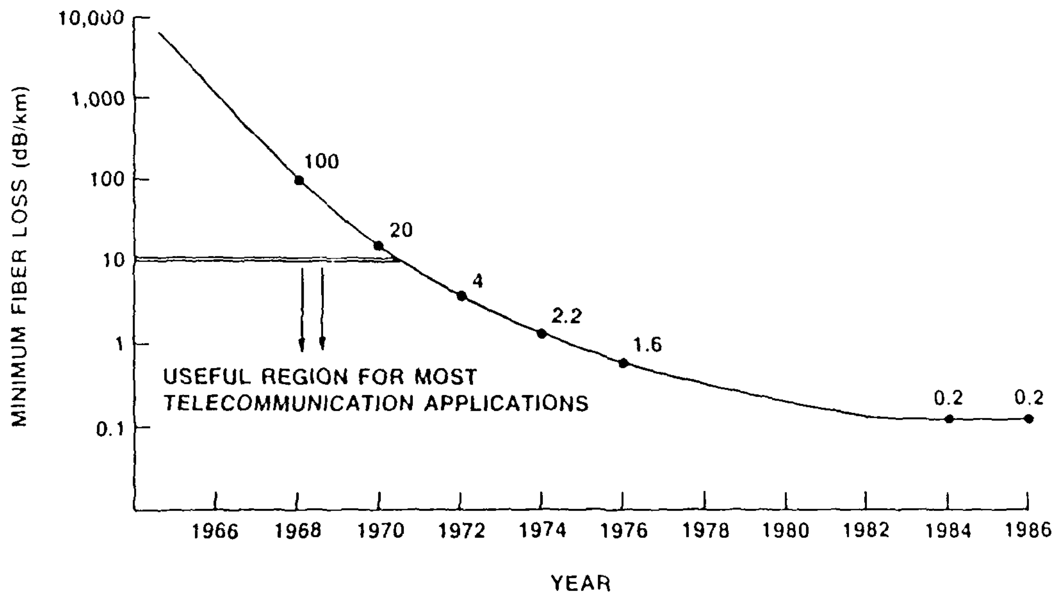


Figure 2

see that, over a very few years, a lot of progress has been made. This curve also tells another story. Because the technology was moving so rapidly, the development of standards and specifications was impossible. Without standards and specifications, the use of fiber optic technology in the Navy did not and will not happen.

As you can see from the graph, since about 1982 the loss has been fairly stable. We now have single-mode fibers that have losses of 0.2 dB per kilometer. Multimode fiber losses are slightly higher.

Figure 3 is a representation of the electromagnetic frequency spectrum. As you can see, the visible light spectrum is in the region of 400 to 750 nm. The wavelengths used in fiber optics transmission are in the infrared region of 820 to 1,600 nm, wavelengths just above the visible spectrum. You can look into a fiber in an active circuit and you won't see light. Multimode fiber systems usually operate at around 820 nm while single-mode systems operate at 1,300 nm and above. There are optimum wavelengths for specific fibers in which attenuation and pulse-spreading are minimized.

ELECTROMAGNETIC FREQUENCY SPECTRUM

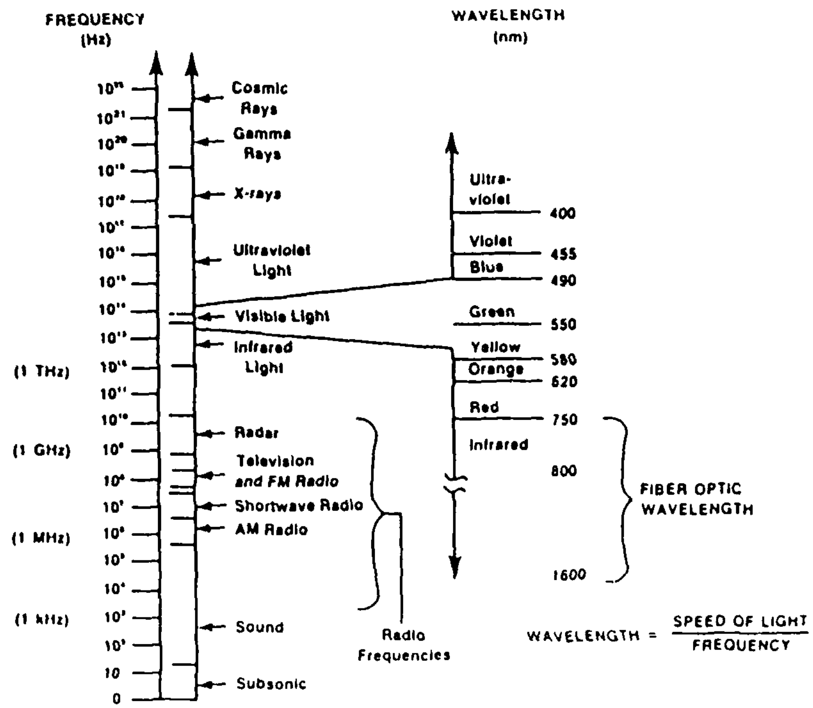


Figure 3

Figure 4 is a standard needle. It's about two inches long, has an eye about one-sixty-fourth of an inch wide--a standard sewing needle. The fiber that you're holding is a typical piece of fiber. What I'd like you to do is take the fiber, wrap it around your fingers, and pull on it ever so gently so as not to cut your fingers. Please don't pass it over the fingernail because you will break it if you bend it too sharply. The fiber you have can withstand a tensile stress of about 400,000 lbs per square inch. It's a very strong material. Its tensile strength is greater than that of steel.

Those of us with some hair left can compare the size of the fiber to a strand of hair. Figure 5 depicts a cross-section view of multimode fiber, single-mode fiber, and human hair. The fiber that I've passed out is single-mode. A single-mode fiber has a smaller core than a multimode fiber.

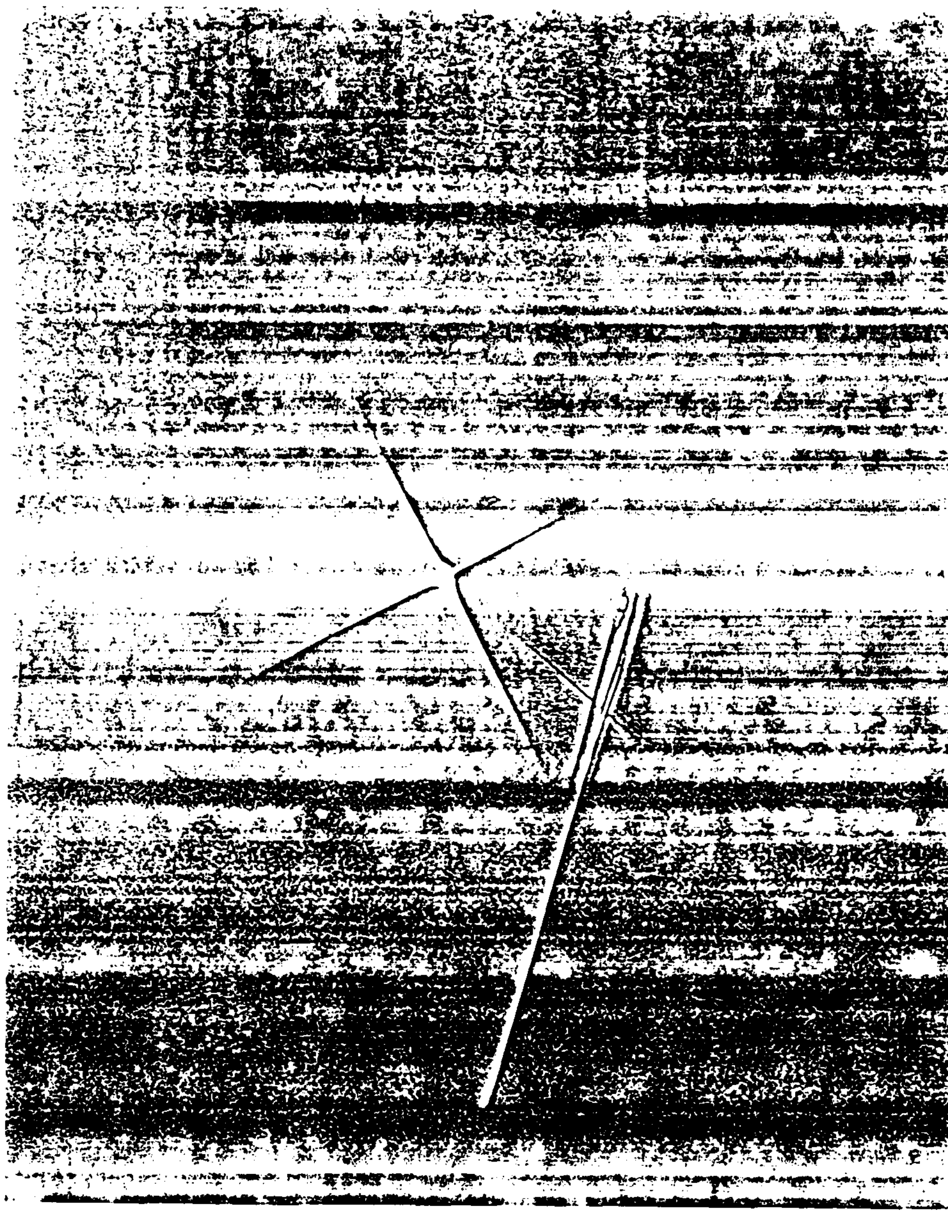


Figure 4

TYPICAL DIMENSIONS OF VARIOUS FIBERS

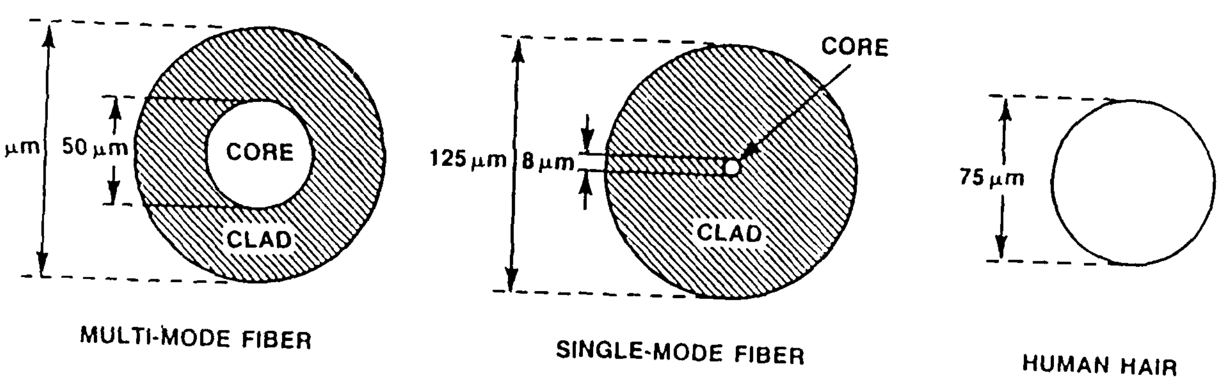


Figure 5

Figure 6 compares the size of a solid-state laser with an ant's head. The photons that are produced in the laser channel are coupled into the core of the fiber. This isn't easy because the laser channel and the core of the fiber are about the same size--somewhere in the neighborhood of 9 microns. The process requires precise alignment of the fiber and lasing channel in order to achieve efficient coupling of the light into the fiber.

A typical optical fiber consists of a core, cladding, buffer, and coating, Figure 7. The buffer is designed to help prevent mechanical damage during manufacture, and to prevent water from getting inside the optical fiber. The coating provides additional protection. One of the questions often asked is: "What's the drawback to fiber? What are its weaknesses?" Well, if it has a weakness, it has to be water--the OH radical. It penetrates the optical fiber and over time will cause the fiber to fail. However, that period of time is directly proportional to the fiber strength. A fiber of 400,000 psi tensile-loading strength has a life expectancy of 40 years before it fails. A failure is a break, not a crumbling of the fiber.

