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Bulletin 50
(Part 1 of 4 Parts)

# THE SHOCK AND VIBRATION BULLETIN

**Part 1**
**Welcome, Keynote Address, Invited Papers**



**SEPTEMBER 1980**

A Publication of
THE SHOCK AND VIBRATION
INFORMATION CENTER
Naval Research Laboratory, Washington, D.C.

**Office of**
**The Under Secretary of Defense**
**for Research and Engineering**

## SYMPOSIUM MANAGEMENT

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**The 50th Symposium on Shock and Vibration was held at the Antlers Plaza Hotel, Colorado Springs, CO on October 16-18, 1979. The U.S. Air Force Academy, Colorado Springs, CO, was host on behalf of the Air Force.**





**Office of
The Under Secretary of Defense
for Research and Engineering**

## PAPERS APPEARING IN PART 1

### WELCOME



### KEYNOTE ADDRESS



### INVITED PAPERS



## PAPERS APPEARING IN PART 2

### MEASUREMENT TECHNIQUES AND DATA ANALYSIS

PAPERS APPEARING IN PART 3

DYNAMIC ANALYSIS



DESIGN TECHNIQUES

FRAGMENTS



TITLES AND AUTHORS OF PAPERS
PRESENTED IN THE
SHORT DISCUSSION TOPICS SESSION

NOTE: These papers were only presented at the Symposium. They are not published in the Bulletin and are only listed here as a convenience.

Session Chairmen and Cochairmen
50th Shock and Vibration Symposium
October 16-18, 1979, Colorado Springs, CO

| Date | Session Title | Chairmen | Cochairmen |
|---|---|---|---|
| Tuesday, 16 Oct. A.M. | Opening Session | Mr. Jerome Pearson, Air Force Flight Dynamics Laboratory, Wright Patterson AFB, OH | Mr. Henry C. Pusey, Director, Shock and Vibration Info. Ctr., Neval Research Lab., Washington, DC |
| Tuesday, 16 Oct. P.M. | Instrumentation | Dr. Peter Baede, Carrier Corp., Syracuse, NY | Mrs. Phyllis Bolds, Air Force Flight Dynamics Lab., Wright Patterson AFB, OH |
| Tuesday, 16 Oct. P.M. | Data Analysis | Mr. Allan Piersol, Bolt, Berenek end Newman, Inc., Canoga Park, CA | Mr. John Ach, Air Force Flight Dynamics Lab., Wright-Petterson AFB, OH |
| Wednesday, 17 Oct. A.M. | Dynamic Analysis | Mr. Robert Dyrdahl, Boeing Co., Seattle, WA | Mr. Sumner Leadbetter, NASA Langley Research Center, Hampton, VA |
| Wednesday, 17 Oct. A.M. | Design Techniques | Mr. William Bangs, NASA-Goddard Space Flight Center, Greenbelt, MD | Mr. Jess Jones, NASA - Marehall Space Flight Center Hunteville, AL |
| Wednesday, 17 Oct. P.M. | Dynamic Properties of Materials | Dr. David I.G. Jones, Air Force Materiale Lab., Wright-Patterson AFB, OH | Mr. Ahid Nashif, Anatrol Corp., Cincinnati, OH |
| Wednesdey, 17 Oct. P.M. | Applicetion of Materials | Dr. Jack Henderson, Air Force Materials Lab., Wright-Patterson AFB, OH | Dr. Lynn Rogers, Air Force Flight Dynamics Lab., Wright-Patterson AFB, OH |
| Thursdey, 18 Oct. A.M. | Vibretion and Acoustics I | Mr. Charles E. Thomas, Air Force Flight Dynamics Lab., Wright-Patterson AFB,OH | Mr. Ralph Bingman, Air Force Flight Dynamice Lab., Wright-Pettereon AFB, OH |
| Thursdey, 18 Oct. A.M. | Shock Testing | Mr. Max McWhirter, Albuquerque, NM | Mr. I.B . Irving, Johne Hopkine University,' Laurel, MD |
| Thursdey, 18 Oct. A.M. | Speciel Topics in Dynamics | Dr. George Morosow, Martin Marietta Corp., Denver, CO | Mr. Charles Moening, The Aerospace Corp., Los Angeles, CA |
| Thursdey, 18 Oct. P.M. | Vibration and Acoustic II | Mr. Tommie Dobson, 6585th Test Group, Holloman AFB, NM | |
| Thursdey, 18 Oct. P.M. | Fregments | Dr. Marcel L. Salive, David Taylor Navel Ship R&D Center, Bethesde, MD | Dr. J. Gordan Showalter, Shock and Vibration Info. Ctr. Washington, DC |
| Thursdey, 18 Oct. P.M. | Short Discussion Topics | Mr. Kenneth Cornelius, David Taylor Nevel Ship R&D Center, Bethesda, MD | Dr. Grant Gerhert, Army Tank Automotive R&D Command, Werren, MI |
| Thursday, 18 Oct. P.M. | Clessified Session | Mr. Jerry Sullivan, Naval See Systems Command, Weshington, DC | |

# WELCOME

## WELCOME

Brigadier General William A. Orth
Dean of the Faculty, United States Air Force Academy
Colorado Springs, Colorado

On behalf of General Tallman, it is very satisfying for me to have the honor of welcoming this fiftieth Shock and Vibration Symposium to Colorado Springs and to the Air Force Academy. Reaching the fifty mark is a singular achievement. Moreover, we are honored that you chose this location to celebrate that golden anniversary.

It seems to me that a gathering such as this is always a celebration. The word symposium itself comes from the Greek, meaning that intellectuals came together to freely exchange ideas. Later, in medieval times, the great European universities rose out of that kind of a gathering of scholars. In fact, it was built into the charters of those scholarly communities that they would not only perform great teaching and unlock the mysteries of nature through experimentation, but also share with each other the truths they would discover as individuals. All of this, then, was to be ultimately shared with mankind for universal betterment.

As the medieval scholars would apprise each other of the discoveries and notions about the metaphysical and physical worlds, so do you relate to each other the State-of-the-Art in the field of shock and vibration. This sharing of knowledge here in Colorado—in 1979—is still very much a *celebration* of learning and research by a community of scholars. As the charter of the early universities dictated, that research and learning should benefit mankind at large, so does your group perform that service to our society.

I only recently read a column written by *the Washington Post's* Daniel S. Greenberg that appeared in the *Post*, then was reprinted in the *Chronicle of Higher Education*. The title of the piece was "Who's Responsible for Scientific Illiteracy?" The main thrust of it was that, and I quote: "Whereas Science Originally Made The World More Understandable, It Has Since Evolved To A Stage Where It Makes It More Complicated, To The Point of Incomprehensibility." Greenberg complained that scientists today can't explain to the public what they're doing, let alone their fellows. I think I would use you as a rebuttal to his argument. I thought immediately of that rebuttal when I read through the pages of your *50th Symposium Issue* of the *Shock And Vibration Digest*.

We teach a technical writing course at the academy that forces our cadets to fight against building word and jargon barriers between reports and audiences—the thing Greenberg was really complaining about. On page one of your *Digest* there is an eight-paragraph narrative written by your director, Henry C. Pusey, that could well be used as an outstanding example in our course, and as an answer to Greenberg's complaint. That narrative not only details a concise history of the SVIC, but also lays out in an extraordinarily readable style what it is that shock and vibration research does for our world, for people. It talks about motion and noise, and how that can "rattle" apart a machine, a vehicle, a spaceship. It talks about how vibrations and shocks can damage bridges, dams, buildings, power plants and people. It clearly demonstrates to even the most unsophisticated reader the need for this research, how your community of scholars helps keep very everyday things running safely. And it sets a tone for your symposium. There was no muddied thought there. Everyone I showed the *Digest* to said, "Hey, I understand what those people are doing!" That's communication. That's the hallmark of the community of scholars, exchanging ideas and helping to make a better world.

We at the academy understand well why you're here in Colorado Springs. The Air Force Academy—at an anniversary point itself, our 25th year—is an institution of higher learning, with its own community of scholars. They are your colleagues. We are particularly proud that Captain Mark Ewing of our civil engineering department will be presenting a paper on Wednesday. Beyond that, it is also very gratifying to see the other Air Force and military people who are participants as well. Military people everywhere are especially aware of what you do in terms of making our systems safer, more flyable, more sea and landworthy. You are here for the exchange of ideas and the betterment of our world. You do that clearly and with a remarkable dedication. I only wish Mr. Greenberg were here. He would understand what you're doing. Welcome.

## WELCOME

Col. Ralph L. Kuster
Air Force Flight Dynamics Laboratory
Wright Patterson AFB, Ohio

It is my pleasure to welcome you today on behalf of the Air Force Flight Dynmaics Laboratory, which is hosting the 50th Shock & Vibration Symposium in cooperation with the Air Force Academy. I want to thank General Orth and the staff of the Academy for providing the auditorium for the classified session on Thursday, and for being in such a congenial location for the entire symposium.

The Air Force has been a sponsor of the Shock & Vibration Symposia since 1949, when the 13th Symposium was held at Wright-Patterson Air Force Base. Then, as now, the Air Force interest in the areas of vibration and shock was the effect of these environments on aircraft structures, equipment, and materials.

In looking over the titles of the technical papers of thirty years ago, one is surprised to see how up-to-date they sound. "Dynamic Stresses in Aircraft Structures," "Pilot Ejection Forces," "Turbojet Aircraft Vibration." There were even papers on missile vibration. At first glance it appears that we still have not solved these problems after thirty years. A closer look, however, shows that we have made great progress.

The reason the problems of thirty years ago look so similar to ones of today is that they are both the result of the same cause. Our fundamental problem in the business of flight is to take the materials at hand and fashion them into the most capable vehicles possible.

This usually means that we want to fly faster and farther and higher; we want to take off quickly and accelerate rapidly; and we want the most powerful engines and weapons that we can make. The result is that our vehicles develop tremendous amounts of power and energy. It is inevitable that a portion of this energy ends up shaking the aircraft instead of propelling it through the air. The faster the flight, the greater these dynamic inputs become. Unfortunately, as you well know, it does not take much energy to cause intense noise and vibration.

Our continuing problem in dynamics has been, therefore, to prevent this energy leakage from damaging the vehicle or its contents. As we progress to more powerful vehicles and weapons, we find that we are faced with the same old problems in some rather new disguises. Let me give you some examples.

The Wright brothers were the first to face the problems of aircraft structural dynamics. During their flight tests of 1902 and 1903 they faced the difficulty of making their flyer's fragile wings and landing gear stand up to hard landings. Several times they had to completely rebuild their craft after a hard thump on the sand dunes a Kitty Hawk.

More than half a century later the Air Force faced these same problems in the giant C-5 cargo aircraft. When the C-5 first flew it blew out several tires on takeoff and lost part of its landing gear, and even now the stress of hard landings is limiting the fatigue life of the C-5 wing structure.

In that sense, we have progressed very little since Kitty Hawk. It might appear that we *still* haven't learned how to design landing gear or wings until you remember that the C-5 weighs a thousand times as much, flies nearly a hundred times as fast, and lands at a hundred times the speed of the Wright flyers.

Along the way we have also learned enough about the elastic responses of aircraft to attempt to modify them to our advantage. The result has been the development of control systems to alleviate the dynamic loads on the structure and to minimize its dynamic responses. These systems have been successfully tested on the C-5 and the B-52.

We have also successfully tested an air cushion landing system, which can be used on plowed fields and other unprepared surfaces where conventional wheels cannot be used.

One area of aircraft dynamics with a long history is the problem of engine vibration. Since the Wright brother's engine threw its first piston we have been troubled by engine vibration and fatigue. As the early aircraft reciprocating engines became more powerful, the problems of absorbing their unbalanced forces grew worse. New design techniques were developed for engine mounts to prevent the engine vibration from exciting the aircraft elastic motions.