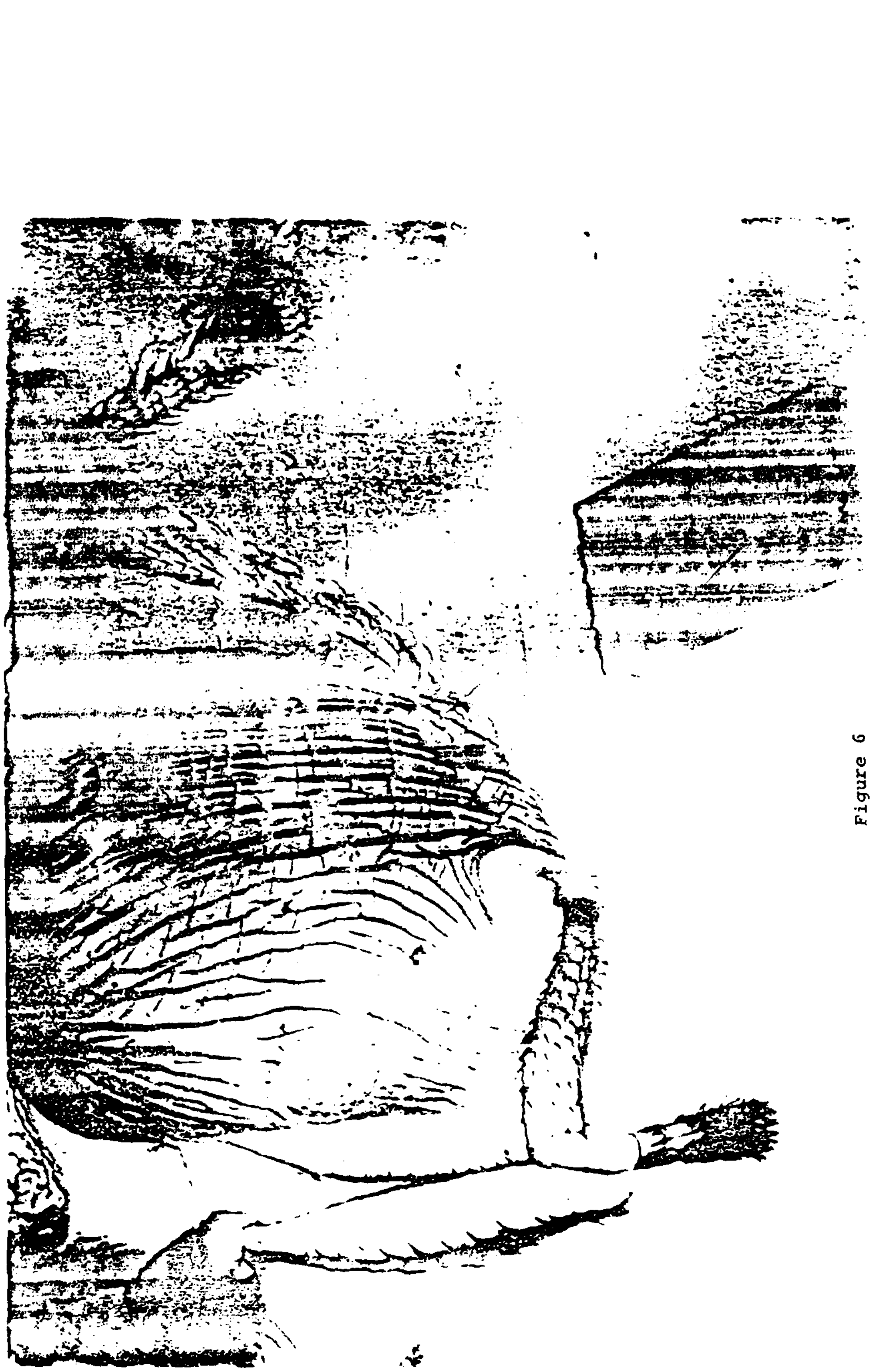


Figure 6

OPTICAL FIBER STRUCTURE

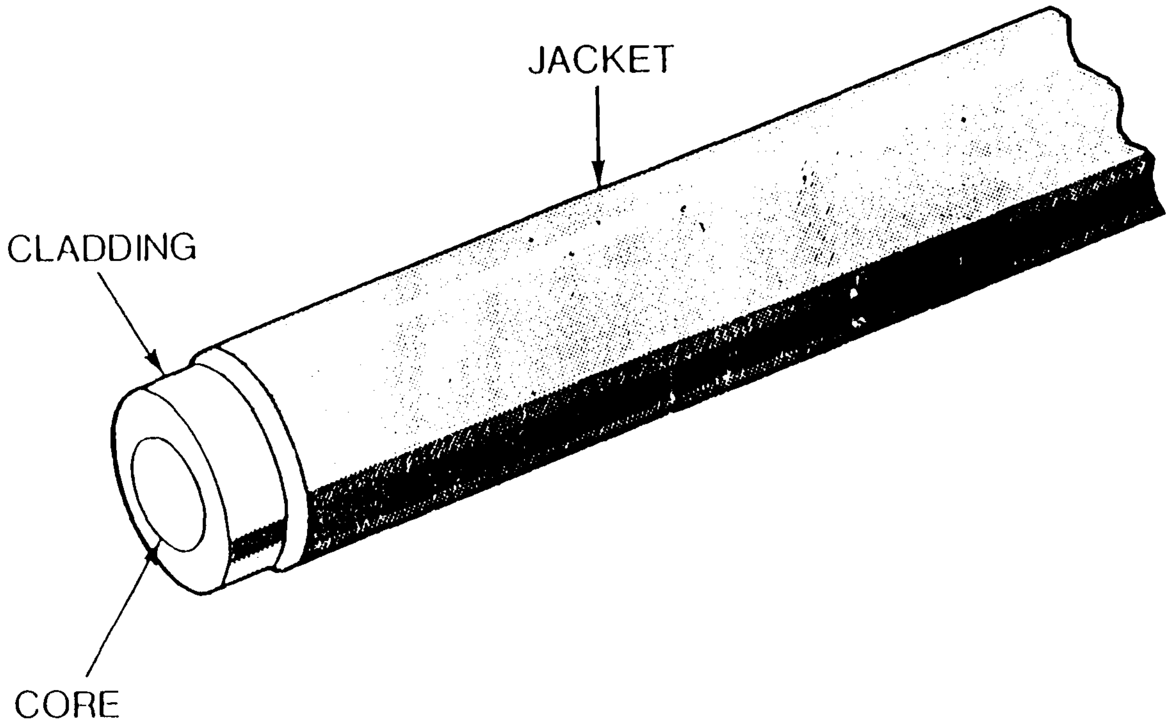
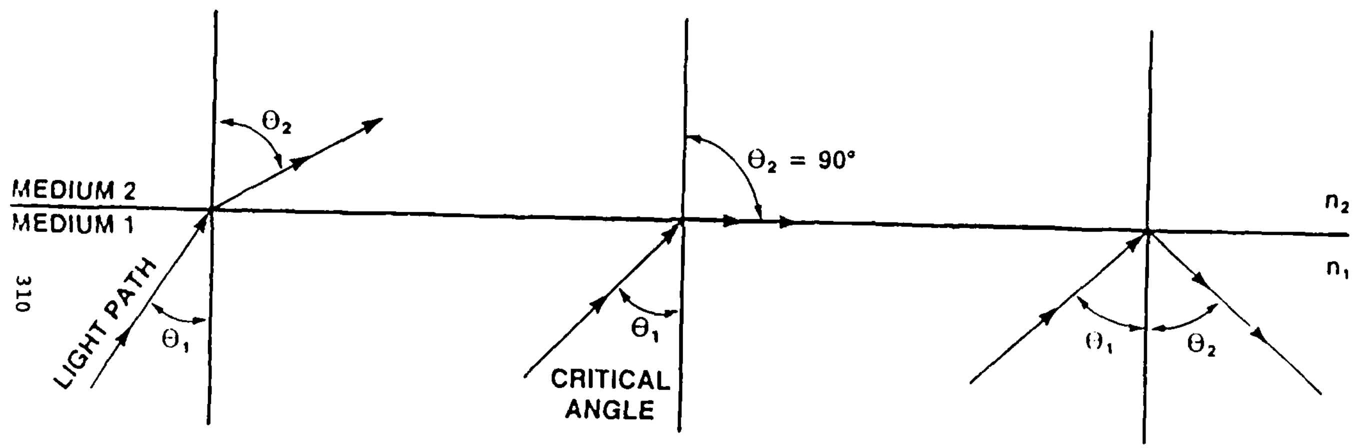


Figure 7

A break in a fiber does not necessarily cause the failure of a system. A break can be nothing more than a very small space between the fibers which will still pass light from one section to another. A little light is lost at the interface, but the system will continue to operate. This break is equivalent to a connector because in a connector you also have a space between the fiber ends. A fiber optic cable has strength members to prevent the cable from rupturing completely.

To pass information over fiber we must trap the modulated light inside the core of the fiber. In the three conditions shown, Figure 8, we assume medium 1 is the core of the fiber with a higher index of refraction than medium 2--the cladding. Let's start in the middle at the critical angle. A light ray approaching the interface at the critical angle is refracted and then travels along the interface surface. It is not reflected back into the core or refracted into the cladding. If the light ray approaches the interface at an angle less than the critical angle, much of the light is refracted into the cladding and is lost. If the angle is greater than the critical angle,

REFRACTION AND REFLECTION AT INTERFACE BETWEEN TWO MEDIA



REFRACTION
$n_1 \mathrm{Sin}\Theta_1 = n_2 \mathrm{Sin}\Theta_2$

CRITICAL ANGLE
$\mathrm{Sin}\Theta_1 = n_2/n_1$

REFLECTION
$\Theta_1 = \Theta_2$

Figure 8

the light is totally reflected back into the core. These are basically laws of refraction and reflection. Therefore, we are able to keep the light in the core by reflecting it at the interface surface between the core and cladding.

I will explain later how the properties of reflection and refraction are used in sensors to measure liquid levels.

Figure 9 is a representation of the refractive-index profile and mode structure of three different fibers. In the multimode step-index fiber, we have the core with one refractive index and the cladding with another. The single-mode fiber has the same construction--however, the core is smaller than that of the multimode fiber. In the multimode fiber, each of the lines represents a mode or wavelength of light. As shown here, multimode fiber is able to support a large number of modes. The core diameter of the single-mode fiber is so small that it supports essentially only one mode, that is, one wavelength.

The core of a graded-index multimode fiber is a series of concentric cylinders of glass, each with a progressively

REFRACTIVE INDEX PROFILES AND MODE STRUCTURE

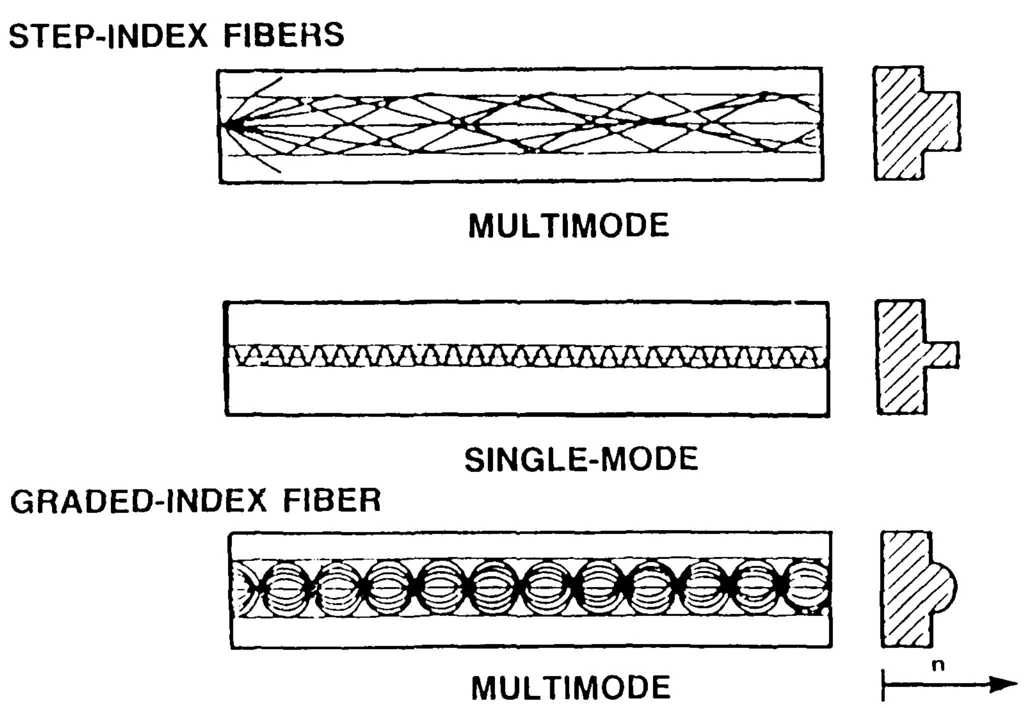


Figure 9

lower refractive index from the center outward--I'll show you this in a later viewgraph--which results in a repetitive refractive process. This refractive process curves the light around so that it remains within the core and makes all rays or modes tend to arrive at any node, as shall be seen in the next slide, at the same time. In the multimode fiber, maximum transmission distance without repeaters is somewhere around 10 to 12 kilometers. In the graded-index fiber, you can push it up to around 30 to 40 kilometers. In the single-mode fiber, you can go in excess of 200 kilometers.

Figure 10 is a diagram of a multimode step-index fiber. The large core allows many modes to propagate through the fiber. Each mode has a different reflection angle because of the different angles at which they entered the fiber. Therefore, some rays travel longer paths than others. This will cause a pulse of light to spread as it travels through the fiber. This spreading is called nodal dispersion. You can see how the light rays are bent so as to remain in the core.

LIGHT PROPAGATION IN A STEP-INDEX FIBER

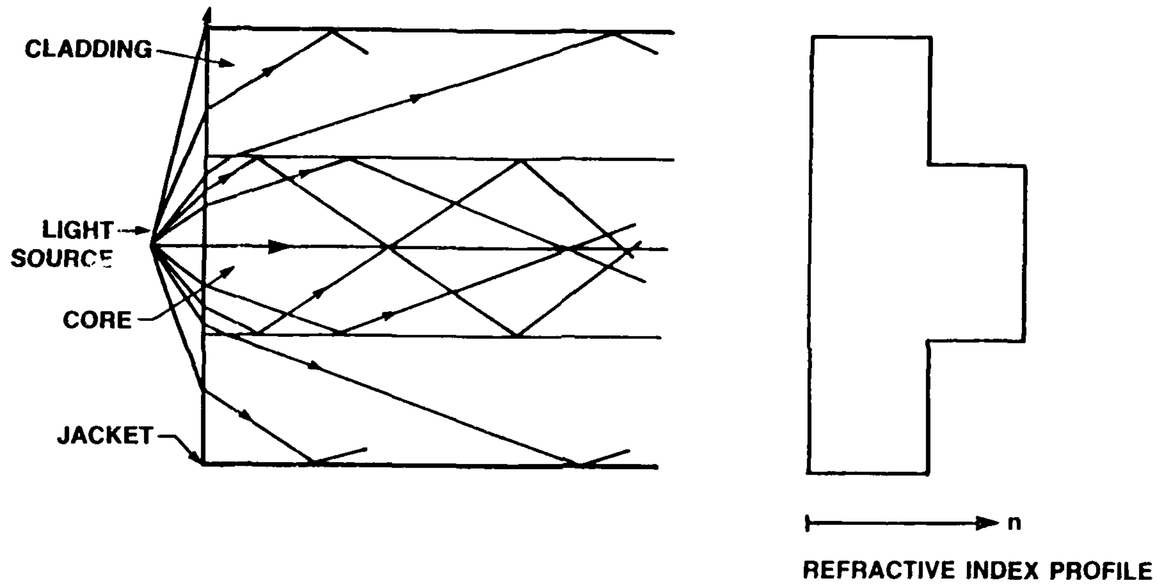


Figure 10

In the graded-index fiber, Figure 11, the light rays travel through a core composed of a series of concentric cylinders of glass, each with a lower refractive index. The light rays following the longer paths through the glass with lower refractive indices travel faster than the light traveling down the center. So, by carefully designing the fiber, you're able to bring the light to the nodes very precisely. This is how you get the longer distance and higher bandwidth. Bandwidth of the graded-index fiber is about 1.4 gigabits. Bandwidth of a multimode fiber is about 800 megabits. Single-mode fiber bandwidth is in excess of a terabit at the zero dispersion point. The terabit is 1×10^{12} bits; the gigabit is 1×10^{9} bits; and the megabit is 1×10^{6} bits. Now, the reciprocal of that is the time devoted to each bit.

How many know what a femto second is? (It's 10^{-15} seconds.) The National Bureau of Standards is working on products that will operate in the femto-second region. What that will allow us to do is take advantage of high bandwidths by being able to enter and detect data passing

LIGHT PROPAGATION IN A GRADED-INDEX FIBER

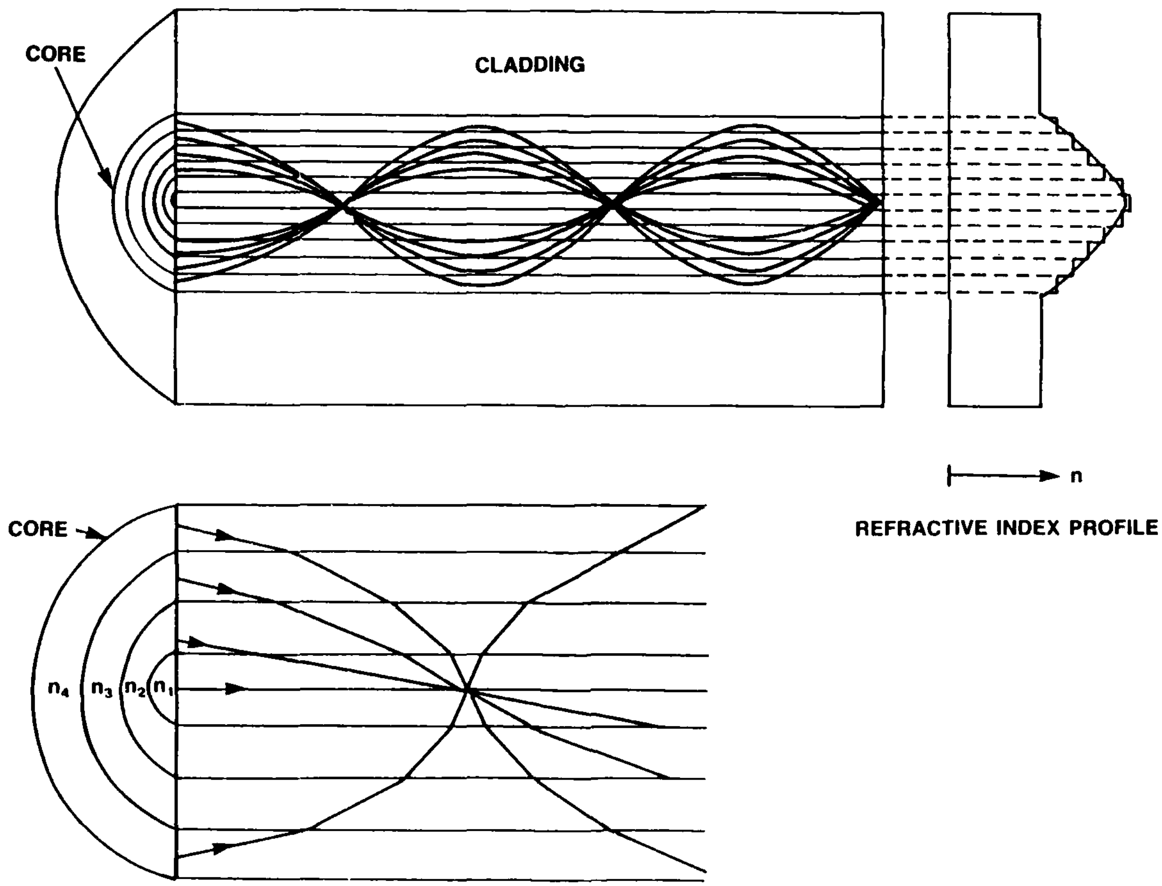


Figure 11

through the glass in excess of the terabit. Now, what does that mean to us? Well, take all the telephone conversations: everything everybody's doing here for one year--all the conversations, video, and computers. With a terabit device, we can pass all that information in less than an hour. It's a phenomenal bandwidth. It's something you can do with glass that you cannot do with copper.