The development of aircraft turbine engines eliminated the problem of reciprocating motion, but replaced it with the problem of turbine blade vibration. As the speed and thrust of modern turbine engines has increased, so has the difficulty of controlling the dynamic responses of turbine blades.

Turbine blade fatigue is still a critical problem, because the failure of a single blade can destroy the entire engine. In recent years new blade coatings have been developed by the Air Force Materials Laboratory to damp out these blade vibrations while still allowing the toughness to withstand foreign-object damage. These coatings are enamels that are very hard at room temperature, but become plastic at the engine operating temperature and absorb a large amount of the vibratory energy.

Despite the enormous progress we have made in engine design, each new jet engine seems to develop its own peculiar turbine blade problems. Our latest modern engines exhibit vibration and fatigue problems which will demand the utmost in dynamics technology to overcome.

Another area of great interest to the Flight Dynamics Laboratory is the vibration of equipment and external stores. We have maintained the Military Standard on Environmental Test Methods in order to qualify equipment for all kinds of vehicles, from trucks to rockets. The standards for vibration testing, for example, have gone from sinusoidal tests for piston-engine aircraft to broad-band random vibration tests for jet aircraft and rockets.

In addition, we have developed facilities for the testing of equipment under combined environments such as vibration, temperature, and humidity. These techniques have revealed many dynamics problems before they were able to show up in service.

The Flight Dynamics Laboratory work in external stores has ranged from flutter clearance to the development of vibration isolation systems for pod-mounted optional systems.

These areas have been of increasing importance in recent years. Faced with the problem of flutter clearance of many aircraft with large numbers of external stores, the Laboratory has developed computer programs to predict flutter in a multitude of store combinations. The result is a readily available tool for rapid flutter clearance of any new combination of external stores.

The Laboratory has also been involved in solving the vibration problems of optical systems installed on pods, such as forward-looking infrared radars, TV cameras, and laser designators and rangefinders. New techniques have been developed for the analysis of pod responses and new concepts have been developed for passive and active vibration isolation.

The Flight Dynamics Laboratory has also been involved in the problems of re-entry vehicles where one difficult problem has been the design of payloads to survive atmospheric entry. When the nose cone of an ICBM hits the atmosphere at Mach 24, the aerodynamic and thermal loads are enormous. Oscillating shock waves cause very high vibration and acoustic noise levels at high frequencies. New techniques of dynamic analysis were required to predict the payload responses.

The statistical energy method was developed to determine payload responses without a detailed finite element analysis of the structure. Large acoustic chambers with banks of sirens were used to simulate the high noise fields of atmospheric entry and to study their propagation through the structure to the payload. These advances have enabled us to develop successful designs for payloads to withstand the highest required entry velocities.

The Flight Dynamics Lab has been in the forefront in solving many of these problems over the years. As new vehicles with greater capabilities are developed, we expect to continue to support new research in shock and vibration.

On behalf of the Air Force and the Flight Dynamics Laboratory I want to congratulate you on your milestone 50th Shock & Vibration Symposium and wish you continued success toward the 100th Symposium.

# KEYNOTE ADDRESS

## U.S. ARMY KEYNOTE ADDRESS

Lieutenant General Robert J. Baer
Deputy Commander for Materiel Development
U.S. Army Materiel Development and Readiness Command
Alexandria, Virginia

Being DARCOM's Deputy Commanding General for Materiel Development—like any job—has ups and downs. Certainly in the "up" category is getting to travel to such beautiful places as Colorado Springs and getting to share a speaker's platform with such distinguished people as you have already met, and will be meeting and hearing from later.

I congratulate you on the choice of Colorado Springs for your Fall meeting. I understand a national poll found it to be one of the ten most desirable places to live in the United States. Certainly its 6-thousand plus feet altitude is a far cry from the sea-level heat and humidity of Virginia, although I must admit that Virginia can boast some beautiful weather in the Fall of the year. I say this with tongue in cheek, because we had snow on the 10th day of October — complete chaos!

I am honored to be the Army's representative on this keynote portion of your symposium—the 50th symposium in the 33-year history of the organization. That's certainly an active schedule, indicative of a progressive and dedicated group of officers and members.

To talk to *you* about shock and vibration is somewhat akin to preaching to the choir. While I realize the importance of controlling or eliminating the shock and vibration problems encountered in the weapons systems we are developing for the Army, you certainly know more about the concepts and theories, and the methods of testing than I do.

It's a situation that reminds me of the story about the fellow who, at the age of 10, survived the Johnstown flood of 1889. It seems the destruction and sorrow caused by that great catastrophe left quite an impression on the boy. In fact, he was so impressed by the scenes he remembered that, as he grew older, he took every available opportunity to recount the story to anyone who would listen.

Well this went on until that inevitable day when he passed on to his final reward. St. Peter met him at the gates and asked if there was anything he would like to say to those assembled there before he took his place among them.

Naturally, the fellow seized the opportunity, as he had done all his life, to answer, "Yes! I would like to tell them about the Johnstown flood."

After a moment or two of awkward silence, St. Peter asked. "Are you sure you want to address *this* audience with *that* story?"

The fellow answered, "Yes sir, I certainly would."

"Well O.K., if you insist," St. Peter said, "But keep in mind that *Noah* is in your audience."

Today, I'm facing a room full of Noahs.

As the program indicates, there are several Army representatives who will be making presentations during the course of the symposium. I certainly don't want to detract from their presentations but, in keeping with the theme of this conference, would like to comment briefly on a few of the shock and vibration problems we have encountered and what we have done or plan to do about them.

My boss, General John Guthrie, had the pleasure of addressing your 25th anniversary symposium 7 years ago. At that time he summarized for you our major hardware programs as well as our RDT&E thrusts. He told you then that it is difficult to think of any significant military system within the Army that does not require serious consideration of shock, vibration and/or noise factors. That is just as true today—probably even more so—as, in spite of our desires for simplicity, our weapons and equipment are more complex, our means of mobility more rapid, and our communication requirements more extensive and sophisticated.

When you think about Army equipment in a historical sense, you have to sometimes wonder how we could have built successful guns and airplanes and so forth with analytical tools that must be classified as primitive—in comparison with those we use today and we used them in what was pretty much of an ad hoc manner. If we could be reasonably successful with such primitive tools, why should we have problems today with our finite codes and precise instruments for design and testing?

One reason is obvious! We are asking our systems to perform in much more severe environments. For example, we are demanding more range for artillery weapons, as well as greater precision accuracy and many fold increases in effectiveness on the target. You can appreciate how these interactive demands challenge our design and production engineers.

There is no question that with all of the advancements in analytical capabilities, design of effective reliable military hardware is a sporty game, and getting sportier. I would like to touch briefly on some shock and vibration problems associated with such diverse types of Army hardware as tanks, projectiles, helicopters and remotely piloted vehicles; and conclude with some comments on packaging and the use of new materials to address some of our challenges.

I am sure many in the audience are familiar with the shock and vibration problems associated with combat vehicles in an operational environment. Travel of 40-60 ton vehicles over rough terrain at speeds of 30-50 mph, along with the shock imposed from firing the very high velocity main armament, severely impacts all sub-systems of those vehicles, probably most severely the electronics, communications, ranging, fire control and night vision systems. Literally every part of the system is subjected to shock and vibration.

A somewhat tougher problem, one that is being worked by the Army's Materiel Systems Analysis Activity, has to do with the structural integrity of our new XM-1 tank to withstand enemy weapon attacks with both large caliber missiles and 125mm high-velocity cannon. As background, the XM-1 tank hull and turret are all-welded armor bodies. During testing, cracks and separations occurred at the weld joints when the tank was subjected to severe large caliber projectile impact. The result was weld joint failure. There were cases where outer armor plate and the special armor package were totally displaced from the tank. These failures were of course caused by the shock loading from the projectile impact.

The tank structure, the hull and turret, is required to resist high energy impact. In our preliminary examinations it appears that we did not accurately estimate or compute the impact loads we would receive. This was a somewhat new game we were in, considering both armor design and attack threat, and some confusion existed within the design community concerning the difference between the significance of environmental "g" values in the field and the dynamic forcing function used in analysis. We know now that in order to analyze the dynamic load on the tank structure and the effects of high rate of dynamic loading on the weldments, it is necessary to transform the impact parameters of mass velocity and explosive pressures to acceptable dynamic forcing functions. Our Materiel Systems Analysis Activity at Aberdeen Proving Grounds is developing a pilot program to study this phenomenon.

There is another reason that we have difficulties in design that really is a subset of the "higher performance under adverse environment" issue. That is, we are now using more complex materials in our designs. The reason for that is that we need better performance. It becomes somewhat of a vicious circle in that, when we need better performance, we often turn toward advanced materials; and when we select a new material, we look around for a high performance application. As a result, not only are we faced with designing against more severe environments, but we are building equipment with materials that often are not well characterized or understood, particularly in those severe environments. Furthermore, in many cases these advanced materials are not as forgiving as those we previously used. But, you'll be hearing more about structural materials tomorrow in the afternoon plenary session with Dick Shea and John Mescall of our Materials and Mechanics Research Center.

To return to the artillery example I mentioned earlier, we have a good case in point. To increase the effectiveness of fragmenting rounds, we have moved to high fragmentation steels. At the same time, to increase the range, new and more powerful propellants are a must, which means higher chamber pressures which increases the launch stresses. By its nature, the high-fragmentation steel behaves in a brittle manner. This is fine at the target, but presents the designer with difficult problems during handling and launch. Let me give you some examples of projectile shock and vibration problems that we've encountered.

During safety testing of the 155mm rocket assisted projectile, testing procedures call for the projectile to be dropped seven feet onto concrete. During this test phase, several projectiles ruptured or cracked in the nose and ogive area. Because the impact forces exceeded the fracture toughness of the HF-1 steel, it became necessary to design a flanged nose plug which would absorb the shock. Since one thing always leads to another, this caused redesigning of the bustle racks for the M1-9A1 Self-propelled Howitzer to accept the new nose plug. A second new development, the duel purpose family of projectiles, also exhibited nose cracks during similar testing, so they too will be fitted with the nose plug. In fact, the plan is to eventually fit all projectiles with this nose plug.

Shock and vibration problems, primarily during transportation and handling, also have been found in propelling charges. The M86 series propelling charge, for instance, is a three increment charge with a center core igniter. The core assembly consists of three rigid polyurethane tubes containing black powder igniter charges. Fielding of the M86 and M86A1 models of this propelling charge soon led to the discovery of a critical shortcoming in design. During transportation and handling, the polyurethane tubes could be crushed and damaged. The result, as you can well imagine, could be catastrophic. With excessive chamber pressures, the destruction of the weapon itself was probable if there was interruption of the ignition train.

This problem was corrected with fielding of the modified propelling charge with a reinforced igniter tube having two layers of dacron scrim molded in place. In addition, wooden overpacks were added to the propelling charge canisters to protect the charges during storage and handling.

Another sensitive subject in this business is our nuclear projectiles. We know of course that a projectile fired in a worn gun tube faces significant vibration increases within the tube which results in increased projectile dispersion at the desired points of impact. But, with nuclear projectiles, the stress levels on fuzing, arming and nuclear components are obviously of even greater concern than with conventional rounds. Thus we must precisely determine, assess and design to give us acceptable safety and performance on the target. In the Army's development program for the 8" and 155mm nuclear projectiles, the effect of shock and vibration levels encountered in tubes having varying degrees of remaining life is being thoroughly assessed by firings in both new and worn tubes. Dispersion effects are assessed, as well as the effects of the increased vibration on the internal components of the projectiles.