There are basically two types of light sources, Figure 12. Light-emitting diodes (LEDs), which have a relatively large spectral width, and laser diodes, which have a smaller spectral width. The spectral width is the difference between the longest wavelength and the shortest wavelength the device emits. Optimally, the laser is coupled to a single-mode fiber. The LEDs are low-bandwidth devices, usually 0 to 200 megabits. The laser is a high-bandwidth device--0 to about 6 gigabits. LEDs are more reliable than laser diodes.

FIBER OPTIC TECHNOLOGY

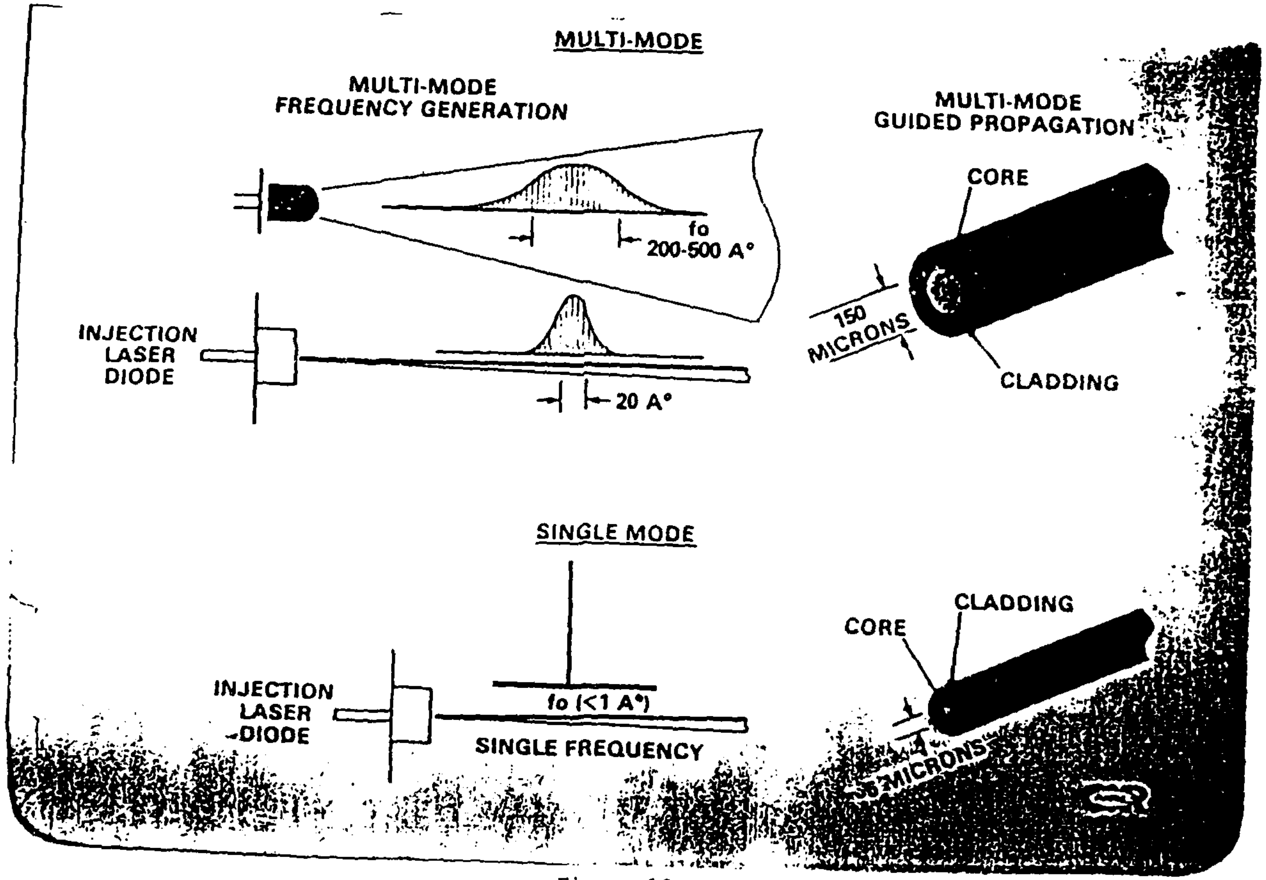


Figure 12

Figure 13 is a list of some of the uses of fiber optics. Commercial and military telecommunication networks are using fiber optics in longhaul and local-area networks. In this country, the longhaul systems have a maximum capacity of 1.7 gigabits/second. Europe is going to 2.2 gigabits/second, and the Japanese are going to 1.5 gigabits, or vice versa. Fiber optic systems are being used in tactical communication systems and aircraft data links. We are looking at using fiber optics for shipboard data links, sensors, motor controllers, and propulsion control. Let me go back to sensors for a moment. There is a multitude of sensors that we can put on ships. One of the things that CNO has asked us to do is to look at developing more sensors to help eliminate some of the people required to man engineering spaces, thereby reducing the number of people on ships. Fiber optic sensors that are made only of fiber have an expected life of 30 to 40 years.

USES

- COMMERCIAL AND MILITARY TELECOMMUNICATION NETWORKS
  - LONG-HAUL
  - LOCAL
- TACTICAL COMMUNICATION SYSTEMS
- AIRCRAFT DATA LINKS
- SHIPBOARD DATA LINKS
- SENSORS
- MOTOR CONTROLLERS

Figure 13

When comparing transmission line attenuation of coax, twisted pairs, and silver waveguides with attenuation in optical fibers, a rather interesting phenomenon is highlighted. The attenuation rate for multimode, single-mode, and graded-index fiber remains constant with regard to changes in wavelength, whereas in the conventional medium, attenuation increases as the wavelength increases, Figure 14. In other words, in fiber optics, you don't have to design your circuitry to accommodate for an increase in attenuation due to an increased bandwidth.

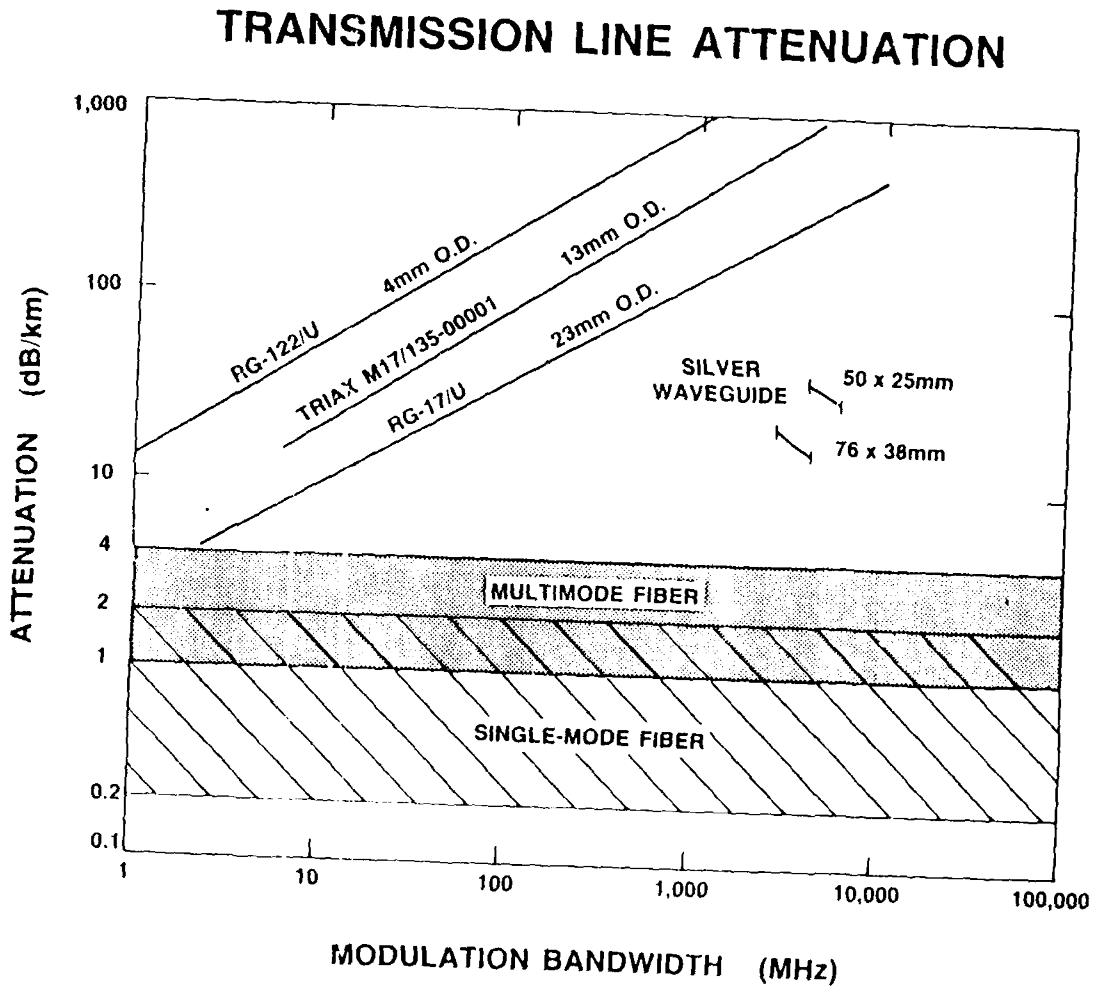
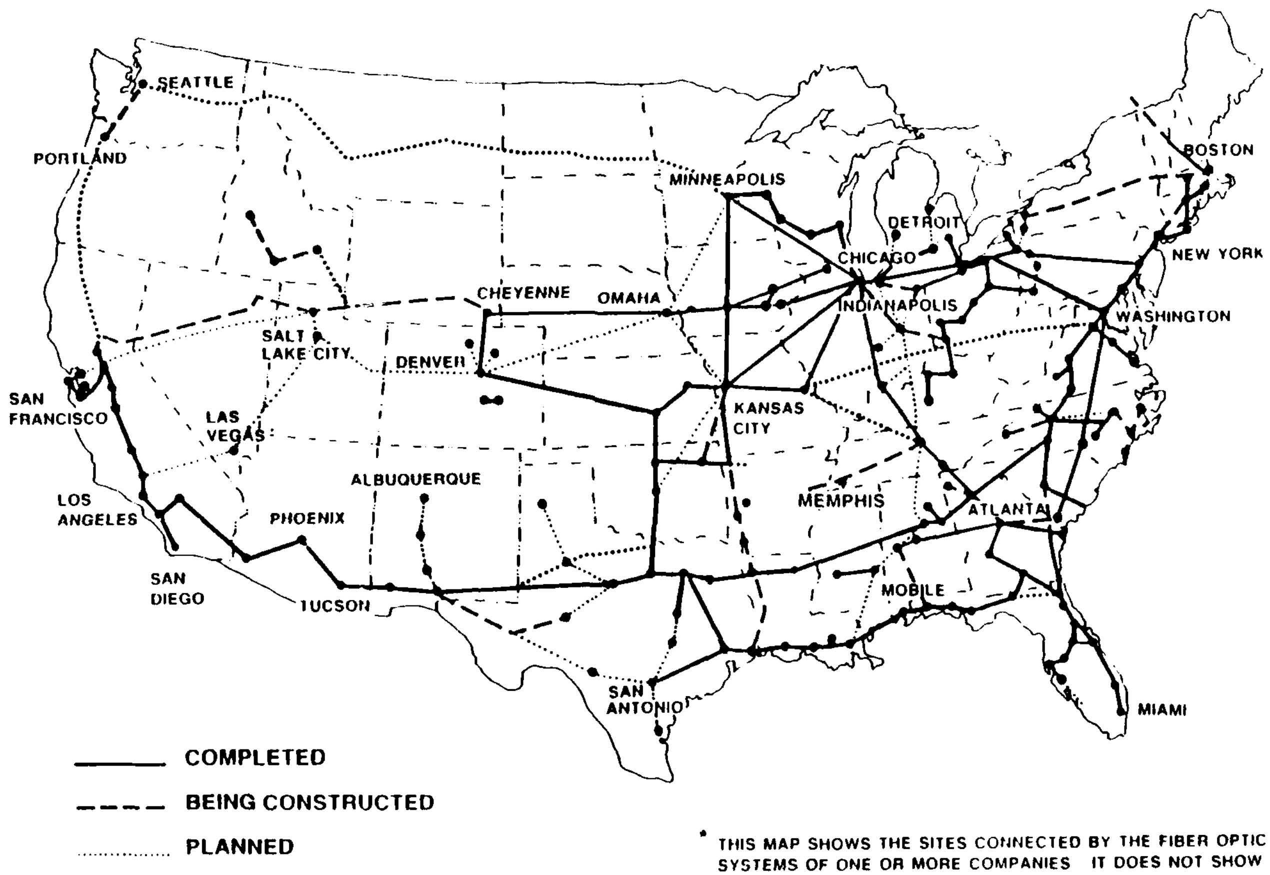

TRANSMISSION LINE ATTENUATION
ATTENUATION (dB/km)
1,000
100
10
4
2
1
0.2
0.1
RG-122/U
4mm O.D.
TRIAX M17/135-00001
13mm O.D.
RG-17/U
23mm O.D.
SILVER
WAVEGUIDE
50 x 25mm
76 x 38mm
MULTIMODE FIBER
SINGLE-MODE FIBER
1
10
100
1,000
10,000
100,000
MODULATION BANDWIDTH (MHz)

Figure 14

Figure 15 gives you an idea of the use of fiber optics in telecommunication networks in the United States. In the Richmond to Boston link, the telephone company replaced the copper cables with a fiber optic cable containing 144 optical fibers. This cable was made up of 12 of these 12 fiber ribbons. Each ribbon has the equivalent transmission capacity of 12 electrical cables. In terms of weight for equal transmission capacity, 20 lbs of fiber optic material is equivalent to 250 tons of electrical cable. The cost to replace the copper in the Richmond to Boston link with fiber was less than the salvage value of the copper being replaced!

FIBER OPTIC TELECOMMUNICATIONS NETWORKS*

6503-852
OCTOBER 1986



* THIS MAP SHOWS THE SITES CONNECTED BY THE FIBER OPTIC SYSTEMS OF ONE OR MORE COMPANIES. IT DOES NOT SHOW THE SEPARATE ROUTES OF EACH COMPANY S FIBER OPTIC LINES

Figure 15

Fiber optics provides several orders of magnitude increase in performance over copper/coaxial cables at a lower cost. To give you a comparison of this increase, Figure 16 shows that coaxial cable for undersea use is capable of 4,200 voice channels at a cost of $3.10 per channel-km. A single fiber in a fiber optic cable is capable of 12,000 voice channels at a cost of 13 cents per channel-km. Actually, this is now down to 4 cents per channel-km.

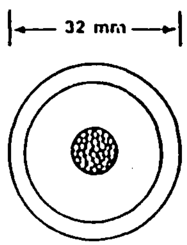
Coaxial cable for land use--1,000 voice channels at a cost of $4.90 per channel-km is compared to the 144-fiber cable, which has a capacity of 115,200 voice channels at a cost of 4 cents per channel-km.

This increase in capacity and reduction in weight and costs has a significant effect on shipboard designs. For example, DD-963 has 56 cables in its cableway, of which 5 are power. Note that each station is 12-inches high and 15-inches wide with 3 layers, Figure 17.