Another system that has challenged us to the fullest in the shock and vibration environment is the 155mm Copperhead SM-712 - CLGP. It's a rather unique item, in that it is essentially a missile being launched from a gun tube that can generate 9-thousand g's acceleration. This rapid acceleration places high stress upon components and is very unforgiving if we haven't done our engineering and assembly correctly. Early developmental testing i : Copperhead quickly identified problem areas which required technical fixes. These problems were primarily uncovered in the firing of projectiles which had not been adequately processed for the shock and vibration environment. Implementation of the fixes has increased reliability to over 70 percent. Experience has revealed wires sheared due to oscillations of internal components and failure of the wings to extend after firing. The latter was due to movement of a hinge pin which, in turn, deformed a spring and thereby increased the amount of force necessary to release the wings to a level above the capability of the firing squib. This has been a real challenge to the engineer, but I am pleased to say that we are moving into production. I should add that we recognize some handling and storage issues, and that packaging containers are also receiving special attention, as well as on-vehicle storage.

Moving to advanced materials we find new challenges in the use of composites. More and more, we are exploring the use of organic composites, metal matrix composites, and ceramics. These materials offer great promise and potential, but we have yet to take full advantage of them. One reason is that we do not have a full understanding of how these materials behave in a static environment, let alone in a severe shock and vibration environment. We are learning, however, and of help in such matters are documents such as the state of dynamics technology with respect to composites which is included in a recent summary* by the Shock and Vibration Information Center.

There are empirical approaches that we can and do use. We have gotten fiber-reinforced plastic composites into Army applications with good results. We have flown all-composite prototype helicopter blades under as severe a dynamic environment as can be imagined. The advanced attack helicopter has been designed from the ground up with composite blades. I expect that we will soon have composites in many other components as well, not only in helicopters, but in other equipment as diverse as tanks and hand-held weapons. The Army not only has plans for these materials, but such materials are critical in meeting new operational requirements at reduced weights for both ground and air systems with significantly enhanced survivability. Thus the push is on us all to gain better understanding of their response to a broad spectrum of dynamic loads, as one of many issues.

In addition to these organic composites, *metal matrix* composites are just starting to make their presence felt. These materials are right now at the point that the more traditional, if I can use that word, organic composites were ten years ago. I would mention two Army demonstration projects for metal matrix composites. The first is for helicopter transmission housings. The goal is to reduce vibration levels in the housing which, in turn, reduces gear wear and noise. The other is for vehicular-launched bridging components which, at first glance, may not seem like a dynamic application. However, when you consider the requirements that these bridges be transportable on armored vehicles, erectable in rugged terrain, and capable of taking thousands of crossings of 60-ton loads, you can appreciate that we are again talking about a severe dynamic environment.

Another class of advanced materials that we must use to advantage is ceramics. We see their use in both diesel and gas turbine engines, taking advantage of their high temperature properties to enhance fuel economy. They also seem promising as bearing materials, in that we may be able to run them without lubrication. Again, the dynamic applications are obvious.

But, let me offer some more about helicopters. If ever there was an area that needs support from the experts, helicopters qualify with ease. When General Guthrie addressed your symposium seven years ago, he talked about development of helicopters for the Army, specifically the attack helicopter and a Utility Tactical Transport Aircraft System (UTTAS). The latter was needed to replace the aging Hueys which had been the workhorse of Vietnam. It was my pleasure late last year to accept the keys to the first production model of the Blackhawk, the Army's name for its new primary combat troop-carrying air vehicle. Let me cite just a couple of shock and vibration problems that arose during development and testing of the Blackhawk.

One problem had to do with the main rotor head. The Sikorsky prototypes were originally designed with the main rotor head placed immediately above the fuselage, a design that was intended to satisfy dimensional air transportability requirements. In early testing, however, this design allowed excessive vibrations to be transmitted into the air frame. The problem was solved by raising the rotor approximately 24 inches. The air transportability requirement was then satisfied by designing a collapsible rotor shaft.

Another challenge in development of the Blackhawk helicopter was the use of a stabilator in the tail to permit flight altitude control necessary for higher speed and better maneuverability in the nap of the earth environment. With mechanical linkages involved and high stresses from very demanding new flight and performance capabilities, the prototype aircraft experienced stabilator hardware cracks induced by vibration loads produced by air flow under a fairing. Cracks in the stabilator and stabilator mounting hardware were occurring approximately every 50 flight hours in the government competitive test. A one-piece stabilator was then designed for the production Blackhawk. This eliminated fairings and mounting hardware of the original two-piece stabilator. No vibration-induced cracks have now been detected in over 400 hours of production vehicle testing.

*Pusey, H.C.; Volin, R.H.; and Showalter, J.G; "An International Survey of Shock and Vibration Technology", Shock and Vibration Information Center, March 1979.

It has long been accepted that Army helicopter reliability and maintainability was significantly affected (negatively) by both natural and induced environments. Early efforts under the R&M program investigated the magnitude of those effects and resulted in predictions that over 65 percent of all failures would be related totally or in part to environmental causes. Typical of such investigations was a comparative analysis of the air force's HH-3 helicopter before and after installation of rotor vibration absorbers. The results of this program indicated that a 50 percent reduction in fuselage vibration levels produced almost a 50 percent reduction in failures. Because of this and other relevant data, two major efforts under the R&M program have been the pursuit of vibration reduction techniques and the development of improved concepts for vibration testing.

With respect to vibration testing, the R&M program reached a major milestone with a full-flight demonstration of a dynamic anti-resonant vibration isolator, better known as DAVI. The system employs a simple mechanical approach that allows the rotor system to be isolated from the fuselage. Test results were most favorable. The DAVI-equipped UH-1H helicopter showed significant reductions in the magnitude of vibration-induced forces in profiles taken at the center of gravity and in the nose of the helicopter.

As mentioned earlier, development testing is essential to achieving maximum reliability. Unfortunately, vibration testing is very difficult to accomplish and normally requires full aircraft flight to assure accurate test conditions. A recently completed effort under the R&M program, however, has been the establishment of a ground-based testing concept at our Ft. Eustis Virginia, Aeronautical R&D Laboratory. The full spectrum of in-flight vibratory loads can be duplicated at a fraction of the costs of development flight tests. This testing concept has recently been demonstrated on the full-scale AH-1 Cobra helicopter. A report on the results is now being prepared. Mission equipment integration is an area where ground-based helicopter vibration testing offers major payoffs.

Let me turn now to the environmental problems of a similar, but still unique, nature — that is, in remotely piloted vehicles, or RPV's.

In the Army's mini-remotely piloted vehicle program — The Aquila, tested in 1977 — we had more than our share of vibration and shock issues. The Aquila System RPV used a one-cylinder engine which induced considerable vibration to the aircraft. It was particularly noticeable with the unstabilized TV sensor package. To be honest, its continual gyrations had the effect of nauseating all who viewed the video for any extended period of time. Fortunately, it was much less noticeable with the stabilized sensor package.

A horizontally-opposed dual-cylinder engine has now been introduced which will considerably reduce engine-induced vibrations. Although the main reason for going to the two-cylinder engine is for increased horsepower, the choice of a two-cylinder engine with horizontally opposed cylinders will have the additional benefit of reducing on-board vibrations and thus reducing the likelihood of vibration induced failure modes.

The solution to another problem area in RPV's is the reduction of the shock induced to the launcher shuttle. The shuttle is the mechanism which travels along the launcher rail and transmits the acceleration force to the RPV for launch. In the Aquila System, the shuttle would come to an abrupt stop at the end of the launcher rail whereupon the RPV was released for flight. The shock of hitting the stops at about 100 kilometers per hour necessitated the routine replacement of the shock mounts after every three or four launches.

The new launcher to be used in this program gradually slows the shuttle after the aircraft is released, thus reducing the shock induced to the shuttle considerably. Although the complete launcher proposed for this system has not been built, prototype launch rails and shuttles of this type have been tested and a greatly reduced shock environment is indicated.

Finally I would comment on the ever-increasing demand for better packaging to deal with handling and storage, where so much of our damage to systems is received. I referred earlier to the fact that our weapons and our equipment are becoming more complex and sophisticated and, I might add, more sensitive. Increasingly we find that equipment, particularly our software, will not stand up to normal troop handling and off-road movement.

A team from the Joint Military Packaging Training Center at Aberdeen Proving Grounds, on a visit to our troop units in Korea, found it was common practice to wrap electronic parts, modules and sub-assemblies in "bubble pack," place it in a foot locker on top of a mattress in a truck — usually without tie down — and move it over 20 or more kilometers of rough, rocky dirt roads to and from maintenance shops. The repaired components are thus exposed to shock and vibration greater than that for which they may have been designed and are therefore succeptible to a loss of calibration. The team also noted that even some new parts, packed and shipped directly from an electronics manufacturer, arrived at remote sites in non-functioning condition. The problem is not unique to Korea, but is aggravated there by the environmental conditions which impact broadly as well as severely.

One horror story related to our team tells of a dual test of human and non-human assemblies. A young captain rode in a jeep to a Hawk battalion site along with some factory packaged electronic parts. The captain had his arm in a cast due to an injury and, by the time he rode the jeep some 18 kilometers, his arm was so swollen inside his cast that he was in considerable pain. The electronic repair parts sustained such shock and vibration damage that they had to be returned stateside for replacements.

The troops are finding, just in sending a movie projector twice a week from the base camp to the Hawk site, that it has to be turned in for repairs every three or four weeks. If there is one thing that would be handled with care it would be the projector. No projector, no movies, and it can get pretty dull in a remote location. The movie projectors we are buying now are strictly commercial, right off the shelf, except for a transformer to let them use 50 cycle current and an extra heavy duty transit case to help them sustain the rigors of off-road transportation.

Our concern, then, is to extend relatively one-sided or severely circumscribed computer programs to include completely packaged items, and to try to take into consideration the many variables which impinge on a packaged item. In other words, consider the "real world" handling situation. Our packaging centers have a major concern that computer programs don't go far enough, that they simulate the uniaxial shock loading of a dummy load on a shock tester with various packaging materials positioned between to reduce the shock loading. In the real world, however, the loads often appear in all three dimensions, and include friction, heat and atmospheric effects which compound shock and vibration loadings. Proper attention to shock and vibration aspects of packaging can surely minimize follow-on problems in equipment which is transported.

Further development in laboratory test equipment for shock and vibration is also showing progress. For example, we have come a long way with the 3-dimensional vibration and shock testing equipment used to check out missile components, avionics equipment and ground support units in lieu of checking them one axis at a time. That kind of system was recently funded at our Harry Diamond Labs to speed up and use computer control in vibration and shock testing of artillery fuzes. A lot of money has also gone into a simulator at Rock Island which permits us to fire helicopter weapons under simulated pitch and yaw motions.

We face and will continue to face any number of major challenges in our business. Our requirements are always changing because of the *threat*. And our capabilities are changing because of advances in technology. Defense systems are ever more costly to develop, produce, and support. The greatest cost factor is always operating and support costs of the fielded system. The greatest driver to operations and support is relative durability, which comes straight home to you I believe that the environment that you are working, shock and vibration, is at the heart of relative durability. Therefore, let there be no question of the importance of your efforts, you contributions, and of such meetings as this symposium addressing this subject area.

Thank you again for allowing me to join you this morning. I wish you success in your efforts and pledge you the Army's support in our mutual endeavors.

## U.S. NAVY KEYNOTE ADDRESS

T. G. Horwath
Director of Navy Technology Naval Material Command
Washington, DC

It is a real pleasure for me to be here in Colorado Springs, one of the better parts of the world. I am really honored to have the opportunity to address your symposium and, by doing so, to stimulate a few thoughts about a subject or two. When Mr. Pusey asked me to speak to you, I must concede that I had very little knowledge about the Shock and Vibration Information Center. As a matter of fact, I was completely unaware of its very existence. Why would I then accept an invitation to speak under such conditions of gross ignorance? This is a good question indeed and there are some good answers.

First, there is always the challenge of finding out and, by doing so, learning something new. This inevitably leads to new insight and new perspectives. Second, I soon realized that your shock and vibration community is a typical representative subset of the overall research and technology community in this country with which I am quite familiar. Your past activities and accomplishments represent and reflect pretty well those of that research and technology community. Your current problems are very similar, and your future aspirations and expectations will again be affected by the same uncertain conditions that affect research and technology as a whole. In other words, your shock and vibration community exists under the same climate, which is a function of national goals, priorities, and attitudes, which research and technology as a whole has to exist. This is essentially the subject I would like to cover. I would like to caution you that the views I will express in this context are entirely my own. They may or may not be shared by my organization.

Let me begin with a historical perspective, or hindsight, if you wish. Your Shock and Vibration Information Center was established at the Naval Research Laboratory in 1946, some 33 years ago, to provide — and I am now quoting Dr. Elias Klein who was the first Director — "a coordinated attack on the Navy's shock and vibrations problems." Two years later the Army and the Air Force joined, recognizing the usefulness of this Navy-pioneered institution. In 1962 the National Aeronautics and Space Administration, very young at that time, followed suit and became the fourth sponsor.

Your Shock and Vibration Information Center came into being and has lived through what I like to call the "Golden Age" of research and technology. This "Golden Age" grew out of the successful completion of the Manhattan Project. It started when Dr. Vannevar Bush, then the Director of the National Research Council, realized and brilliantly articulated the immense benefits this country would accrue from a well-managed synergistic relationship between the scientific community and the military, or the federal government. This was the time that the Office of Naval Research was established by Public Law 588. Twelve years later, when Sputnik went up, the nation received another strong reminder about the importance of science and technology. The favorable conditions that I have described were reinforced. They continued with full momentum and produced spectacular accomplishments that culminated in the landing of men on the moon. This period was characterized by abundant resources and few controls on research. The United States had a clear lead in research and technology over all other nations of the world.

During these times your community, by diligently pursuing its interest and mission, scored a number of impressive accomplishments across the board. I will try to enumerate a few of these that relate to the Navy.

As a result of your effort, it is fair to say that the United States Navy now has the most shock-resistant ships in the world. You have helped the Navy evolve its own methods for shock and vibration testing of ships. Full-scale ships are being shocked with explosive charges at appropriate standoff distances, while shipboard-mounted equipment undergoes standardized tests on various high impact test rigs. Much of this information has been passed along to the private sector.

You developed a comprehensive understanding of vibration phenomena enabling the Navy to build the quietest ships and submarines. This extensive knowledge of noise and vibration phenomena is now being used over and over again in ships and submarine design. It enabled us to make the optimum tradeoffs between silencing and shock hardening, the contradictory requirements governing soft-mounted machinery platforms.

Your efforts in shock and vibration analysis is unparalleled. An important example here is your dynamic design analysis method (DDAM). This method derives shock spectra from underwater explosions, laboratory tests and theory, and translates this into realistic damage criteria. The DDAM method has served as the cornerstone of the Navy's shock survivability analysis and prediction efforts.

The DDAM was later followed by the underwater shock analysis code (USA code) that includes the fluid structure interface. The development of this code represented a breakthrough. It permitted an efficient analysis of the interaction between the shock wave and the hull structure with significantly less computer time requirements than older, less sophisticated techniques.

Having discussed the significant accomplishments of the last 33 years, it is perhaps in order to project into the future. We can ask, "What accomplishments will we be able to point to at the 100th Shock and Vibration Symposium?" I will not attempt to give you a precise answer, since I am not good at telling fortunes. I would like, however, to observe and point out some existing processes and trends that are indicative of where we could be going.

Without doubt, computer simulations and modeling are here to stay. We could be seeing strong gains in this area in the future. Large finite element codes, such as NASTRAN and CASDAC, could be used more and more by the Navy as well as by private industry to expedite ship design and reduce cost.

NASTRAN, or even more advanced codes, could be coordinated and possibly integrated with codes like DDAM and USA and yield more accurate results under realistic conditions.

Drastic advances in computer technology and computer graphics, especially in the area of minicomputers, preprocessing of data, and post-processing with interactive data terminals, could extend the usage of these codes way beyond the huge computer centers. They could be available at the fingertips of every Naval architect and structural engineer.

We could see a comprehensive model describing accurately all the vibration modes of entire structures as a function of the excitation by all kinds of machinery, which would furthermore predict the radiation of sound into the fluid medium that results from these vibrational modes. Such a model would describe the vibrational power flow in all parts of the structure and would therefore predict accurately the effectiveness of vibration isolation and quieting measures, before they are implemented.

All these things could happen; sounds optimistic, doesn't it?

But unfortunately, if you look at the near past you can get a somewhat different impression, that is far less optimistic. In spite of all those possibilities, which we have had the opportunity to pursue for some time now, we seem to have had a hard time making real progress lately. Things seem to be dragging excessively, I will give you a few examples.

All of the high power computer modeling techniques, like DDAM and USA, do not seem to progress beyond the applicability to present conventional hull forms.

There is very little effort, and therefore great uncertainties, in the prediction of the shock survivabilities of hydrofoils, surface-effect ships and swath ships. These ships will after all play a major role in the future Navy.

Codes like NASTRAN and CASDAC have been available for some time but have not yet found full application by ship designers and in the shipyards, nor are there any indications that they might be applied in the near future. They are going begging in spite of their promise.

We seem to be preoccupied with current problems and we are paying little attention to the next generation Navy, the shock and vibration needs of which we are too ill prepared to support. This does not speak to cost reduction, which will be of paramount importance. One cannot help asking how come? How come, with all these possibilities for the future, we are making so little progress? What has gone wrong?

Is it that we may not be working hard enough to realize these potential gains of the future? No, I don't think so. Are the problems too complicated to solve? Hardly, since we have dealt with tougher ones in the past where the uncertainties were much greater. Then it must be due to the general atmosphere and conditions under which we perform our work. I would like to assert that this slowdown in progress comes back to a central and core issue, the currently prevailing research and technology climate in this country. This climate began in the late sixties, when "The Golden Age of Research and Technology" came to an end.

At that time we saw a drying up of resources for research and technology with the winding down of the space program. We witnessed the passage of the Mansfield Amendment that for the first time put stringent controls and restrictions on fundamental research. We experienced a trend in military research and technology that pointed towards more and more near-term, short-range goals, and clearly defined needs, if not out-right specific requirements. We could not help but notice a general disenchantment of the country with research and technology as a whole. We heard statements like: "We should not spend all that money on the moon since we have more important problems down here on earth." The fact that we indeed spent all of it down here by paying salaries, providing jobs, and so forth, was completely and conveniently overlooked. We saw research and technology become the "public enemy number one" of the environmental movement and the counterculture, and we saw the public's esteem for scientists and engineers hit low levels never experienced before. And we saw, and still see, the country teeming with self-proclaimed experts in almost any field who are more than willing, who are indeed eager, to testify about all kinds of evils technology could bring upon us. By doing so they add to the pandemic neophobia that already engulfs us to a large extent. Is it really so hard to comprehend why our technology base has eroded and the advancement of the state-of-the-art has come to a near standstill? I don't think so and I am sure you don't either.

This situation I described is further exacerbated by some additional points. As our rate of new technology developments, our innovation, decrease the need to export technologies increases, for reasons connected with our balance of payments. At the same time competition forces us to sell the newest technologies since our allies, and worse, our adversaries have been catching up. They stepped on the accelerator while we were slamming on the brakes. They are busy adopting and refining the technologies we sold them in the first place and are competing, and sometimes even beating us, in the world markets. They also use our technologies to modernize their armed forces, and I have to admit, they do it very successfully. We find ourselves in the dilemma of having to choose between not selling technology and facing immediate adverse economic consequences, or selling it and only postponing the crisis that will inevitably hit us later with greater force.

The situation is bad and is self feeding. It is a vicious circle. The more we fall behind in innovation, the more we tighten controls to focus on a quick payoff. The less willing we become to take risks, that are so essential to innovation, the more we export our latest technologies and the more we fall behind again. We have to break this circle; it is imperative that we do. We have to realize that innovative technologies are the key to our nation's prosperity and military strength. We have to provide conditions under which innovation can flourish. We further have to realize that we cannot go on asking for "Golden Eggs" while we are at the same time "Beating The Goose To Death" that lays them. What can we do specifically? We are at a decision point, a fork in the road so to speak. The road we take from here will undoubtedly affect the next 33 years as we approach your 100th symposium, and will certainly have immense influence on the accomplishments you will be able to point to at that time.

One road, to continue the metaphor, is easy to travel. It is smooth and all downhill and there is no resistance ahead. All we have to do is do nothing and let the present trends continue. Make research and technology efforts more relevant, pursue only those activities that lead to immediate payoffs, and make sure that everything gets applied expediently. We will soon have reached our goal of "rock bottom," by having killed off all innovation, we will have scored one-hundred-percent success in applying the state-of-the art over and over again. We will have assured that our future economy will be bankrupt and our future armed forces will have weapons and equipment of the past.

The other road takes considerable effort to travel. It has a steep uphill grade and many rocks and potholes. There will be hostile fire ahead. We are not accustomed to traveling such a road, but I am sure we can master it by increasing and coordinating our efforts so that everybody contributes his share.

At the working level we just have to try harder. We have to identify innovative technological approaches, sell them to our sponsors and make maximum use of them by solving problems that could not be solved by incremental product improvements. We have to demonstrate that innovation pays off. This is the area where information centers like yours are extremely valuable. They prevent wasteful duplication, disseminate information efficiently and help technology transfer.

On the management and sponsor level we have to increase our willingness to take risks. Controls should not be too tight for innovative alternatives, which we tend to neglect too often because of uncertainties connected with them. We have to keep in mind that innovation comes from taking risks; and that without risks there is no payoff and no progress.

At the policy level we have to strive hard to establish a climate that is conductive to taking risks. We have to assure the allocation of a significant fraction of the overall resources to high risk ventures. We have to persuade our managers and sponsors to identify the innovators in their organizations and solicit their contributions. I know that they are not the easiest kind of people to work with, but I think they are well worth the "special care and feeding" they require. I am firmly convinced that on the average, over every R & D Organization, the real innovators represent only 5 percent of the population and are nevertheless responsible for 95 percent of progress. Examples are abundant to this effect.

At all levels we have to be more outspoken and more articulate about innovation. We have to convince people around us and those in responsible positions that a healthy technology base is the lifeblood of our society and that every penny spent on it is definitely worth spending, including that spent on those projects that do not have an immediate payoff.

This latter road is worth traveling in spite of the difficulties ahead. I see it as the only alternative that, in the long run, will restore the technological lead that is so vital to us. Admiral Kidd, now retired, as Chief of Naval Material used to ask the question, "what have you done for the fleet today?" I am sure that many of you remember the life size posters on the walls from which he was pointing his finger at you just like Uncle Sam saying, "I WANT YOU." In the same spirit, I would like to ask your shock and vibration community, as well as the R&D Community at large, "what are you going to do for the fleet of tomorrow?" Please keep this question in mind during the next 33 years.

## U.S. AIR FORCE KEYNOTE ADDRESS

# THE ROLE OF DYNAMICS IN FUTURE AIR FORCE SYSTEMS

Brigadier General Brien D. Ward
Director of Science & Technology
Air Force Systems Command
Andrews AFB, DC

It is a pleasure for me to join you today in opening the 50th Shock and Vibration Symposium. On occasions such as this it is worthwhile to pause a moment to reflect on how far we have come in the past and where we are headed in the future. Colonel Kuster has talked to you about pa t dynamics problems in Air Force flight vehicles and how ea new advance in vehicle capability has brought its ow nique difficulties.