By replacing the data transmission cables with a fiber optic cable, each cableway station is reduced to 2.5-inches

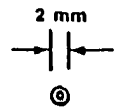
TRANSMISSION CABLES

UNDERSEA CABLES



COAXIAL

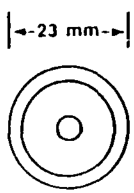
4200 VOICE CHANNELS
10 km REPEATER SPACING
1300 kg/km
$3.10/channel-km



FIBER OPTIC

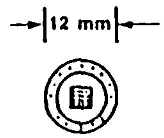
12000 + VOICE CHANNELS
40 km REPEATER SPACING
1 kg/km
$0.13/channel-km

LAND CABLES



COAXIAL (RG-218/U)

1000 VOICE CHANNELS
10 km REPEATER SPACING
850 kg/km
$4.90/channel-km



FIBER OPTIC (AT&T 144 FIBER)

115200 VOICE CHANNELS
32 km REPEATER SPACING
225 kg/km
$0.56/channel-km

Figure 16

WIREWAY STATION 45
CONVENTIONAL CONFIGURATION, DD963

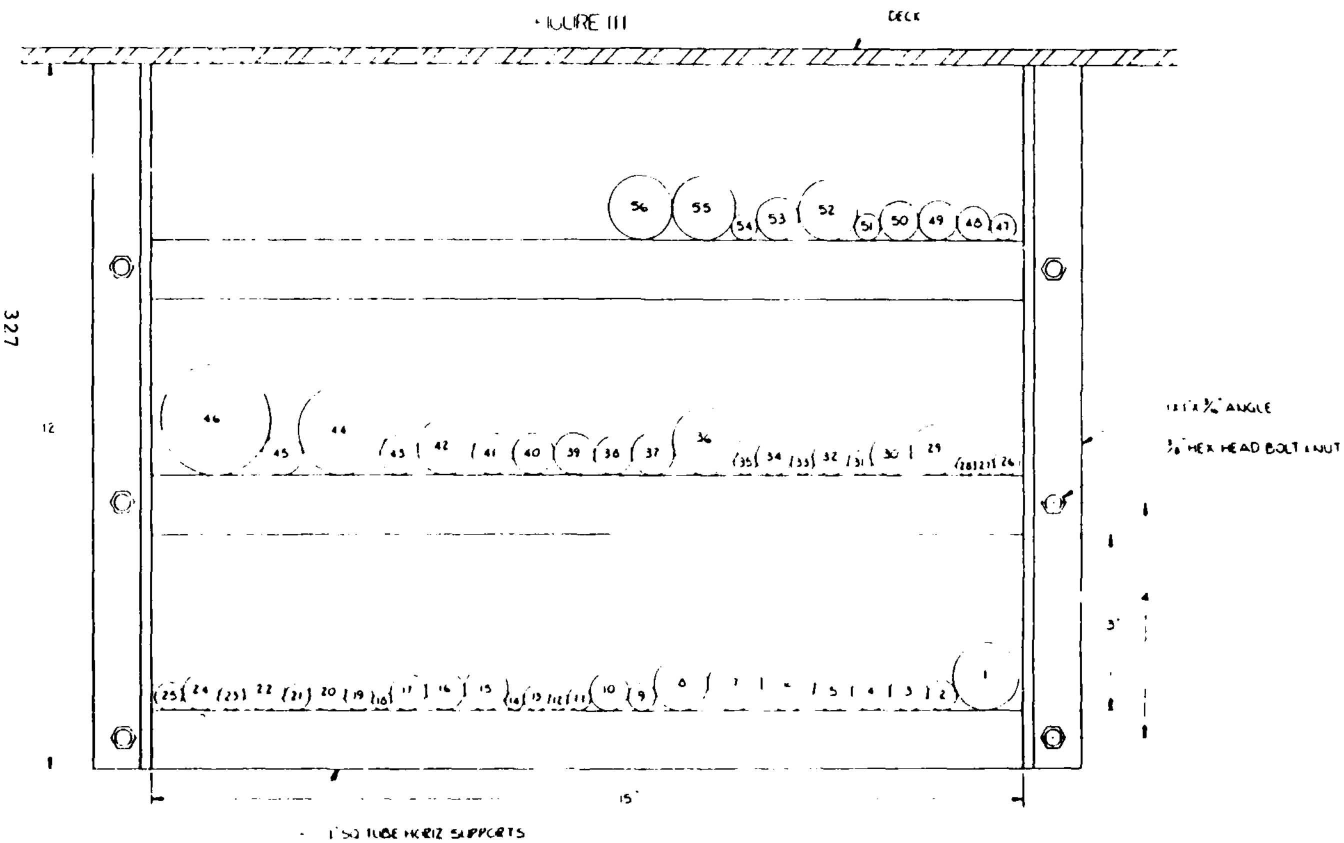


Figure 17

high and 5-inches wide with 1 layer, Figure 18. The number of cables is reduced from 56 to 6 (one fiber, the rest power). The reduction in the number of cables and size of the cableway hangers results in a significant weight reduction or avoidance.

In another study, wire was compared with fiber on a 2SWU19 AEGIS cable trunk, as shown in Figure 19. A total of 2,880 feet of wire could be replaced by 720 feet of equivalent fiber cable. Look at the weight avoidance and cost savings.

Another example is the SPS-48 radar cable installation on the USS KITTYHAWK--13,700 lbs worth of cable can be replaced with 15 lbs of fiber optic cable. Total cost for the 13,700 lbs of cable installed is $1M. Cost of the fiber materials and installation is $30K. Significant cost avoidance. It costs about the same to pull one fiber optic cable as it does one electrical cable, but the fact is you have to pull only one fiber optic cable compared to many electrical cables in the same cableway. One of my objectives for the Navy is to put in this large 0.49-inch-diameter multifiber cable. There's no cross-talk or mutual

WIREWAY STATION 45 WITH FIBER OPTIC DATA BUS & LIGHTWEIGHT CABLES ON SINGLE TIER

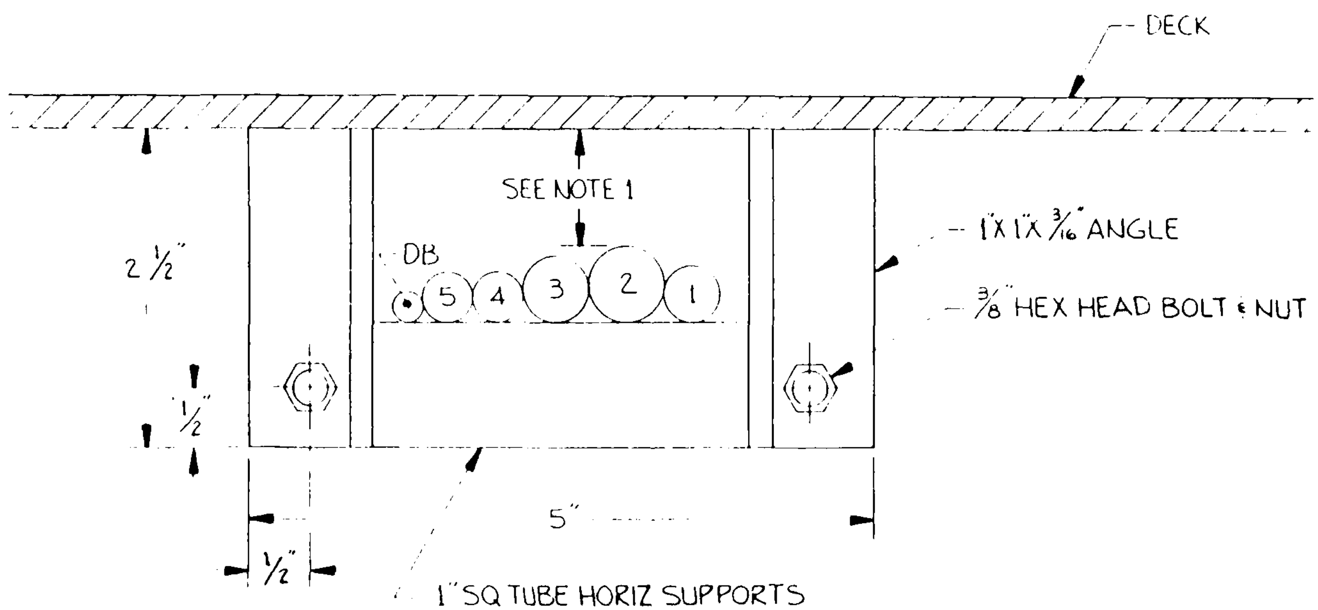


Figure 18

AEGIS FIBER OPTIC STUDY
COMPARISON OF WIRE VS FIBER OPTIC CABLE TRUNK

	TOTAL LENGTH (ft)	TOTAL WEIGHT (lbs)	TOTAL VOLUME (ft^3)	INSTALLATION COST	CABLE COST	TOTAL COST
Wire cable trunk (2SWU-19)	2880	2204	26.6	$11k ($3.80/ft)	$34,560 ($12.00/ft)	$45.6k
Fiber optic trunk system	720	225	7.4	$2.6k ($3.61/ft)	$0.9k (1.25/ft)*	$3.5k
Savings with F.O. system	2160	1979	19.2	$8.4k	$33,660	$42.1k

*Estimate for 6-fiber shipboard cable

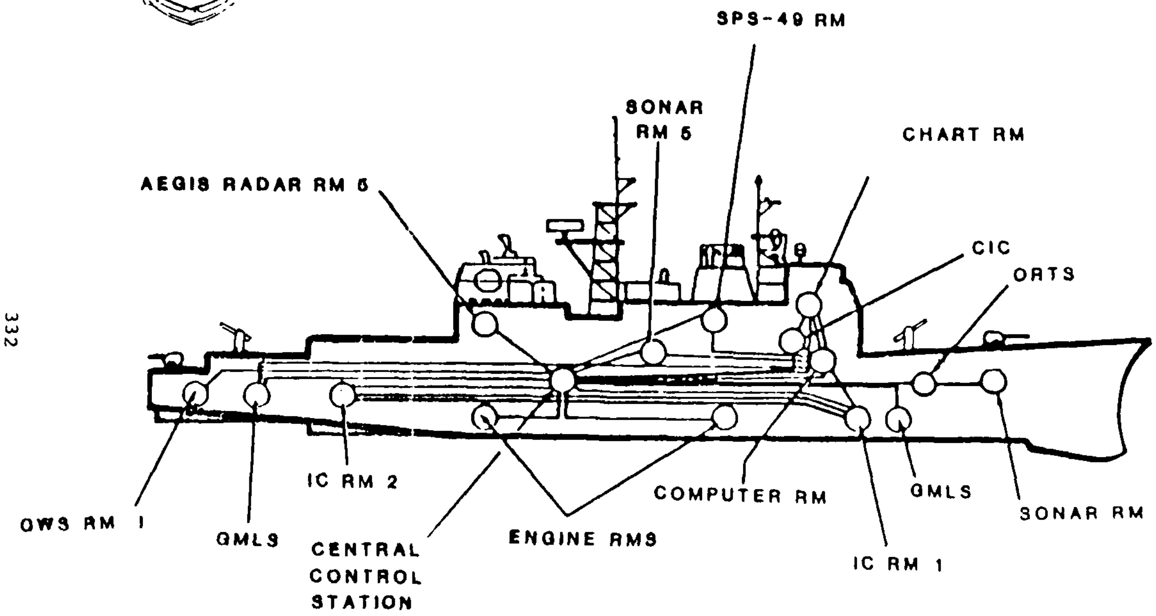
Figure 19

interference in the cable. Therefore, I can pull one cable and treat it like a trunk line on the ship. Now, I can pull multiple trunk lines on the ship for survivability and redundancy. By using simple multiplexing techniques, any single cable is capable of carrying the maximum communication traffic load of any combination of cables on the ship.

The capacity of a single fiber is unimaginable. Say we pass one gigabit/second in each wavelength channel and say there are approximately 50,000 wavelength channels available, that's a lot of capacity. It takes care of any volume of traffic at any point on the ship. Now, that's in one direction. We can turn it around and broadcast in the other direction at the same wavelength. For those of you that may doubt that, this is a device built by ADC. It's a bidirectional transmitter, using the same wavelength in both directions. It's on the market. It's very simple and straightforward.

Figure 20 is the diagram of the fiber optic installation on the CG-50. It's a test bed available for future connection and demonstrations. It was installed to

INTERCOMPARTMENT CABLE SERVICE



- INSTALLED IN CG 50 (1984)
- PROVIDES OPERATIONAL ENVIRONMENT FOR SEA DEMONSTRATION
- PROVIDES SHIPYARD TRAINING AND INSTALLATION EXPERIENCE
- PROVIDES FIBER OPTICS TEST BED FOR FUTURE INSTALLATIONS

Figure 20

determine whether any problems might be encountered during installation. No problems were encountered.

Figure 21 pictures fiber optic sensors. These are overfilled fibers, but really it's three hydrophones. This is a differential hydrophone. This is called a slinky and this is called a planar hydrophone. This is the latest model. It has been tested at sea in an optical towed array. This has also been tested at sea in an all optical array. The electronics are located on the ship. Infrared light is passed down the fiber to the hydrophone. The return signal (light) is returned on the same fiber or a parallel fiber to a receiver on the ship. There are no electronic devices in the wet end. They are all onboard the ship. If the electronics fail, they are repaired on the ship.

What can we do with sensors? Well, we have basically three types: phase, amplitude, and intensity detection. For phase detection we use an interferometer, one of which is the Michelson interferometer. With this device, you're able to measure one quarter of the width of a hydrogen

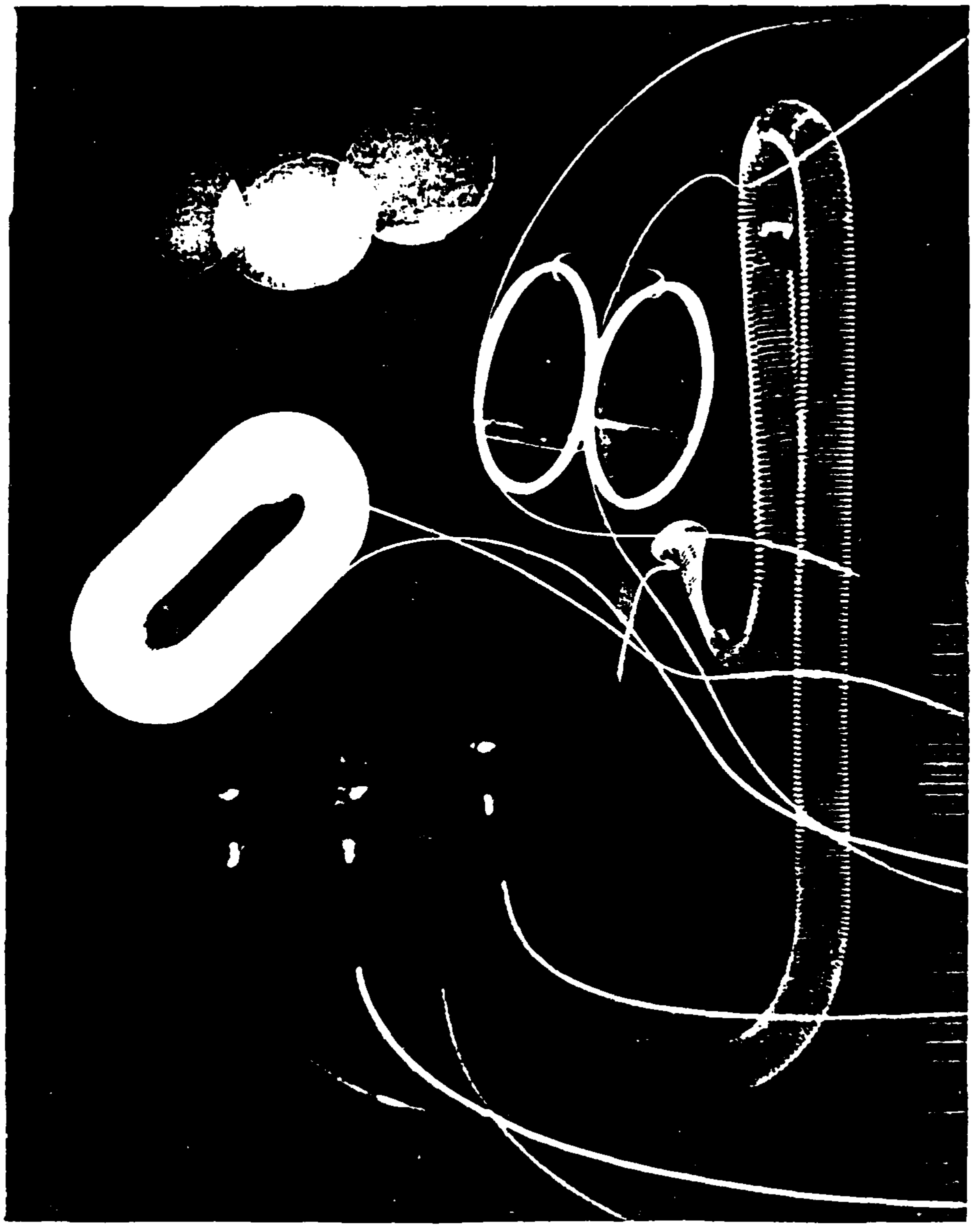


Figure 21

atom. Figure 22 shows some of the things you can do with fiber optic sensors and this is not an all-inclusive list, but is just the tip of the iceberg. Static pressure, acoustics, ultrasonics, strain, acceleration, magnetic fields--I've here a little piece of coated fiber that, believe it or not, we're trying to develop into an antenna. The coating is made up of polymers, with no metal involved. The polymer is excited by the RF energy field, which strains the glass fiber, coupling the RF energy into the fiber. It's just like an RF antenna--temperature, fluid flow, liquid level, rotation rate--very interesting. Inertial guidance systems, current measuring devices that are already out there, radiation devices that are already deployed in satellites. Displacement, seismic--and the list goes on.

56ZC-47

SENSOR TECHNOLOGY THRUSTS

PHASE DETECTION
- HIGH SENSITIVITY
- GEOMETRIC VERSATILITY

AMPLITUDE DETECTION
- SIMPLE CONSTRUCTION
- UTILIZES AVAILABLE TECHNOLOGY

SENSORS

STATIC PRESSURE	MAGNETIC FIELD	CURRENT
ACOUSTIC	TEMPERATURE	EM ANTENNA
ULTRASONIC	FLUID FLOW	RADIATION
STRAIN	LIQUID LEVEL	DISPLACEMENT
ACCELERATION	ROTATION RATE	SEISMIC

Figure 22

Why fiber optic sensors? (Figure 23.) One reason is that they are geometrically flexible, another is the extremely small sensor probes, and they can be coupled directly into a fiber optic transmission system. In other words, sensors can be coupled into a transmission system without using electronics. I can basically send the energy out and bring it back without having to put power at the source of the sensor as we do now. What this allows us to do is to put many sensors out, bring the information back to a single detector, thus cutting down on the amount of required electronics. It's immune to EMI and EMP; has low volume, and has low power requirements--in the microwatt region.

One way to make a fiber sensor is to coat a fiber with a material which, when exposed to a stress to be measured, such as a voltage, current, electromagnetic field, force, or pressure, will react in such a way as to strain the fiber. This strain results in a change in length of the fiber, which is measured as a change in phase of a lightwave propagating in the fiber. My example of a hydrogen atom is only to point out that we can measure very

WHY FIBER OPTIC SENSORS ?

- GEOMETRIC FLEXIBILITY
- EXTREMELY SMALL SENSOR PROBES
- DIRECT COUPLING TO FIBER OPTIC TRANSMISSION
- DIRECT COUPLING TO OPTICAL PROCESSING
- EMI IMMUNITY
- LOW VOLUME
- LIGHT WEIGHT
- LOW POWER

Figure 23

small changes in length in the fiber caused by the mechanical constriction of the coating material bonded to the glass.

We have, as I've indicated in Figure 24, acoustic, magnetic, thermal, and electric sensors--and here are different materials that are potential candidates for coating the fiber to make it sensitive to a particular energy field. They are not exotic materials, but ones that we sometimes discover by accident.

Changes in light intensity is another sensing technique used to detect changes in an energy field. The microbend sensor is a common type of intensity sensor. It works by placing a fiber between rows of teeth, as shown in Figure 25. When pressure or force is applied to close the teeth, the fiber is deformed by the teeth causing small microbends in the fiber. Some of the light in the core is lost due to changes in the incidence angle of the light at these microbends. The variation in applied stress can be calculated from a function of the light intensity.

COATINGS FOR FIBER OPTIC TRANSDUCTION

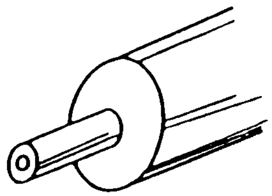
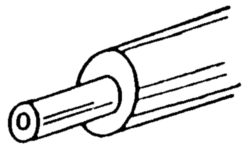
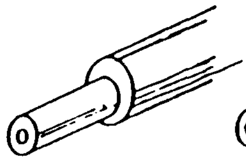
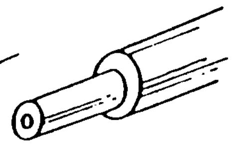
SENSOR	ACOUSTIC	MAGNETIC	THERMAL	ELECTRIC
				
COATING	ELASTOMERS	MAGNETOSTRICTIVE	THERMALLY EXPANSIVE	PIEZOELECTRIC
	• POLYSTYRENE • NYLON	• NICKEL ALLOYS • MET GLASS	• NICKEL • ALUMINUM	• PVF_2 • CO-POLYMERS
APPLICATION TECHNIQUE	EXTRUSION	ELECTROPLATING EVAPORATION ION SPUTTERING	ELECTROPLATING EVAPORATION CHEMICAL DEPOSITION DIP-COATING	EXTRUSION
SPECIAL CONSIDERATIONS		ANNEALING BIASING		POLING MOLECULAR-ORIENTATION

Figure 24

CORE-CLADDING COUPLING CONDITION

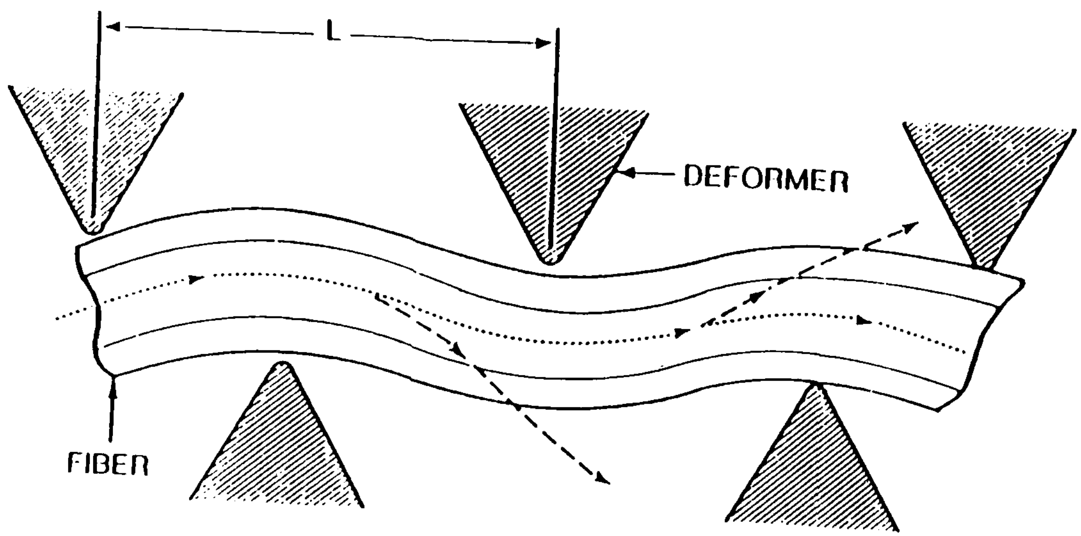


Figure 25

Next is the liquid level sensor, Figure 26. This one uses the technique of refractive-index difference. Many of you have seen this particular application used as the magic eye in automobile batteries. If the eye is bright, add water. When the eye is bright the light in the eye is totally internally reflected because the refractive index of the air surrounding the tip of the eye is lower than the refractive index of the eye material. When the liquid is at the same level or higher than the tip, light in the eye is refracted into the liquid because the refractive index of the liquid is higher than the eye material. The eye then appears dark. This technique can be applied to sense when a liquid reaches a certain level, for example the liquid level in the bilge of a ship can be read at locations remote from the bilge.

Optical interferometers use two sensing arms, one isolated from the energy field to be measured and the other exposed to it. The change in length of the arm exposed to the energy field and its resulting signal change is compared to the signal in the isolated (reference) arm. The difference translates into phase changes that can be

LIQUID LEVEL

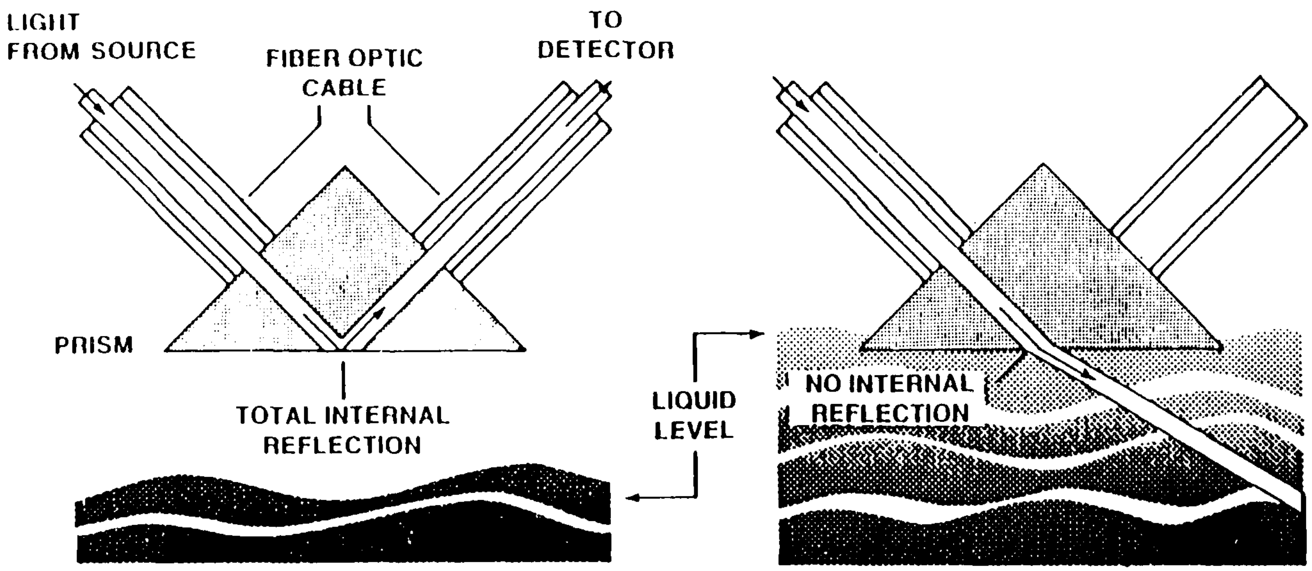
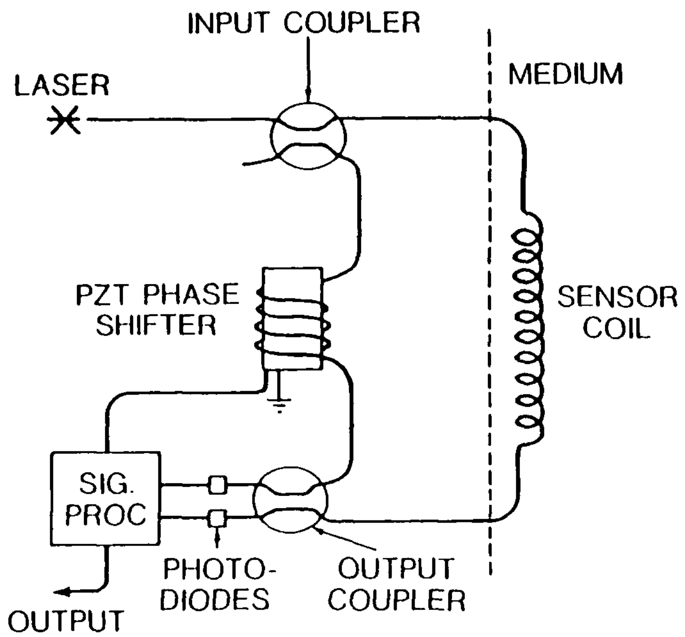


Figure 26

precisely measured. What that basically says is this. I start out with a fiber this long, I react with it, and now it's this much longer and this increased length results in phase shifts relative to the lightwave in the reference arm. When these two waves are combined, changes in intensity at the detector occur. It's basically that simple.

You don't need a very sophisticated detector, and this (Figures 27 and 28) is how the acoustic array works; it uses a phase-shift-detection mechanism.

INTERFEROMETRIC SENSOR CONCEPT



- DETECTS INDUCED OPTICAL PHASE SHIFT

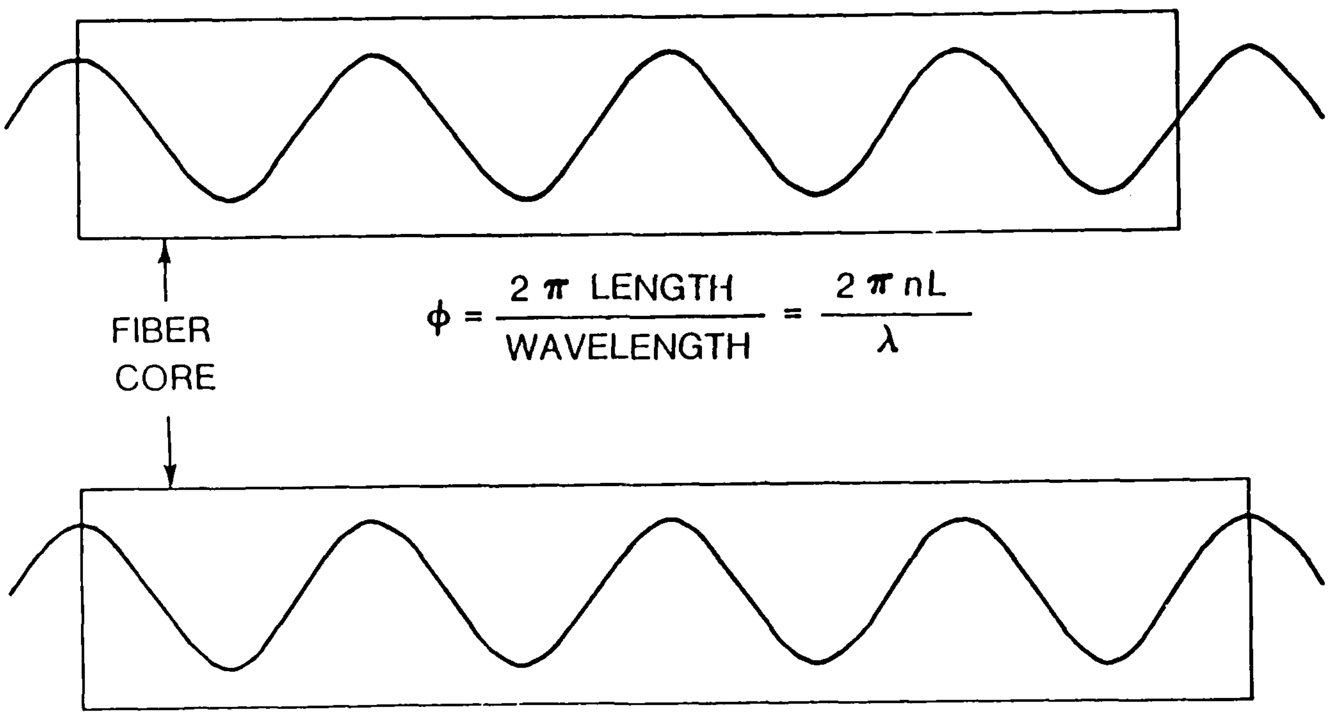
$$\Delta \phi = \left(\frac{1}{n}\frac{\delta n}{\delta P} + \frac{1}{L}\frac{\delta L}{\delta P}\right) knL \Delta P$$