I would like to review with you a few of the planned, proposed, or possible future Air Force systems and point ut how the nature of these systems will create new dynamics problems, much more difficult than you have faced in the past. Many of these problems will be a result of pushing today's vehicles technology to its limits to attain greater performance. Some problems will be new. Vibration and noise must be completely controlled in order for some of the new devices to operate effectively. Examples of these devices are laser weapons and large antennas and reflectors in space.

The first area I will cover is aircraft. In the past, some important concerns with dynamics in combat aircraft have been the reliability of the airframe, the dynamics of external stores, and the fatigue of high-speed turbine engines. These problems are expected to continue in the future.

As we head into the 1980's and 1990's, we will be faced with the need for very large, long-range aircraft. Our experience of re-supplying Israel by C-5 aircraft from U.S. bases demonstrates this need. Because of the political situation of the Arab-Israeli conflict, our aircraft used just one refueling stop, in the Azores. This seriously reduced the C-6 payloads, and the operation required more aircraft and more time than it should have. As the world situation becomes more complex, we may be faced w th the requirements to supply distant allies, non-stop, directly from the U.S. This possibility has required new concepts in strategic airlift, such as spanloaders. These aircraft, reminiscent of the flying wings of the 1950's, will have greatly increased wing area and interior volume. These new aircraft will be multi-engined, perhaps up to ten engines each, and will be structurally complex and lightweight. These characteristics guarantee that the aircraft will pose new problems in dynamics.

In the next two decades we will also see continued changes in fighter aircraft. The use of advanced composite materials will allow new design for wings and control surfaces. Forward-swept wings using stiffer composites to resist twisting and divergence will allow highly improved performance. Direct lift control by canards or thrust deflectors will insure greater maneuverabili , and better firing accuracy, by enabling the aircraft to move laterally and vertically without turning. But, all these advantages will be paid for in increased complexity. The added aerodynamic surfaces will increase the problems of turbulent wakes impacting on the aircraft. Less fasteners in composite materials will re lt i lower inherent damping of the structure. These ch ristics all add to the difficulty of the design problem.

As far as we can foresee, perhaps for the next 25 years, we will have a continuing need for an advanced manned bombe. No other part of our strategic defence Triad has the versatility of the manned bomber, its ability to be recalled after launch. The manned bomber can be used in tactical warfare for observation, mine-laying, show of force, and conventional bombing. It is safe to predict that the engines developed for such a bomber and the airframe designed for its operating environment will exhibit dynamics problems similar to present ones. The turbine engines will run hotter, rotate faster, and drive more air. The wings and exterior skin will need to withstand the stresses of oscillating shock waves and supersonic dashes "on the deck," but the principles we have used on present and past generations of aircraft will enable us to successfully solve the problems of fatigue and reliability.

There will be new and more complex problems, however, because of some concepts now being developed for weapons systems. One of these concepts is that of high energy laser weapons for aircraft. As you probably know, the Air Force is experimenting with the Airborne Laser Laboratory, or ALL. This is a C-135 aircraft equipped with a high-power, gas-dynamic laser. The ALL is designed to test a complete airborne laser system, the laser energy device and laser cavity performance, the beam control mechanisms, and the target acquisition and automatic pointer-tracker systems.

The ALL tests have shown that the laser mirrors must be aligned very accurately to provide a stable laser cavity. Unfortunately, the mirror alignment is very sensitive to vibration and acoustic noise. To compound this difficulty, the gas-dynamic laser used in the ALL is a pow rful noise source, similar to a rocket engine whose high-velocity exhaust gas provides the lasing medium. Finally, the output beam must be aimed with extreme accuracy. This combination of factors makes the stabilization of an airborne laser weapon exceedingly difficult.

To minimize the effects of vibration and noise, the ALL laser mirrors are mounted on a large optical bench, large tanks are used to store the laser reactants, and a large telescope is used to focus the laser beam on target. As a result, the ALL is very heavy, nearly at the weight limit of the C-135 aircraft. Before an airborne laser system can be developed into an operational weapon, it must be reduced in size and weight. One possibility for doing this would be to use a shorter wavelength. The shorter the wavelength, the smaller the dimensions of the beam-directing telescope. Another way to reduce weight is to eliminate the heavy optical bench. This could be done by mounting each laser mirror on its own actively-controlled vibration mount. Such techniques hold the promise of drastically reducing the total system weight.

In addition to using active vibration control systems on the laser mirrors, advanced techniques may be required to control the beam after it leaves the aircraft. Because of atmospheric distortion, the intensity of the beam on the target may not be as high as the optical system would theoretically allow. To compensate for this a feedback system could be used to optically detect the spot intensity on the target, and then to mechanically warp the output mirror to maximize the energy on the target. Such target feedback is possible only because the laser is the first weapon that operates at the speed of light. These advances could make the laser cannon the most accurate and lethal weapon ever used on a fighter or bomber aircraft.

The initial tests of laser weapons by the Army, Navy, and Air Force have been most encouraging. High energy lasers have already destroyed target drones, tethered helicopters and anti-tank missiles. Because of the problems I have previously described, however, the Department of Defense is concentrating on demonstrations of laser weapon lethal effectiveness before developing operational weapons. In contrast, the Soviet Union may already be developing some operational laser weapons.

I want to comment on the area of spacecraft, and review several of the new Air Force systems. The most important change in the 80's may be the shift from expendable launch vehicles to the space shuttle. With the development of the shuttle, and the Inertial Upper Stage for geostationary launches, the Air Force will be able to launch all its satellites on this reusable space transportation system. The increased shuttle capacity, twice the weight and three times the volume of the Titan III, will change our method of designing and using satellites. We will be able to build larger but cheaper spacecraft or to use many smaller spacecraft, including decoys, to confuse the enemy. We will be able to launch extra satellites and park them in orbit, to be activated only when needed. The shuttle may permit us to return malfunctioning satellites to earth for servicing and reuse, at great savings. This new capability will certainly change the designs of future spacecraft. They may be composed of individual modules which could be tested in space and replaced by shuttle crewmen without having to return the satellite to earth.

The shuttle does have its own set of dynamic problems. The unique design of the orbiter places the payload in a large cargo bay 15 feet in diameter and 50 feet long, located near the midpoint of the orbiter. Two large clamshell doors provide access to the payload. This design, with the parallel installation of the solid rocket boosters, places the payload much closer to the rocket engines and lessens the sound absorbing capacity of the structure. The result is that the shuttle payload bay is extremely noisy. Even though additional soundproofing has been applied to the cargo doors, the noise levels inside are expected to be so high that unprotected equipment must be specially designed. Because the shuttle is a complicated design with new liquid fuel rockets, it is likely to be faced with the "POGO" problem. The "POGO" problem has shown up in virtually every liquid-fuel rocket, and was not completely solved during the Apollo program.

The space environment offers several opportunities to employ lasers. Laser satellites could provide completely secure point-to-point communication by modulated laser beams. These beams would be so narrow that only the target would receive any energy from the transmitter. These secure signals would effectively be undetectable and jam-proof. Space lasers provide the potential for transmitting large amounts of power to supply remote satellites with maneuvering propulsion, or use as weapons. Satellite-based laser weapons have inherent advantages over aircraft-based or ground-based lasers. If the beam path is entirely in the stratosphere or above, atmospheric interference is negligible. Ground-based lasers and low-altitude airborne lasers must choose wavelengths at which cloudy or hazy air is partially transparent. Space lasers also have less of a size and weight constraint than airborne lasers. This means that short-wavelength and large-diameter, beam directing telescopes can be used to give great concentration of energy on the target.

A final area of endeavor is the development of large space structures to support antennas and lasers for future space missions. In the past few years possible new military space programs have been considered in anticipation of the space shuttle. The size and frequency of shuttle launches make possible the construction of enormous satellites to perform new and difficult tasks. The use of the shuttle crew to deploy, erect, or even construct new satellites leaves almost no limit on the kinds of structures possible.

One important use for large space antennas, being studied by our space division, formerly known as SAMSO, is to provide communication between a large number of ground units and a central control unit. For instance, a multi-beam, phased-array antenna in stationary orbit could provide theatre-wide communications with 100,000 voice channels. The antenna would have to be 220 feet across and weigh about 25,000 pounds. It would provide jam-resistant coverage over an area 1100 miles across. The same size antenna in stationary orbit could continuously monitor and control 3000 remotely-piloted vehicles over an area the same size. A two-mile wide antenna in stationary orbit could provide sophisticated battle management by giving ground positions, accurate to 150 feet, to troops equipped with two-frequency wrist radios. Other large space antennas could provide radar surveillance of ICBM launches or act as passive microwave reflectors.

These space applications will enable the Air Force to accomplish important new missions, but they will not be developed without careful attention to system dynamics. The key dynamics problems presented by these large space systems are pointing accuracy and surface figure control. In the use of a large antenna, its mission may require that the entire structure be slewed to a given direction in space, pointed accurately for a time, then moved to a new direction. The difficulty is caused by the very high flexibility of the structure and its low-frequency bending and twisting modes. Turning and pointing such a structure is a bit like aiming a wet noodle floating in a bowl of water. If you do it *very* slowly, it can be done. Any abrupt motion in turning a large space antenna causes waves of distortion to travel across the surface, ruining the surface shape, or figure, and its output accuracy.

One way to handle this problem is to use many forces applied simultaneously at many places across the structure. Theoretically, these forces can be tailored to the size and shape of the structure so that the bending and twisting of the structure are cancelled out when it comes to rest at its new pointing direction. Practically, however, this technique requires a precise knowledge of the structural parameters and a complex control system. Any change in the structure, such as a damaged component, would require the control system to adapt. This area is certainly ready for new advances in structural control dynamics. As we have noted, to optimize the output of large-aperture lasers requires extremely accurate control of the jitter vibration and the figure of the mirrors. Some applications of large space lasers require output beams ten to one-hundred feet across. Controlling the vibrations of such large, high-power structures is very difficult.

One possibility of reducing the vibration inputs to the sensitive optical system is to separate the laser itself from the final optics. The laser cavity mirrors would be isolated from the lasing medium in a power module that would, in turn, be isolated from the beam expander, keeping the beam centered in the receiving mirror. The final output mirror would be a large, concave, parabolic reflector, about 30 meters across. It would act like a gigantic optical telescope in reverse, sending out a large-diameter, coherent beam with very low angular spreading. The large mirror surface could be controlled by constructing it in segments and controlling each segment separately. The optical feedback from the target could be analyzed, and the system used to control all segments simultaneously, to optimize use of the feedback signal. Even for extreme ranges, the reflected light from the target would arrive in less than a tenth of a second, allowing ample time to optimize the mirror figure for maximum energy on the target. The design of cavity mirror isolation systems and the structural designs of the segmented, figure-controlled mirrors will provide new challenges in the field of structural dynamics.

With the problems of today and those unique to operating in space, we have challenging work ahead of us. Additionally, some changes taking place here on earth will make our jobs even more difficult. With the disappearance of fossil fuels, we are coming to the end of the era of cheap energy. In the future, we may derive our fuel from oil shale, coal gasification, or perhaps even by synthesizing it from organic chemicals. Whatever the method, it will be *much* more expensive. This means that our future flight vehicles will have to be more energy efficient. Making vehicles more energy-efficient will require lighter, stronger materials, larger vehicles, and very sophisticated aerodynamic designs. As an example of what can be done, the Air Force plans to apply winglets to the KC-135 tanker fleet to reduce drag. The savings from this relatively minor structural change is estimated at 43 million gallons of fuel per year. The potential exists for changes in other flight vehicles as well.

The second change that we will have to adjust to is the chronic inflation we have suffered for the last decade. The same, or slightly increased, number of dollars we have each year simply do not keep up with increased costs. Each year our money buys fewer manhours and less material; therefore it is imperative that every dollar counts.