- SENSITIVITY PROPORTIONAL TO LENGTH OF FIBER, L, IN SENSOR

- DIRECTIVITY DEPENDS ON SENSOR FIBER CONFIGURATION

Figure 27

PHASE CHANGE THROUGH FIBER



$$\phi = \frac{2\pi \text{ LENGTH}}{\text{WAVELENGTH}} = \frac{2\pi nL}{\lambda}$$

$$\phi + \Delta\phi = \frac{2\pi n}{\lambda}(L + \Delta L)$$

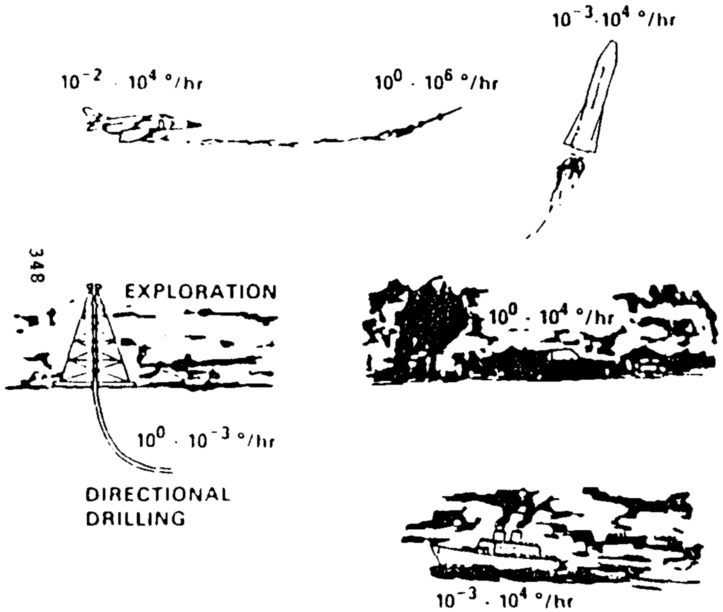
Figure 28

Optical interferometers are also used in fiber optic gyroscopes, Figure 29. Optical gyroscopes are being looked at for use in aircraft, missiles, ships, land vehicles, and in oil exploration for logging drill bit location. The size of an optical gyro is dependent on the application and accuracy desired. I have seen them as small as my thumb. The Army is using them to stabilize projectiles--not missiles--projectiles.

A comparison of the theoretical limits between fiber, conventional, and ring-laser gyros, Figure 30, shows the quantum limit for the ring-laser gyro is in this region, the electrostatic gyro is up here, while the fiber optic gyro is way down here. We calculated that if we put a fiber gyro with a 5×10^{-7} degree drift per square root hour in a ship we could go to sea for 90 days and, with no correction to the system, return to within 5 feet of where we started! This represents a significant increase in performance.

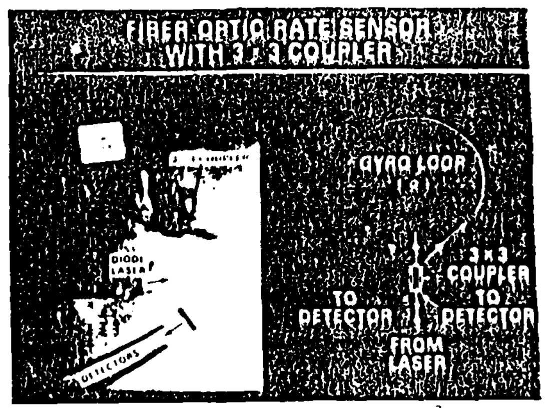
FIBER OPTIC GYROSCOPE

TYPICAL REQUIREMENTS



TECHNOLOGY

LOW COST 1°/hr FIBER GYRO



STATE OF ART PERFORMANCE ~ 10^{-3}°/hr

Figure 29

FIBER OPTIC GYRO PERFORMANCE

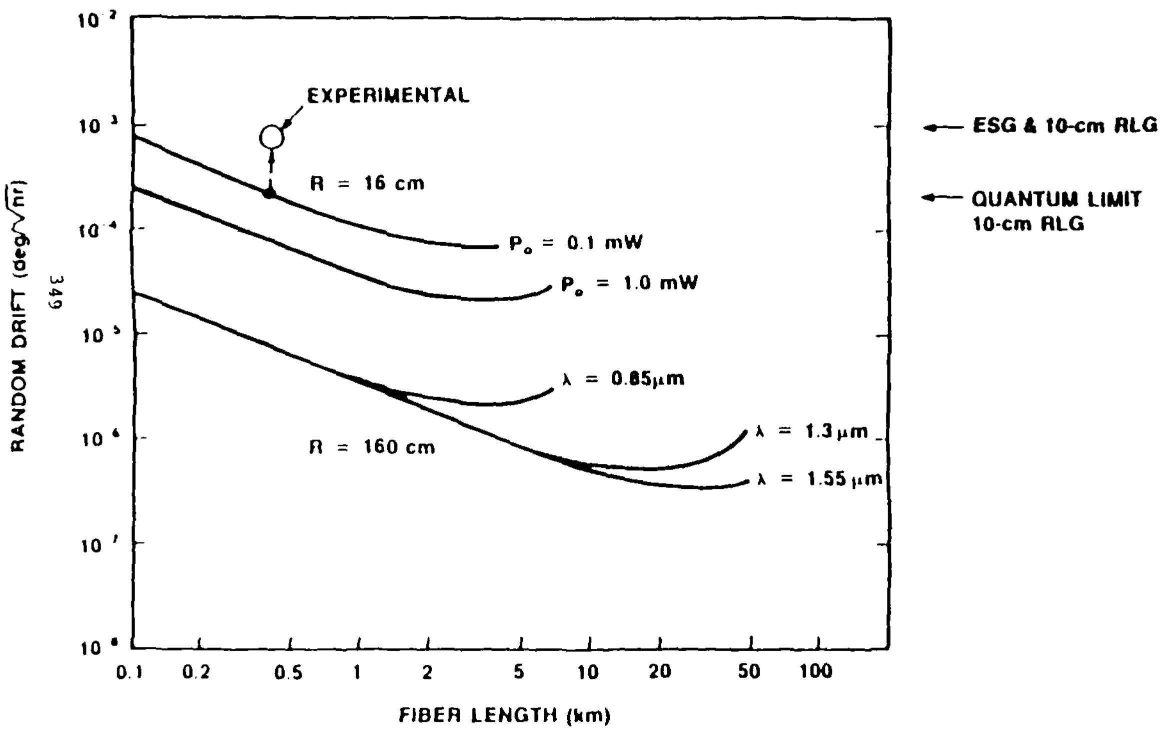


Figure 39

Advantages of the fiber optic gyro over the ring-laser gyro, Figure 31, include: no locked-in phenomenon, no plasma flow, no complicated base block fabrication, no critical mirror fabrication or aging problems, and no high voltage requirements.

Figure 32 depicts a series of sensors coupled into a single-fiber fiber optic cable connected to a single detector. By spatially separating the sensors, the one detector can interact with each sensor, even though they may have different applications. I bring each signal back in spatial relationship and therefore in specific time slots so that now my computer can distinguish the signals from each sensor. This is simply time-division multiplexing.

Figure 33 shows the Navy program schedule for developing combat systems, radar, being the most complicated--interior communication, motor control, and sensor standards and specifications. The sensor portion is the only three-year program because the technology is not as mature as it is for communication, data-transfer network topology, and propulsion control. All of this is a two-

ADVANTAGES OF FIBER OPTIC GYROS VS. RING LASER GYROS

- NO LOCK-IN PHENOMENA
- NO PLASMA FLOW PROBLEMS
- NO COMPLICATED BASE BLOCK FABRICATION
- NO CRITICAL MIRROR FABRICATION OR AGING PROBLEMS
- NO HIGH VOLTAGE REQUIRED

Figure 31

ALL-OPTICAL FIBER SENSOR SYSTEM

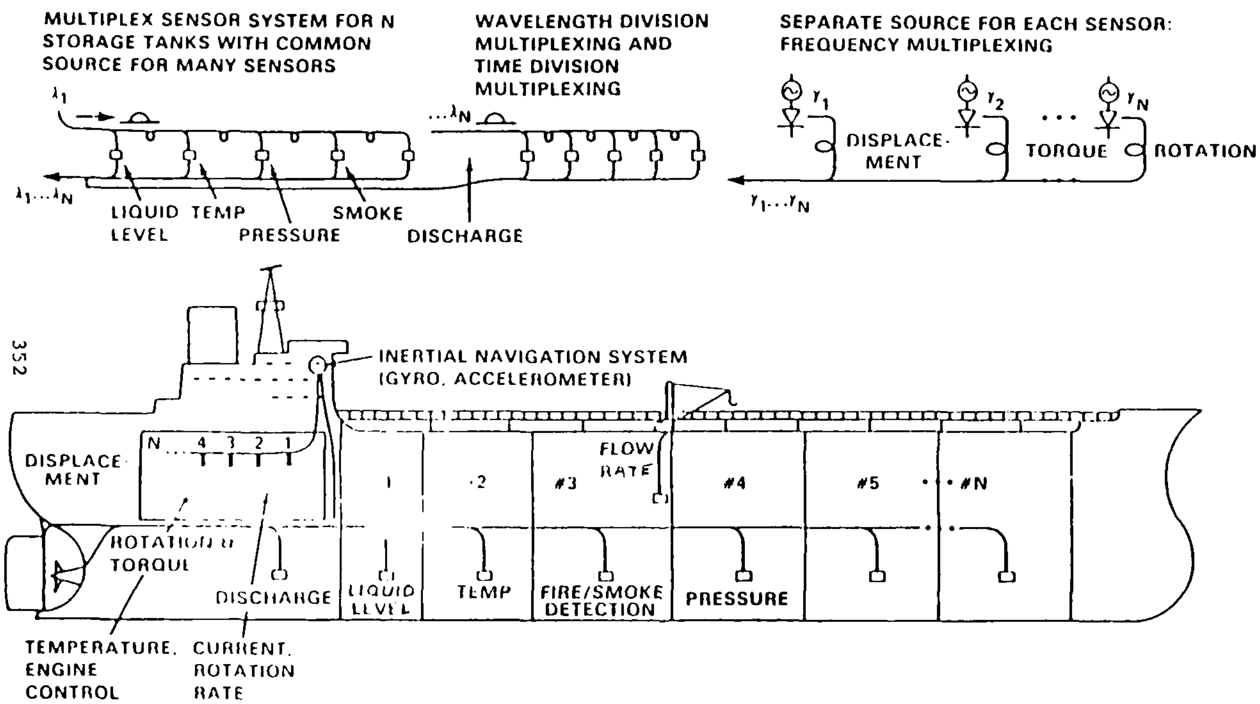
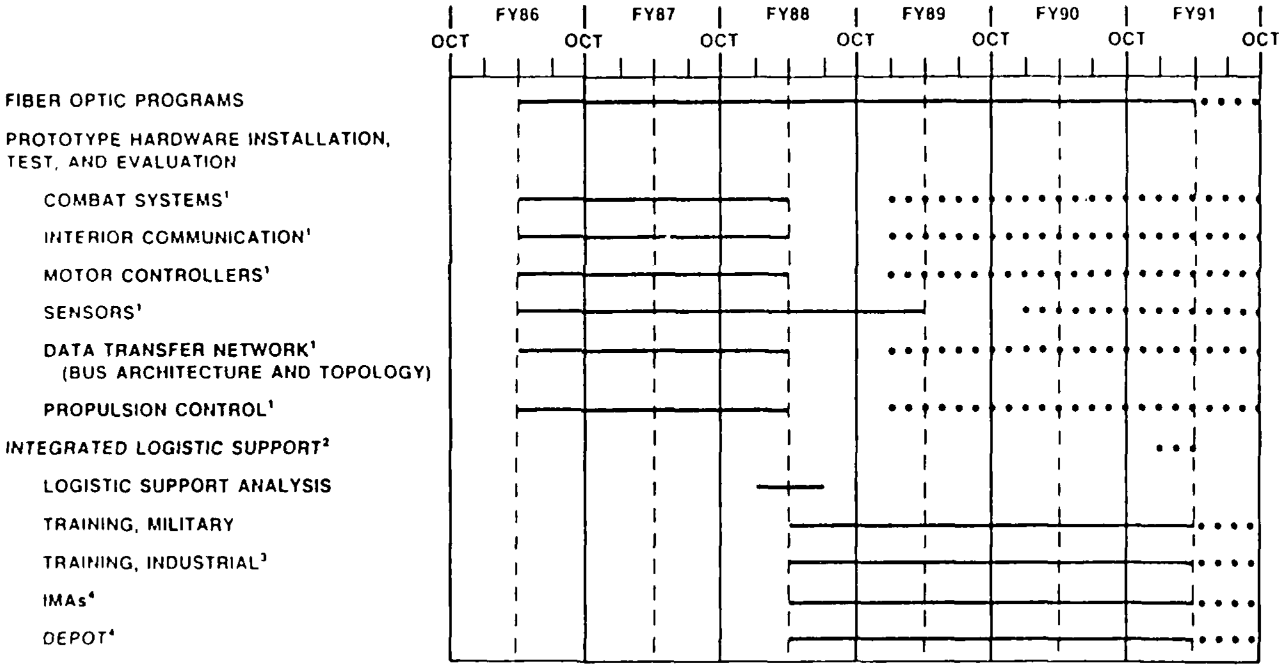


Figure 32

FIBER OPTICS STANDARDIZATION PROGRAM: SCHEDULE



[1] PRODUCT: NAVY STANDARDS AND SPECIFICATIONS

[2] *FULL ILS SUPPORT*

[3] INCLUDES TRAINING FOR GOVERNMENT AND PRIVATE INDUSTRY PERSONNEL IN INSTALLING AND MAINTAINING FIBER OPTIC EQUIPMENT

[4] ESTABLISH IMA- AND DEPOT-LEVEL FIBER OPTIC CAPABILITY

• • • PROGRAM CONTINUES IN OUT YEARS

Figure 33

year window.

The objective is to develop fiber optic standards and specifications that the acquisition managers can use to procure components from industry at a reduced risk to their programs. In doing this, we're approaching the problem a little bit differently in that we're doing the standards and specification work up front. The Services have opposed this approach in the past. We're going to put fiber in land-based test sites, onboard ships, test it, proof it, prepare and validate the documents, and then turn them over to the system. In the past, we bought the equipment, wrote the documents after the fact, and spend the next 15 to 20 years trying to get well. It's a known fact that if you can solve standards problems in the early parts of the development cycle for a few dollars, you can save yourself millions of get-well dollars in the long run.

The logistics program doesn't start until mid-1988. When the logistics program goes in place, we're looking at a full logistics program of training, not only for the military, but also for the industrial components. We're also looking at developing IMAs and depots. We're looking at putting into the ship the full logistics package that is supportable.

People have questioned the repairability of fiber in the operational environment. There are a couple of ways to repair fiber operationally. You can fusion splice it, put in a connector, or simply do nothing. I've got a 220-megabit system here that has a transmitter and receiver, one on each end. What happens to the system if the glass breaks in the middle? The system may not necessarily be broken. The break may look as though a connector were placed in the system. Most of the light will pass across the gap. On the other hand, a broken wire is an open circuit. Therefore, several fiber breaks can be introduced into a single-fiber cable and the system will not necessarily be down. So we have to rethink what "broke" is. We have to ask ourselves, "What do we mean by MTBF?". We're reevaluating it at this time, not only the general ship design specifications and how we put fiber optics into them, but also the maintenance concepts that we have to go through, and the design concepts used.

We're treating this effort as a total program. We have looked at the documentation requirements and have determined that 600,000 combinations of documents will be required. Obviously, we can't write that many in two years, but we have to address the most important subject areas required by the user. We have to tell the user how to design it, what type of components to consider--not only for the MTBF, but also for the maintenance side of it.

In conclusion, fiber is rugged, has a high tensile strength, is lightweight, small in size, has high bandwidth, is low-cost, and is benign, Figure 34. I mean by "benign" that it is kind to the environment. It does not contribute to, nor is it influenced by, the electromagnetic environment in which it is placed. You can put fiber in an electric power generator, in cableways, surround it with 400-volt power lines and you're not going to interfere with its operation. It is a marvelous transmission medium to work with. It also has another nice characteristic in that if your system has to be worked on, you need not power anything down or tag it out to prevent people from getting hurt. You simply work on it. You take your two pieces of fiber and you work on it. We're

- RUGGED (HIGH TENSILE STRENGTH)
- LIGHTWEIGHT
- SMALL SIZE
- LOW COST
- BENIGN

Figure 34

dealing in microwatts of optical power. Even the lasers aren't going to hurt you. You put it back together and the system works. You also don't run the risk of turning the system back on only to blow something up.

Fiber is also very secure from intrusion and very difficult to tap, Figure 35. I know of only one tape recorder that records in the 560-megabit/second region, and if I happen to be putting a gigabit/second of data across a fiber, the guy's going to get a lot of garbage. He has to understand what's there, and if I happen to be putting more than a gigabit/second across, he needs a computer to determine what I have. It has the potential of eliminating sophisticated encryption processes. We can put out raw data, intersperse our intelligence with it, and pull it off with an algorithm and throw the rest of it on the floor, so to speak.

Thank you very much.

- ULTRA HIGH BANDWIDTH
- EMI/EMP IMMUNITY (ELECTROMAGNETICALLY COMPATABLE)
- SECURE (INTRUSION IS DETECTABLE)
- NON CONDUCTIVE

Figure 35

THE NATURAL ENVIRONMENT IN THE STRATEGIC DEFENSE INITIATIVE PROGRAM

by

Dr. Paul F. Twitchell*

Today I will briefly describe a middle atmosphere research program funded by the Strategic Defense Initiative Organization (SDIO), Innovative Science and Technology (IST) office. Before I proceed, let me explain where I fit into the program management scheme of things. For the program I am about to describe I report to the Innovative Science and Technology (IST) office of SDIO. They provide the funds but

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*Dr. Paul F. Twitchell earned B.S. and M.S. degrees in Physics from Boston College, a B.S. degree in Meteorology from Penn. State University, and a Ph.D. degree in Oceanography from the University of Wisconsin, Madison. He did additional graduate study at MIT, Harvard, and Northeastern Universities and attended the Air Force Command and Staff School, Industrial College of the Armed Forces, and the Air Force War College. Industrial experience with Melpar, Inc. preceded his joining the Office of Naval Research in 1962. During the academic year 1981-1982 he was Visiting Professor, Oceanography Department, U.S. Naval Academy. Since 1986, Dr. Twitchell has been manager of atmospheric, oceanic, polar, and middle atmosphere programs of the Applied Research and Technology Directorate of the Office of Naval Research.

delegate technical management to what are called "agents." I am the SDIO/IST agent for the natural environment but work for the Office of Naval Research (ONR) in a new group, The Applied Research and Technology Directorate (ARTD). As the title implies, this new directorate's mission is to bridge the gap from university basic research to laboratory and industry development efforts. Many of the SDIO/IST programs, at least the one on natural environment, are designed and managed within the mission goals of ONR's Applied Research and Technology Directorate.

My part of the IST program is concerned with the environment or, specifically, the middle atmosphere. I define the middle atmosphere to be that region above conventional meteorological observational altitudes of about 10 kilometers (km) to the ionosphere, or approximately 100 km. Many people refer to it as the ignosphere, and I've heard other people call it the no-funds-sphere. But, for as long as I've been in the business, since the early 60's, we've never found a good reason to support research in what is generally called the middle atmosphere. The Air Force doesn't operate that high, the Navy doesn't operate that high, missiles go through it, communication people aren't worried about it, so the region went unexplored. Along comes SDI, and there are a number of things in the middle atmosphere that are potential problems. One potential problem is the characterization and understanding of noctilucent clouds. These clouds, if you pick up a text book as recent as the early 80's, are referred to as dust clouds. The term noctilucent implies that they're night time only. This is because they generally are only seen in the evening at latitudes of about the Arctic Circle. So hence the name noctilucent. They're not dust, they're ice. They don't just exist there, they were only seen there by the naked eye from the deck, because the sun angle was right at that time of year and at that latitude. Figure 1 is a photograph of noctilucent clouds--note the structure indicating wind motion in a wave manner. From space flights the Soviets have reported noctilucent clouds at middle latitudes in both Northern and Southern hemispheres. The Soviets ran a big conference in 1984 on noctilucent clouds and I felt that some of the information coming out of that conference was of interest to us. So James Hughes, an ONR

Figure 1. Noctilucent Clouds 600 to 700 km north of Poker Flat Range (near Fairbanks, Alaska) on 14 August 1984. Note wave-like structure indicating the presence of atmospheric waves at estimated 84 km cloud altitude. The bright area, left center foreground, on photograph is aurora estimated to be 150 km away and 140 km altitude. Photograph courtesy of Neal Brown, Director, Poker Flat Research Range, University of Alaska.

colleague and I, proposed a program on the Natural Environment which has a subtitle Mid-Atmospheric Effects. The program was designed to provide SDI some engineering data, and maybe, if we could understand what's there, predict the variables.

What I want to do right now is to give you an anatomy of how this program evolved. The rationale, basically, was that the existing data base, primarily the cloud data, was inadequate. If one went to the archives and used the cloud data, one could be misled, draw maybe a wrong conclusion and design a system that may or may not work. For example, cirrus clouds (ice clouds about 10 km altitude) are often not reported, especially at night. The research goals of this new program focused on some of the really unknowns. First great unknown is the variability of the middle atmosphere. For example the propagation of long waves in the general atmospheric circulation flowing around the globe. (The "jet stream" depicted by television meteorologists is a manifestation of these long waves in the lower atmosphere.) These waves of air travelling around the globe are like any wave, they become unstable and break in what Prof. Michael McIntyre at University of Cambridge calls a surf zone. One surf zone is the mesopause, which is about 80 to 85 kilometers up or about 275,000 feet or, maybe think of it in miles, some 50 miles up. It is a layer of sharp temperature difference. We have surf zones in the lower atmosphere like at the tropopause. If you're ever flying in a commercial aircraft at about 30 to 40 thousand feet, and all of a sudden encounter turbulence, a probable cause may be the aircraft went over a leaf of the tropopause, and that's another surf zone. This is where the waves actually break, just like an ocean wave, and cause quite a problem if you're flying there. But the other interesting part about it, of course, is you have rapid density changes. Material collects in the atmosphere wherever there is a sharp temperature change, such as found at the mesopause around 85 km. The turbulent transport of material in that region due to breaking of waves will also change optical scattering from the still unknown particulates.

In broad categories there are two major middle atmosphere unknowns; (a) the dynamics or circulations (winds), and (b) the constituents (optical properties).

Atmosphere scientists from the turn of the century have been modeling atmospheric circulation and today with state-of-the-art computers are capable of depicting, and to a limited extent (3-6 days) predicting, atmospheric flow in the lower 10 kilometers. The same equations apply to middle atmosphere and, indeed, dynamic models are now being developed by a few pioneering scientists. During World War I, a British scientist, L. F. Richardson, formulated numerical models for atmospheric circulation but attempts to apply these models were thwarted by lack of data. During World War II a global atmospheric observational network up to altitudes of 10 km became a reality. Forward-looking scientists in the U.S. Navy and particularly in the Office of Naval Research recognized the potential of numerical models in predicting weather and, with the advent of electronic computers, initiated a numerical weather prediction program. These ONR contractual efforts that started in 1946 were phased out of basic research in the 1960's when weather centers, such as the Navy's in Monterey, California, were operational and civilian agencies were funding the university research. The Navy continues applied research in numerical modeling at Naval Environmental Prediction Research Facility, also in Monterey.

In the 1960's the Atmospheric Science research programs in the Navy began a cloud physics effort to improve the understanding of aerosols, cloud particles and precipitation processes. Twenty-five years later chapters in textbooks have been rewritten and electro-optical weapons systems designers now have limited information on atmospheric attenuation. The understanding of lower atmospheric particulates is far from complete, but new military systems are being designed to operate through a region of the atmosphere where knowledge is extremely minimal. In situ observations of particulates in the high middle atmosphere (50 to 100 km) are essentially non-existent. As in the case of dynamics, where the same fluid equations are assumed to apply up to 100 km altitude, it is also assumed that the basic cloud physics of the lower atmosphere should also apply in the middle atmosphere.

Unfortunately there are few observations of the middle atmosphere dynamics or particulates. Advanced theoretical models depicting middle atmosphere circulation using the super computers of the 1980's will remain as interesting academic exercises until the necessary observations are available. In the 1950's conventional numerical weather prediction was limited by computer power. Today the middle atmosphere modelers have, or will soon have, adequate computer power but there is a lack of observations to develop reliable prediction models. Similarly, the cloud physicist can develop theories and simulate in his laboratory the optical properties of hypothetical middle atmosphere particulates, but he lacks observational data. Therefore, the third part of the SDIO middle atmosphere effort is a measurements program that will provide data for both the dynamic modeler and the cloud physicist.

The SDIO Innovative Science and Technology Natural Environment Program was first announced in the Spring of 1985 and I was designated as the "agent." I recall 128 preproposals were received for which there were funds to support only a limited few. Originally Mr. Hughes and I read the preproposals but soon the volume and wide range of scientific disciplines being addressed required a new approach, specifically, a multi-agency committee of experts

(Table I) was established. One of the committee meetings evaluating the proposals was held here at the Naval Academy.

TABLE I

MIDDLE ATMOSPHERE ADVISORY PANEL

1985	1986
Dr. Paul Twitchell, NAVAIR	Dr. Paul Twitchell, ONR
Mr. James Hughes, ONR	Mr. James Hughes, ONR
Dr. Douglas Brown, ASL	Dr. Douglas Brown, ASL
LTC Gerald Dittberner (PhD), AFOSR	LTC James Koermer(PhD), AFOSR
LCDR Stan Grigsby, SPAWAR	Dr. Robert Hudson, NASA
	Dr. George Reid, NOAA

ONR	Office of Naval Research
NAVAIR	Naval Air Systems Command
SPAWAR	Naval Space and Warfare Command
ASL	Army Atmospheric Science Laboratory
AFOSR	Air Force Office of Scientific Research
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration

That first year (1985) six contractors were selected. They were a balanced group addressing parts of the major gaps in knowledge that were previously discussed. The initial "six" are listed in Table II indicating the area of research.

TABLE II

INITIAL MID ATMOSPHERE EFFECTS CONTRACTORS

PRINCIPAL INVESTIGATOR AND INSTITUTION	TOPIC OF RESEARCH
Prof B. Vonnegut State University of New York, Albany & Prof A. Roddy University College, Galway, Ireland	Microphysics of Noctilucent Cloud Particles
Dr. W. Finnegan & Dr. R. Pitter Desert Research Institute Reno, Nevada	Habit Forms of Middle Atmosphere Clouds
Dr. T. Vonder Haar & Dr. T. Brubaker Colorado State University	Fast Algorithms to Depict Clouds From Satellite Data
Prof V. Suomi, Dr. D. Wylies & Dr. E. Eloranta University of Wisconsin	Cloud Distributions and Structure From Satellite and Ground-based Systems
Prof. R. Pfeffer Florida State University	Global Circulation Modeling, Focus on Stratospheric Warming
Prof T. Wilkerson University of Maryland	Middle Atmosphere Measurements From Ground-based Laser

The need for understanding the middle atmosphere was recognized by SDIO and this IST program funding increased four-fold in the second year plus arrangements were made outside of IST for additional resources. It is now the third year of the program and, like the second year, arrangements are in progress for additional resources from other groups within SDIO and from the Air Force to enhance scientific achievements. The additional principal investigators acquired in years 2 and 3 of the program are listed in Table III.

For improved understanding of the middle atmosphere there is a need for additional investigators studying the dynamics. This shortcoming was evident at the annual review held in November 1986 at Boulder, Colorado. All of the principal investigators, or their colleagues, presented their programs and plans in Boulder. Participating were members of the advisory panel, other SDIO, Air Force, Navy, Army, NOAA, and NASA program managers of related middle atmosphere efforts. The lack of measurements has been restraining progress in understanding the dynamics and the cloud physics of the middle atmosphere.

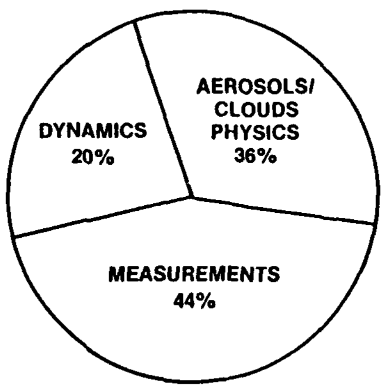
TABLE III

ADDITIONAL MID-ATMOSPHERIC EFFECTS CONTRACTORS

PRINCIPAL INVESTIGATOR AND INSTITUTION	TOPIC OF RESEARCH
Prof David Fritts University of Alaska	Gravity Wave Variability and Mass Transfer Between Layers
Prof Theodore Pepin University of Wyoming	Measuring and Charting Properties of Stratospheric Clouds From Satellites
Prof Gary Thomas University of Colorado	Measuring Mesospheric Clouds and Particulates From Space
James Ulwick University of Utah	Ground-based, Rocket, and Shuttle Measurements
Dr. John Grant Gould, Inc. Newport, Rhode Island	Breaking Atmospheric Internal Waves
Prof Michael McIntyre University of Cambridge Cambridge, England	Planetary Waves and Mid-atmospheric Dynamics

Shown in Figure 2 are the efforts and the percentage of resources being allocated to each major category indicated. Let me briefly discuss each effort, pointing out how they are related, and draw upon other program resources to accelerate progress. I will start with the aerosol and cloud category.

Dr. Bernard Vonnegut is considered by many to be the leader in weather modification research. His distinguished career began at General Electric working with Dr. Irving Langmuir.



- Dynamics
  - University of Cambridge
  - Florida State University
  - University of Alaska
  - Gould Inc.
- Aerosols/Clouds
  - State University of New York and University College of Galway Ireland
  - Desert Research Institute
  - University of Wisconsin
  - METSAT Inc.
- Measurements
  - University of Wyoming
  - University of Colorado
  - University of Maryland
  - Utah State University

Figure 2. Middle Atmosphere research areas, funding distribution and institutions.

Dr. Vonnegut and A. Roddy teamed on a proposal studying the microphysics of noctilucent cloud particles with a goal to understand possible artificial means of changing these clouds. Professor Roddy presented a landmark paper at the 1984 Soviet noctilucent cloud conference summarizing the contemporary knowledge on these clouds. Vonnegut and Roddy are developing hypotheses on the cloud particle nuclei, lattice structure, and formation process. The plan is to extrapolate laboratory experiments by similitude arguments to the mesosphere. There is a <u>need</u> for measurements of mesospheric clouds to support or refute the emerging hypotheses.

At the Desert Research Institute, Reno, Nevada, Dr. William Finnegan and his young colleague, Dr. Richard Pitter, are investigating the habit (shape) of cloud particles in a cold environment such as found at high altitude or in Polar regions. Using deuterium-free water they have found ions separate in the crystals setting up electric fields which influence the habit and aggregation. In other words they have created cubic ice particles believed to be similar to mesospheric cloud particles, and the Desert Research Institute team also have a hypothesis on the formation of cubic ice. These results will help to understand the electro-optical scattering in mesospheric clouds and may advance understanding the structure of other materials.