Finally, in response to the problems of energy and inflation, we need to improve the use of all the resources available to us. This means we should look to closer cooperation with our NATO partners, as well as Japan and Australia. If we have a full technical interchange, research in these countries can be used to complement our efforts in the United States. I am gratified to see that the Shock & Vibration Information Center has just completed the herculean task of reviewing international work in shock and vibration. This survey has been distributed and contains valuable information on what our allies are doing in your technical areas. Continued interchanges such as this will help us in achieving fuller cooperation in other areas.

This morning I have shared with you some of the hopes that the Air Force has for future systems. However, conceptual dreams have a way of becoming operational nightmares unless the fundamental structural problems are well understood and solved. I hope that with your expertise and dedication, the 72nd Shock & Vibration Symposium, hosted in the year 2001 by the Air Force Space Dynamics Laboratory, will be able to report how all these problems, and many more, were successfully solved.

## INVITED PAPERS

### MEASUREMENT IN PERSPECTIVE

Professor Robert M. Mains
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The art of making accurate measurements has a long and interesting history which parallels the growth of science. Advances in science have occurred usually in one of two ways: an hypothesis is generated which requires validation by measurement to become an accepted theory; or a measurement observation requires the development of a theory to explain it. The result of either process is a piece of information which is available for engineering design. Our bag of scientific tricks is hardly ever sufficient to cover all aspects of an engineering design problem, so development and acceptance testing has become an important part of the design process. Development and acceptance testing, of course, requires measurements, which in turn require interpretation before decisions can be made. If an acceleration momentarily exceeds 10g, or if a strain exceeds 0.002, a catastrophy is not necessarily indicated.

First let's lay down some historical background. In 1609 Gallileo improved upon Lippershey's invention of the telescope and broadened the scope of optical observations. In 1680 Newton conceived the interferometer, the principles of which are the basis for radar, sonar and electronic distance measurement. In 1856 Lord Kelvin reported the effects of strain on the resistance of iron and copper wire, but not until 1938 was the bonded resistance strain gage (SR-4) developed by Simmons and Ruge. Carlson, in 1931, developed the unbonded resistance strain gage, many of which are still functioning in the Hoover Dam. In 1887 Hertz demonstrated experimentally the validity of Maxwell's theory of propagation of electromagnetic waves, which paved the way for Marconi to invent the wireless telegraph in 1896. De Forest's invention of the audion (3 element vacuum tube) in 1906 led to amplifiers and AM radio transmitters as we know them today. Frequency modulation (FM) is attributed to Armstrong in 1929, but it was not until 1948 that FM became commercially available. Guillet reported, in 1908, the use of an inductance gage; Whiddington, in 1920, a capacitance gage; Tuckerman, in 1923, an optical strain gage; and Vose, in 1935, an interferometer strain gage. Cathode ray oscilloscopes (De Forest, 1928; Crookes, 1878) were commercially available in the 30's, as were stylus oscillographs (1893), d'Arsonval galvanometer (1882) oscillographs, magnetic tape recorders (1899) and various discrete-step printing recorders. Stroboscopes, photocells and piezoelectric materials were commercially available in the 30's, too.

This abbreviated look at some history shows that, by 1940, the basic principles of measurement and recording by various techniques were well established, at least for laboratory use, with some commercially available equipment. Most of the detailed information on equipment and techniques was scattered through technical journals, so Instruments Magazine engaged Howard C. Roberts to produce a series of articles for the magazine to wrap up the whole works in organized fashion. These articles began appearing in the late 30's and continued, with some interruptions, through World War 2. Then, in 1946, the articles were updated and published in book form as "Mechanical Measurements by Electrical Methods" by H. C. Roberts, Instruments Publishing Co. This book was (and still is) an excellent source for measurement principles and practice.

World War 2 caused rapid, intensive development of dynamic testing and measurements, as well as automatic control devices and systems. Early in the war, it was found that shipboard equipment could not withstand the shock of the firing of the ship's own guns, or the vibration of sustained operation at full speed. Truck and tank borne equipment had similar problems, especially with glass-envelope vacuum-tube electronics. Field measurements of vibration were made with unbonded strain gage accelerometers, shocks were measured with inductance-type velocity meters, and blast pressures were measured with quartz-crystal gages and resistance gages bonded to diaphragms. The Navy light-weight and medium-weight high-impact shock testing machines were developed for equipment weighing up to about 4500 lbs. Resonant-beam vibration testing machines driven by eccentric-weight oscillators were built for testing gun directors weighing up to about 3000 lbs. Small mechanical shakers were too low in frequency for testing vacuum tubes, so electrodynamic loud speakers were adapted for this purpose. Stroboscopic photography was perfected and the high-speed camera became a production item. Drop-table shock testers were developed and widely used for small equipment. Supersonic wind tunnels were built and measurement systems were devised for them.

All of these dynamic testing machines required measurement equipment that was accurate, rugged, compact, dependable, and at the same time available in quantity. As a result there was steady improvement in end instruments, amplifiers and recorders. In aircraft manufacturing, extensive data acquisition systems were developed, with multi-channel balancing and automatic switching and recording. For one supersonic wind tunnel a fully automatic system was installed in 1945, which used analog computers to calculate Mach number, the six components of force on the model, angle of attack and temperature. All of these functions were sampled every 30 seconds, recorded on a strip-chart recorder, punched on cards for later statistical studies, and teletyped to the laboratory 1200 miles away. The linear variable differential transformer became available in 1946 and was used to improve the measurement of drag in this system.

In the late 40's the development of synthetic piezoelectric materials (barium titanate and lead zirconate) made possible the design and manufacture of accelerometers which were much more sensitive, had a much higher frequency range, and could be miniaturized. These accelerometers improved shock and vibration measurement because their small masses distorted the signals less than the heavier accelerometers did.

Another development of the late 40's was FM-FM telemetry. As many as ten subcarrier oscillators ranging in frequency from 1.6 kHz to 70 kHz were frequency-modulated with the desired signal, and they in turn modulated the main carrier at about 105 MHz. In the experimental development of one of the guided missiles, two 10-band carriers were used to carry more than 200 information signals, with the more slowly varying signals commutated onto one subcarrier. The main carrier signal was recorded on high-fidelity tape, which was later demodulated and each subcarrier was separately recorded.

During the 50's, electrodynamic shakers became available with force capabilities from 25 to 5000 lb. At first, these shakers were driven by motor generators with manual frequency and force control. The determination that missile flight vibration was random (1952) prompted the building of a 1000-watt power amplifier, so that it could be used to drive a 500-lb shaker from tape records of flight vibration. For the next eight years, intensive study, research and development was applied to sinusoidal, swept sinusoid, step-programmed, random and simulated shock testing. The effort was to develop an understanding of damage accumulation so that designing could be more rational and the various testing techniques could be "equalized" in damage effect. By the end of the 50's, one could buy a 5000-lb, amplifier-driven shaker with automatic sweep control, random spectrum control and many other special accessories. Even larger force capability was available in servo-controlled hydraulic shakers, but with a lower frequency range.

During the 50's, the piezoresistive (or semiconductor) strain gage appeared, and the development of printed circuits brought forth the foil strain gage. Printed circuits and solid-state electronics cured most of the shock and vibration problems in guided missiles. The state of the art in shock and vibration as of July 1955 was well covered in the "Handbook of Guided Missile Packaging", edited by Klein, Ayre and Vigness, Naval Research Laboratory No. RD 219/3.

A major event of the 50's was the appearance of the "first generation" of digital computers which rapidly took over much of the work in shock and vibration analysis previously done with analogs. Weeks of hand and analog work could be done in a day, and the normal modal analysis of multi-degree-of-freedom systems with as many as 25 or 30 modes could be done quite readily.

The invention of the laser in 1958 by Townes and Schawlow was out together with Gabor's invention of holography (1948) in the early 60's. X-ray holography in the late 60's made it possible to see how the interior parts of equipment responded to shock and vibration Photo multipliers, counters, timers (EPUT meters) and faster computers brought forth the Fast Fourier Transform and spectrum analysis became an on-line item instead of several days wait. Also in the late 60's, fiber optics instruments were developed to see inside of people and things in places which were previously impossible. In recent years, fiber optics cables have been replacing telephone cables carrying voice, data and video signals with greater efficiency and many more lines per cable.

The decade of the 70's has brought the conversion of everything electronic to solid-state, with miniaturization a natural by-product. A computer the size of a postage stamp now replaces what was formerly a room full of equipment, with computing times measured in pico seconds. Programmable calculators of hand size are now commonplace, and units smaller than a portable typewriter do in seconds the work that an IBM 650 required hours to do. Digital readouts have replaced analog readouts in almost everything, including theodolites and electronic distance measuring devices. These theodolites read directly to 0.01 a second of angle, and EDM's measure several kilometors in one shot with accuracies approaching 1 cm. Strains in the earth's crust are being measured along fault zones (with lasers) for earthquake research. The earth's dimensions and details are being corrected through the use of satellite photography and communication. Signals from the Earth Resources and Technology Satellite (ERTS) are continually providing data on forestation, crop conditions, water distribution, air pollution, cloud cover, storm paths and a host of other items.

In a time when the ocean's bottom has been explored, the moon's backside has been photographed and the planets have been probed, it is difficult to anticipate what the next decade will bring. With the current interest in energy problems, it seems likely that new developments in instrumentation will be associated with fusion reactors, coal gasification, solar cells and the like. As in the past, new gadgets will be devised to get on with what needs to be done, while the work on miniaturization, improved accuracy, faster response, lower cost and portability continues.

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# DYNAMIC ANALYSIS AND DESIGN—CHALLENGE FOR THE FUTURE

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It's a pleasure to be invited here today to address the 50th Shock and Vibration Symposium. The Shock and Vibration Symposia have covered a period of 32 years, roughly the same period of time that I have been engaged in, or dependent upon, dynamic analysis and design. For the 20 years prior to my program management assignments, I was directly involved in dynamic testing, aeroelastic and dynamic analysis, and structural design.

I have been responsible for overall program management for the past ten years and have had a different perspective of where dynamic analysis fits in, being responsible for the final product and the cost-effective execution of the effort to get to the final product. I am, therefore, the recipient of good or poor dynamic analysis, interpretation of requirements and the resulting structural design. I can assure you that the quality and timeliness of the analysis has a significant impact on the cost, schedule and ultimate capability of the final product.

My involvement with dynamics started with my graduate work in hydrodynamics and research studies of ocean waves and interaction with structures. Our problems in those days were to tie our theoretical knowledge to the real world of testing when our methods of dynamic measurement were limited. Electronic instruments and oscillographs were just being developed. Dynamic analysis involved laborious, lengthy manual calculations using, at best, electric calculators. Electronic digital and analog computers were in their infancy. The approach to design was based on past experience and extensive testing of the prototype design.

I looked back at the first few shock and vibration bulletins to set the stage for discussing the progress that has been made. The first meeting was in January 1947 and Dr. Klein's most significant concern at that time was to get some standardized method for measuring acceleration. The information discussed was predominately testing, instrumentation and measurement of the dynamic environment that the equipment would see in operation.

The first dynamic analysis report was that of J. W. Wrench from David Taylor Model Basin comparing the measured and calculated response of a single-degree-of-freedom mass plug accelerometer to underwater detonation and the use of shock spectra as a description of shock. This was about the limit of the dynamic analysis and design capability. Even the more sophisticated field of aircraft flutter was limited to two or three degrees of freedom and lengthy calculations. Testing was the method of assuring that the design was adequate, using full-scale prototypes under the actual operational environment. Analysis was used mainly to understand the test results if it was attempted at all.

When we look back to that time it is clear there has been tremendous progress in dynamic analysis and design, as reflected in the depth of detail and number of degrees of freedom in the calculations we are conducting today. I hope we have also made the same progress in understanding system response and the optimization of the design, however that is not as clear. This progress has come because of the analytical tools, digital computer capability development and the understanding and training of the analysts. But we have problems today in fully utilizing the capability we possess and in applying the analysis to the final product design.

The future for dynamic analysis and design is bright. Ten years from now I believe we will have the capability and the need to do analysis that is as advanced from what we are doing today as our current analyses are to the one-degree-of-freedom analysis of 1947. The challenge is whether we are doing the things now so that we are ready to use the incredible capacity that we are going to have available. We are going to have to overcome today's problems and be prepared to change not only our analysis methods and the role that the analysis contributes in the design, but also our attitudes and organizational structure to accomplish the design. I would like to take a brief look backward. Sometimes seeing where you have been gives you a better idea of where you are and where you may be going in the future.

Thirty-two years ago our dynamic analysis and design capability consisted of one-degree-of-freedom, or at the most two or three-degrees-of-freedom. Figure 1 shows the one-degree-of-freedom analysis that was presented by J. W. Wrench in 1947. Although the limited dynamic analysis capability could give some guidance to the designer, designing was mainly a static approach based on past experience. What little dynamic analysis was done was to try to understand what was happening in testing. The major method of proving the design was extensive testing under simulated or actual operational environment. And when it didn't work, fix the design. Really, it was a "cut and try" method.

We move on to the early '60s for the next snapshot, roughly halfway between the first symposium and now. We

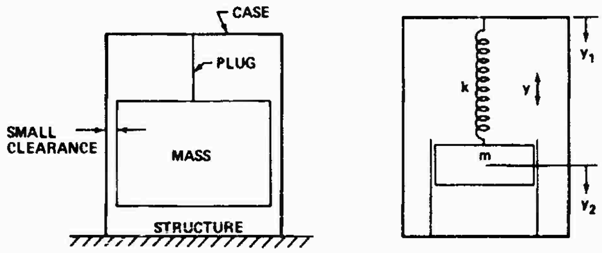


Figure 1 — Single Degree of Freedom Systems

had progressed to sophisticated analog computers, those which solve the equations of motion in real time as well as those which directly replace elements of the structure with electrical elements. We were limited in size and detail of analysis by our pocketbook and the limits of our patience in setting up the analog. We were beginning to make substantial use of the digital computers. Their speed and storage capability were increasing rapidly and the capability to solve dynamic problems was just beginning to exceed what could be done with the analog. In fact, we were at the peak of the analog capability. The CEA Direct Structural Analog was the largest, as shown in Figure 2. It took a room 50 feet by 50 feet and required nearly a drawer of equipment for each structural element being simulated. The cost, size, time and complexity limited the analog's future in solving larger problems. We had the capability to solve problems with 20 to 30 degrees of freedom—an order of magnitude greater than 16 years before.

An example of the analysis at the time was the dynamic analysis of the minuteman missile and its transporter-erector (Figure 3) to road surface roughness, reported in the 33rd session. The analysis model (Figure 4) consisted of modeling the tires and axles with the suspension, the vehicle and container structural modes, the suspension of the missile within the container, and the structural modes of the missile.

The analysis model could be varied to determine the effect of structural stiffness variations, suspension spring rates and damping characteristics on the critical load locations in the missile. The missile structural response and loads could be determined quickly and inexpensively for a wide variation in road surface conditions and speeds once the analysis model had been set up. The analysis could set the requirements for the design and eliminate the expensive and time-consuming "cut and try" testing method. The testing could be done on the final design and become a verification

Figure 2 — An Analog Computer

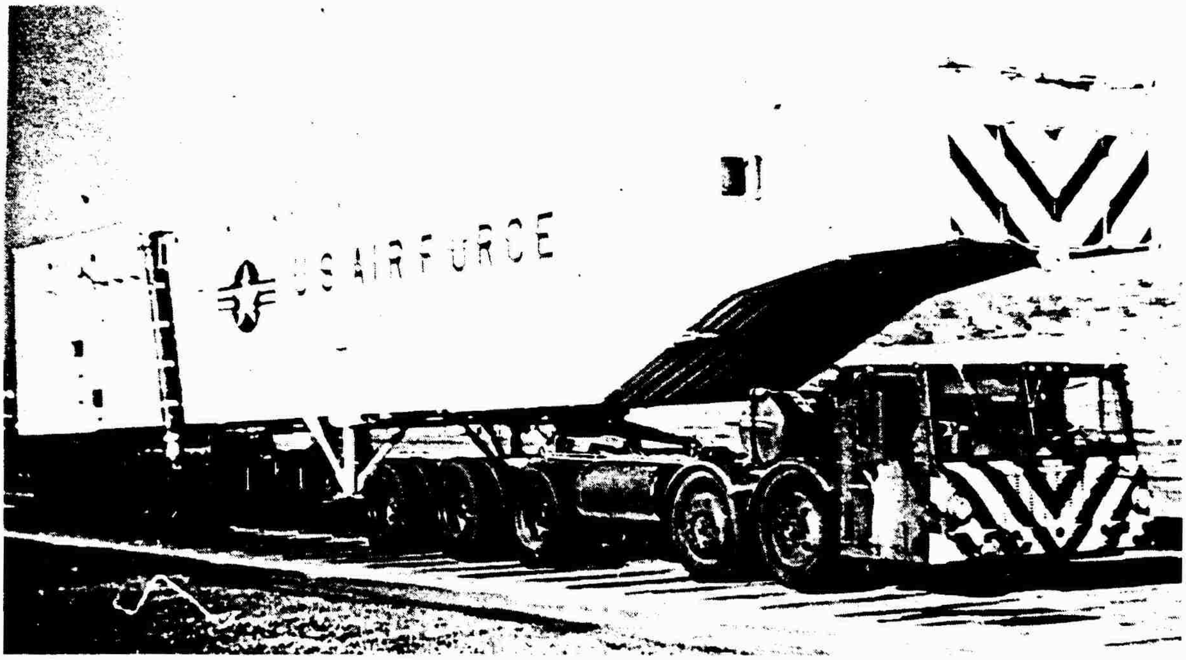


Figure 3 — Transporter Erector

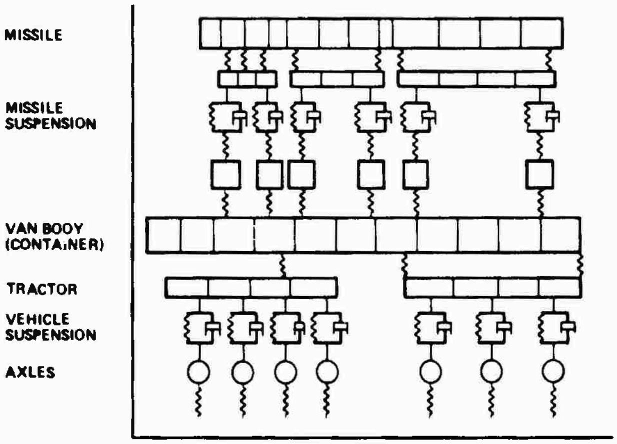


Figure 4 — Analysis Model

of the design rather than being the design approach. Not only had the dynamic analysis capability increased, but the role of analysis in the final design of the product had changed.

We now move to the present. The large structural analogs have disappeared. The digital computer capability has grown by three to five orders of magnitude in speed and capacity. Our problems now are the time to get the data into the machine, in understanding the output, and in being cost-effective in our usage. Our products have changed. They are more complex. Weight optimization and performance are critical, or optimization of the design to reduce cost for large hardware production runs is paramount. We must rely on analysis because we can't afford the expensive development tests or we can't simulate the real operational environment.

An example of the complexity of the systems being designed and the degree of dynamic analysis and design interaction can be found in the space shuttle program (Figure 5). Full testing under operational conditions isn't possible. We can simulate some environments and test components, but the major structural loadings which come during launch and landing can be obtained only during the actual operation. You don't get to stop and redesign in the middle of the operation. The first time it's launched it must go all the way.

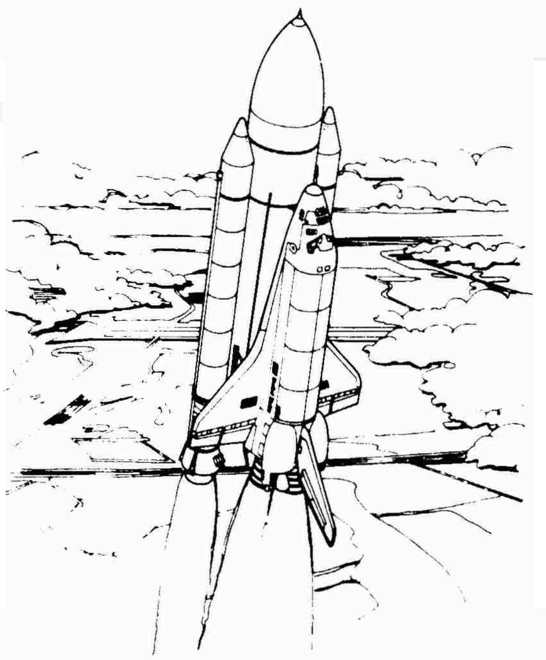

Figure 5 – Artists' Concept of Space Shuttle

Coupled to the complexity of the orbiter, the external tanks and the solid rocket motor boosters is the spacecraft and its booster, which are carried in the orbiter cargo bay. Figure 6 shows the inertial upper stage and the spacecraft in the orbiter which must be analyzed as a part of the total orbiter system for launch and abort launching conditions. This is in addition to being analyzed for requirements as a separate system when it leaves the cargo bay. The analysis is complex with a large number of degrees-of-freedom in the finite element structural models and a large number of modes in the dynamic models, as shown in Figure 7. Each of the separate systems must be modeled and analyzed on its own, and then a somewhat more simple modeling of the elements must be merged to obtain a model of the total system.

The results of the dynamic analysis of the complete dynamic model, in terms of loads, accelerations, stress and displacements, are then fed back into the finite element structural models to determine stress in the detail structure. This results in some structural changes which require a revised dynamic analysis model and loading. The interaction continues until we have a compatible design with the external forcing functions and system requirements. There is also a complicated organization and contractual arrangement with several companies involved in the dynamic analysis and design. Dynamic modeling and input/output information must be passed from one organization to another.

We have now progressed another order of magnitude in the number of dynamic modes we can include in the analysis. Testing is becoming more expensive and our ability to simulate the environment is limited. Dynamic testing is being used extensively to support the dynamic analysis, both dynamic tests of models and full-scale modal tests of the flight hardware. The role of the analysis has changed again, not only is it providing the design requirements, it is the only method of verifying the design for some operational conditions. But we have problems with the dynamic analysis and design processes today.

The first problem, and to me the most critical from a hardware design standpoint, is the excessive amount of time it takes to complete the analysis/design cycle. Because of the complex nature of most systems and interactions, the analysis and design cycle must be an iterative process. Initial requirements are established based on the concept. These are translated into a preliminary design for which an initial dynamic analysis can be conducted. This generates new loads and dynamic requirements for structural stiffness, damping, mass distribution, etc. which are then introduced back into the design. Depending upon the complexity of the design and the need for optimization of performance or payload, this process can proceed through another or several iterations. Then, after the fabrication of development hardware and dynamic tests to check the characteristics, usually another iteration is required.

In the case of the shuttle, inertial upper stage, spacecraft configuration I described, this process is even more complex. There are several different dynamic analyses models being done by different companies with different design goals. The dynamic interactions between elements in one analysis must be inputs to another analysis. In the case of the total configuration for launch, we have completed our third iteration of the dynamic forcing functions. It has spanned more than one year and during that time the loads have nearly doubled from the initial static load estimates. The impact of this slow iterative process on the cost and schedule of a program with a fixed deadline is substantial.