At the University of Wisconsin the innovative mind of Professor Verner Suomi suggested a unique way to compile realistic cloud statistics from operational satellites. These are not ordinary cloud statistics, found in the archives. At Wisconsin Dr. Donald Wylie has pioneered a method using satellite-derived data to determine if clouds are present while his colleague, Dr. Edwin Eloranta, calibrated the satellite data with ground-based lasers. In addition, the Wisconsin group has measured subvisible cirrus clouds thousands of feet in vertical extent with the lasers. These clouds above 25,000 feet are not visible but are a problem for conventional infrared weapons systems designed in the belief the air is clear above the visible clouds. For strategic defense ground-based lasers, all clouds including subvisible cirrus, must be considered in the design. Figure 3 is an example of cirrus detection with the

Figure 3. Infrared imagery of clouds over southwest United States from operational geostationary weather satellite. White Sands Missile Range (WSMR) is in center of box.

Wisconsin laser system.

A small company in Colorado led by Dr. Thomas Vonder Haar and Thomas Brubaker has exploited state-of-the-art computer graphics, cloud physics and cloud modeling to develop a system that can, in real-time (approximately seven seconds), process a satellite image. The system was recently demonstrated at White Sands Missile Range. This system can provide continuous cloud free line-of-sight information to a ground-based laser operation or for any weapon system. Today the cloud data are extrapolated using models from the satellite images available every half hour. Figure 3 is an example of a typical infrared cloud image for the White Sands area. Note a thin window in the clouds south of the WSMR label. In Figure 4 are depictions of clouds at different elevation angles looking up from WSMR. Notice the pie-shaped wedge on the display indicating clear air. The technology developed for ground-based lasers can be applied to aircraft and missiles. Figure 5 is an example showing clear air below a cloud deck. This has potential application to Navy over-ocean surveillance systems. In the 1990's a civilian satellite called GOES-NEXT (Figure 6) will

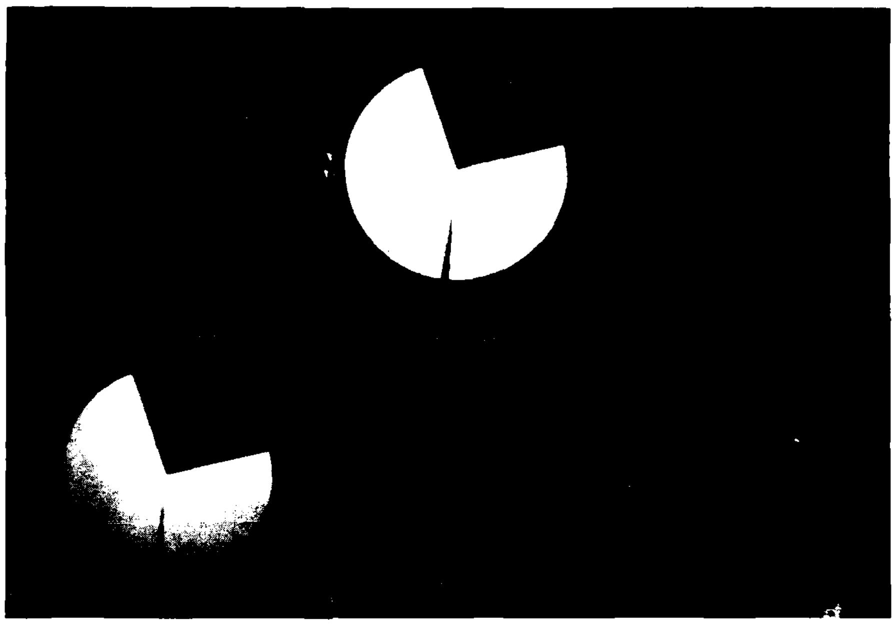


Figure 4. Cloud free line of sight (shaded) at different elevations and azimuth angles from White Sands Missile Range. White indicates clouds.

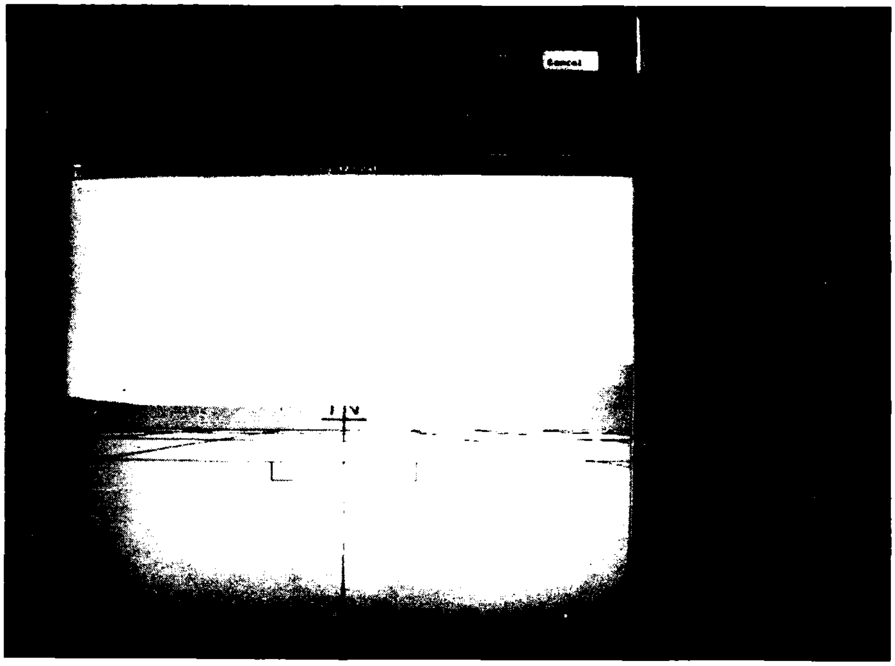


Figure 5. The technology developed for ground-based laser systems could be used by aircraft or missiles. Shown here is ground, a clear region, and clouds above.

Figure 6. The GOES-NEXT series of satellites will be launched by the United States during the 1990-1995 period. As the second generation of operational geostationary weather satellites, two from this series will be on station at all times, thus covering the Western Hemisphere, most of the Atlantic and the Eastern Pacific. Separate imaging and sounding instruments will remotely sense clouds, atmospheric gases and surface features.

have operational capability to provide a cloud image in time intervals of less than one minute.

Clouds change rapidly, but with ultra fast algorithms and frequent data input, the system developed at Colorado can keep up with nature. This real-time capability will make it possible for the strategic battle manager to advantageously use the environment (clouds) as a force multiplier. Last week Professor Suomi used a cartoon in a scientific lecture at an American Meteorological Society Meeting. He showed a person sitting on a curb side, trying to get a drink out of a fire hydrant that was just blasting the poor guy to death with water, and that's basically what happens with these satellites. They're dumping data at such a rate that they're drowning us, and these fellows in Colorado have come up with what I think is really advanced state-of-the-art technique for rapidly processing these data. I am sure that this work for SDI will find applications in the operational Navy. Contemporary operational satellites do not detect optically thin clouds such as cirrus clouds. Visible cirrus are those high wispy clouds that look thin to the naked eye. Some are so thin a ground observer looking up concludes no clouds are present and these clouds do not appear in satellite imagery. The University of Wisconsin group has developed a method to determine the extinction of a laser beam by separating the backscattered light from cloud and aerosol particles from the Rayleigh scattering of air molecules. From these components of the backscatter, a direct computation of radiative extinction is possible. An example of Dr. Edwin Eloranta's (University of Wisconsin) scanning laser system is shown in Figure 7. The technical advances by the Wisconsin group also have application to Air Force and Navy aircraft infrared search and track systems test planning.

Aerosol distribution and cloud formation results from air mass transport. Sometimes that transport is turbulent when waves in the atmosphere break. Clouds at all levels often manifest the air motion showing a wave-like pattern. The cloud patterns are one way to study dynamics. Last summer three of the investigators were urged to conduct an experiment using satellite, rockets, and ground-based measurements of atmospheric dynamics. They called the operation, or campaign, Mesospheric Ionization/Infrared

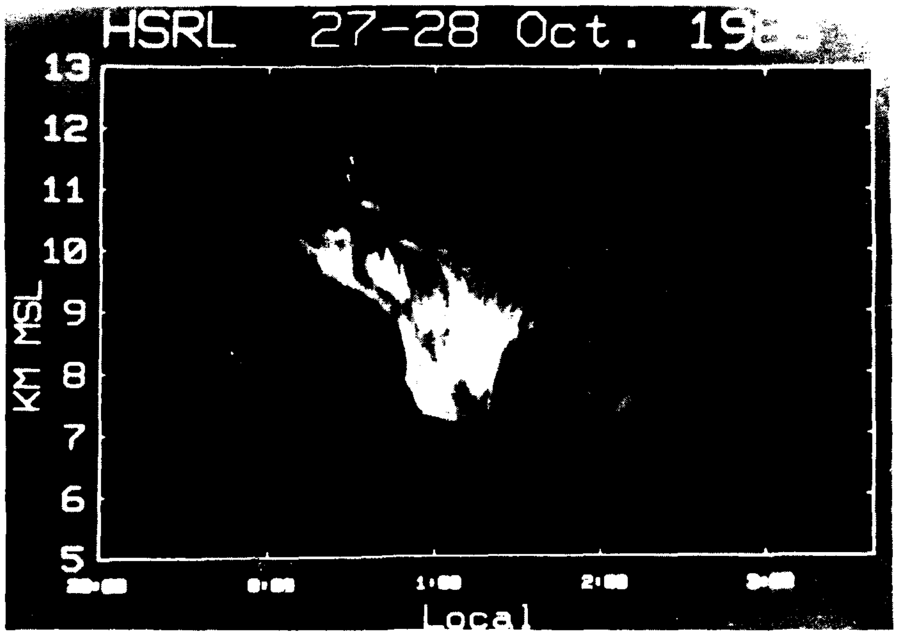
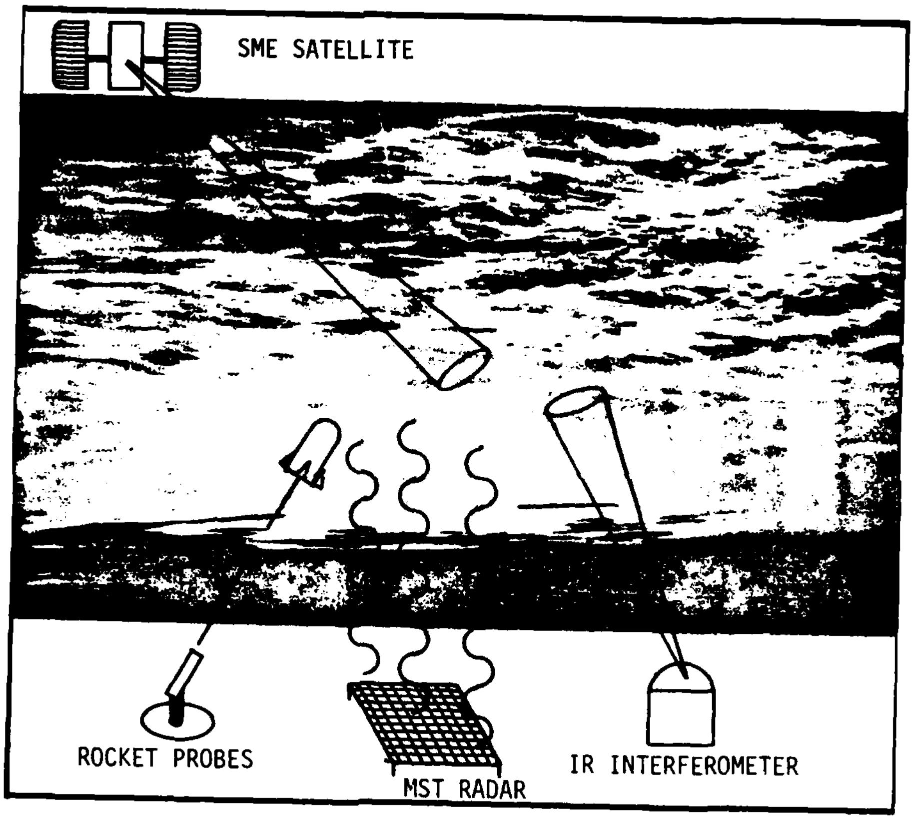


Figure 7. Ground-based laser return from night cirrus clouds over Madison, Wisconsin. Note the vertical extent from 7 - 11 km in mean sea level (MSL) altitude.

Structure and Turbulence Investigation (MISTI). Figure 8 is a cartoon indicating the measurement techniques. This was carried out last summer at the University of Alaska Poker Flat facility near Fairbanks. It is a good example of cooperative science and links the aerosol, dynamics, and measurement parts of the program. The Solar Mesospheric Satellite (SME) was "turned off" by NASA last month (December 1986) after a long and successful operating period of several years.

The Mesospheric Stratospheric Tropospheric radar is being moved by its sponsor, National Science Foundation, to another site. The August 1986 campaign was successful. Mesospheric clouds were detected by the radar, rockets were launched, and satellite data acquired. The rocket data obtained by James Ulwick of Utah State are believed to be the first in situ mesospheric cloud measurements. David Fritts, University of Alaska, analyzed the MST data for winds indicating gravity waves were propagating through the regions, while Gary Thomas, University of Colorado, SME data indicated polar mesospheric clouds were present. From SME's 265 nm sensor system data it is now known mesospheric clouds



MISTI CAMPAIGN

Figure 8. Mesospheric Ionization/Infrared Structure and Turbulence Investigation (MISTI) was a multi-university effort conducted in August 1986.

cover extensive regions during summer months. While SME was capable of charting summer mesospheric clouds, other satellites have charted what Professor Theodore Pepin calls the world's largest cloud. Professor Pepin, University of Wyoming, flew a satellite and, like Professor Thomas, is now building the next generation system. The Wyoming instrument is a multi-channel limb scanner (Figure 9) which detects stratospheric clouds. These winter-time clouds are believed to be mostly volcanic dust.

If progress is to be made in understanding the middle atmosphere, specific measurements are needed. These measurements are those which the aerosol scientists and the numerical modelers need to validate hypotheses. Observations of opportunity provided by other experimenters may or may not be useful in gaining understanding of the middle atmosphere. Without this understanding the SDI systems' architects cannot intelligently suggest design criteria.

Well with that, I'm looking at the clock. I skipped quite a bit. I didn't want to get into too much detail, this late in the afternoon. But I've given you an overview

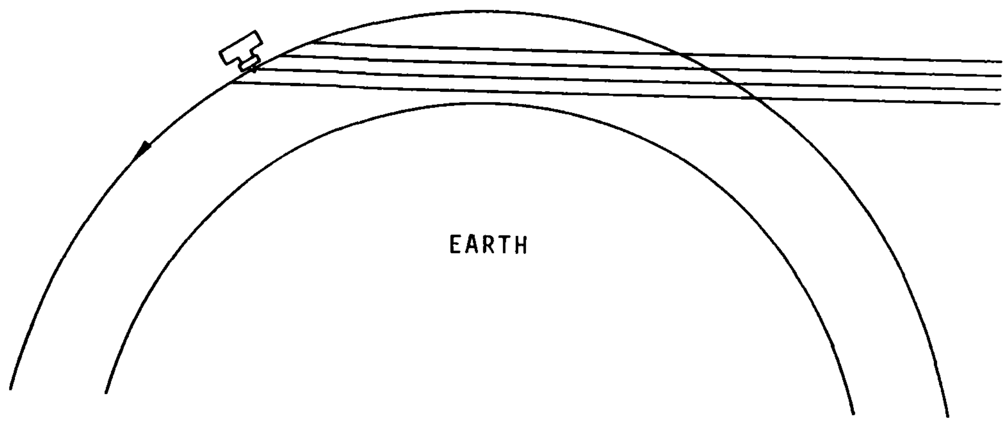


Figure 9. Shown is a limb scanning satellite orbiting above atmospheric region of interest but passive sensors "look" through the region of interest measuring atmospheric properties.

of what the natural environment, middle atmosphere program is at SDI, some of the players, and what we're focusing on at the moment. I'm open now for any comments or questions.