This example, I'm sure, to most of you seems overly complex. In this case we are dealing with a system which has

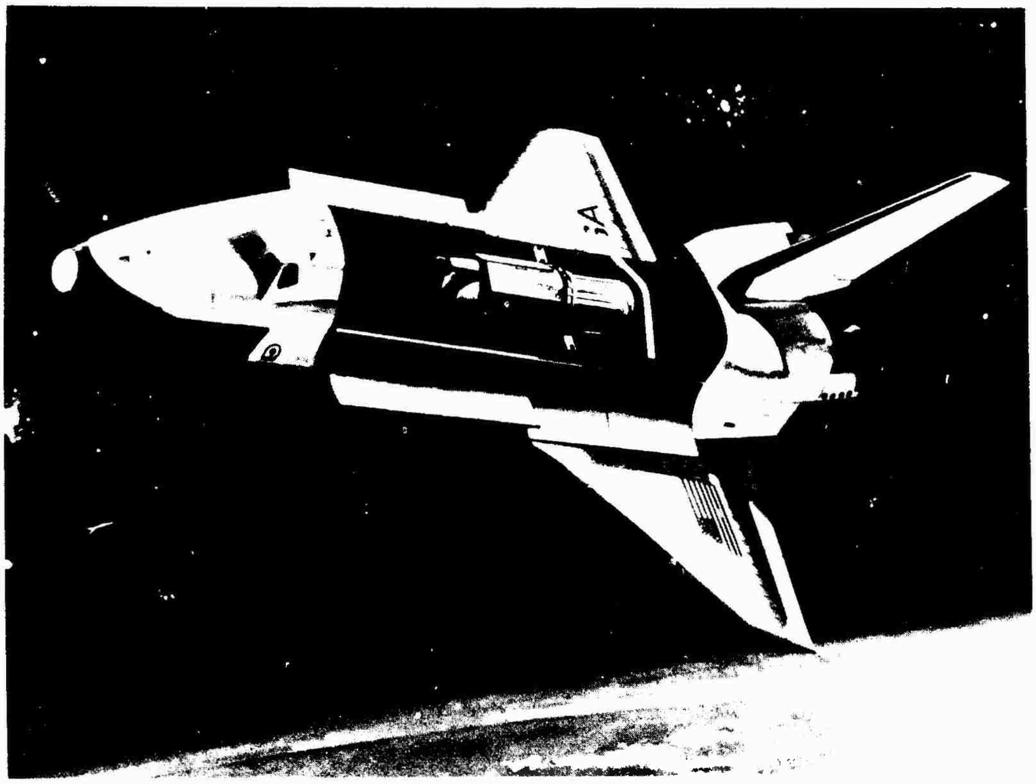

Figure 6 — Space Shuttle Payload

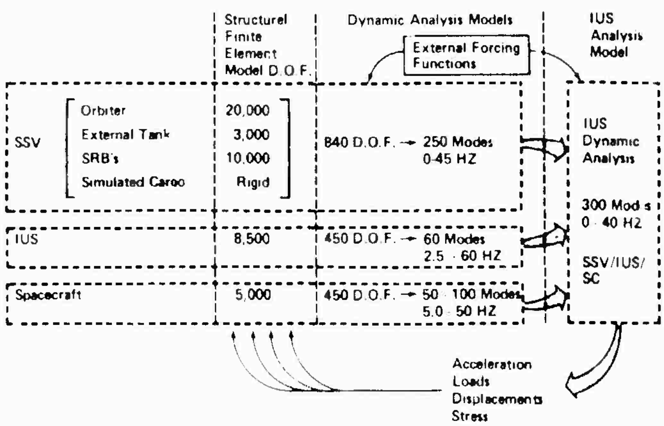


Figure 7 — Dynamic Analysis Model

many elements that cannot be fully tested prior to flight and in which there must be confidence in the design. However, it is probably the leading edge of what the future will hold for most designs, even the less complex systems, when computing becomes much less expensive than it is now and design optimization is cost-effective. Second, we are not fully utilizing the analytical capability we have today in the designs. We still rely to a great extent on structural analysis with static load factors. The dynamic analysis is conducted to assure that the loads do not exceed the simplified static loads. This is the case in the shuttle design I described. Even though we are searching for every kilogram of weight reduction and every second of ISP propulsion performance we can get, we still aren't taking full advantage of the dynamic analysis capability we have today. Each element of the structure could be designed to the maximum condition that it will actually experience in the dynamic operational environment, rather than to a peak static load factor applied to the total structure.

I'm not sure why we aren't taking advantage of our capability. It's partly historic, tradition to do the design the way we do. It has been successful in the past and there is confidence in the method. It's due to the way we are organized and the assignment of responsibility. It's probably due in a significant way to the experience of the managers who are planning and directing the dynamic analysis. Their experience may be years behind the capability of today's tools and analysts, and it may be due to a lack of communication by analysts to management on what the real capahility of analysis can be.

This brings me to the last point. There is a lack of confidence in relying on the dynamic analysis results. There must be more effort in verifying the analysis results, in checking the analyses with limited testing, short of full-scale testing. We must get beyond a typical attitude today that, given enough test data, the analyst can adjust his model to get the right answer after the fact. It is really a selling job. The role of the analyst in the detail design is going to grow and the time is coming when it will be mandatory that we rely on the analyst and not on testing.

Now I'd like to look to the future, make a few predictions, and lay on the challenge we are faced with. Predictions for the future are usually difficult. We have to rely on our past experience and knowledge to predict and we often fall short of what really happens because we can't visualize it. Other times predictions are too optimistic, based more on desire than what really can happen because of technical limitations, a lack of real need and, more recently, just plain economic considerations. Recognizing these constraints, I'll try to avoid them in my predictions.

There are three areas that will affect the future of dynamic analysis and design (See Figure 8); the types of products, the improvements in the analytical tools, and change in the way we design and manufacture hardware.

Many of the products we will design and develop in the next two decades will be similar to those we are doing today—vehicles, equipment, and aircraft. There will be extensions or modifications of these products and the type of dynamic analysis and design could be done in the same manner as today. However, there will be a drive for more economical design activities and efforts to reduce the cost of analysis and the time required to accomplish the effort. More importantly, there will be a need for closer ties to manufacturing, eliminating the input/output stages and drawings we have today. The other type of hardware will be that for which there is no way to assemble and test because of size or the inability to simulate the dynamic environment except by actual operational use after the equipment is built (See Figure 9). The hardware that goes into space in the future will be large antennas, space stations, or even solar power satellites. In many cases these structures won't even be built on earth. Only the materials will be transported with the structural beams actually fabricated in orbit. There won't be any way to test the systems. We will have to rely entirely upon the analysis to set requirements and to qualify the design. This may even require independent verification and validation as we do today in software.

The second area where the future is going to impact us is the development of the analytical tools. As you read everywhere, we are on the threshold of a revolution in the field of computers. The low cost and availability will proliferate into every facet of our lives. The technology which is producing these changes will result in far more outstanding changes in our scientific computing, not only in the ability of each designer to have the capacity of our largest computer capability today at his fingertips, but in the increased speed and storage capacity being predicted.

Figure 10 shows the estimates being made for speed increases in microprocessors in terms of millions of operations per second (MOPS). Today's microprocessors will give way to the processors with three orders of magnitude increased capability and will lead ultimately to the processors with potentially a million times greater throughput than the capability today. Within the time frame we are considering, the next one to two decades, we can reasonably expect three orders of magnitude increase in speed and capacity at a comparable or lower cost than today. Of course, our major concerns are going to be as they are today, the time and capability to input the information and retrieve the analytical results. This will drive us toward minimizing the data shuffling between computers and design organizations to make the operation cost-effective. The low cost of computers will allow unique computers for each type of analytical application where today we must rely on main frame computers and inputting the computational program each time or calling it up from storage. Computer software or firmware will control the function by being able to draw on massive stored data and interpret the results to those final output parameters which are necessary. This will force us to have utmost confidence in the analysis and in the competence and understanding of the analyst and the computer programmer. The size of computer storage and speed of throughput will be such that there will be no limit to the number of degrees of freedom or the depth of detail to which we can define the dynamic loads or stresses if it is economically justified or needed. We will be able to look in detail at sections of the design and tie sections together into the total system.

The third area that is going to impact us is the way we do design. We are being driven to be more cost-effective in our design and development as well as in hardware produc-

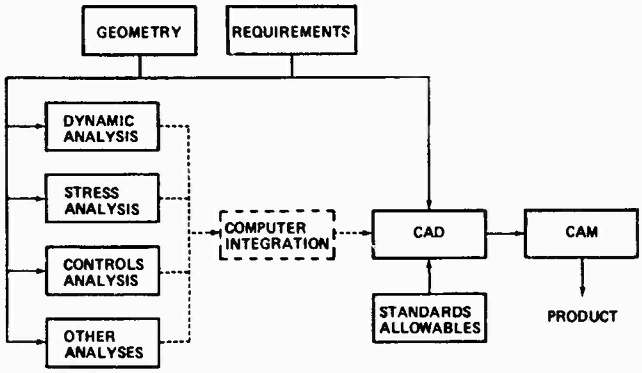


Figure 8 — Analysis and Design

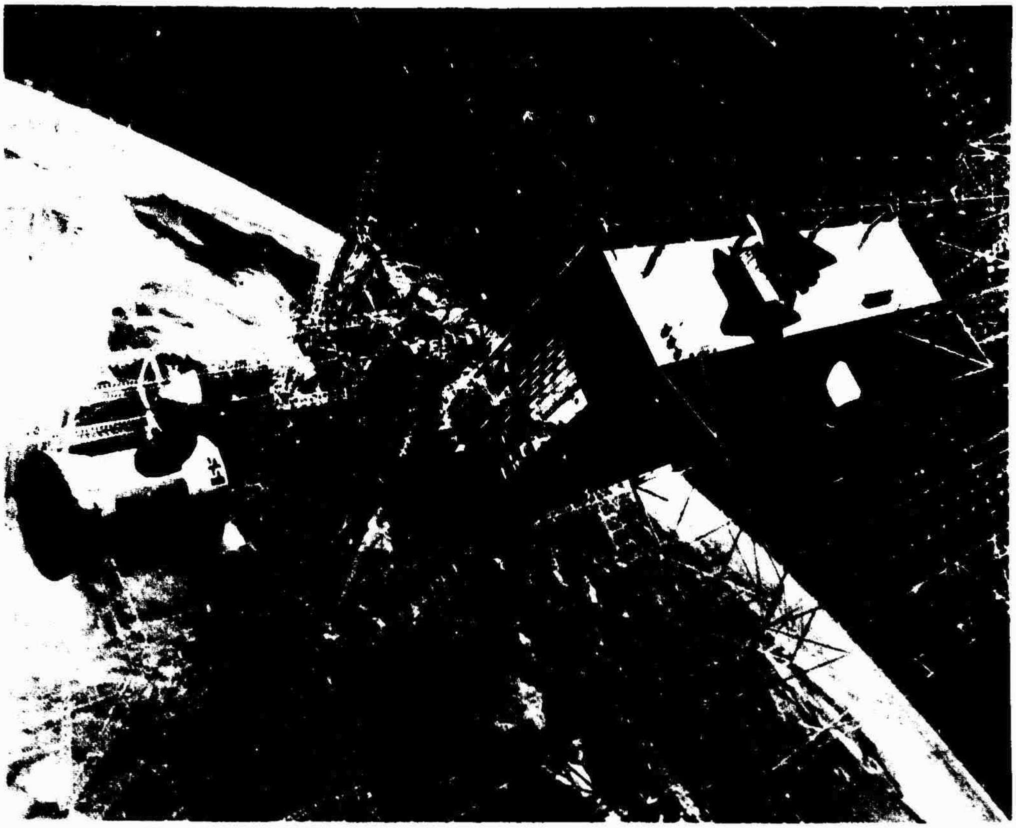

Figure 9 — Complex Space System

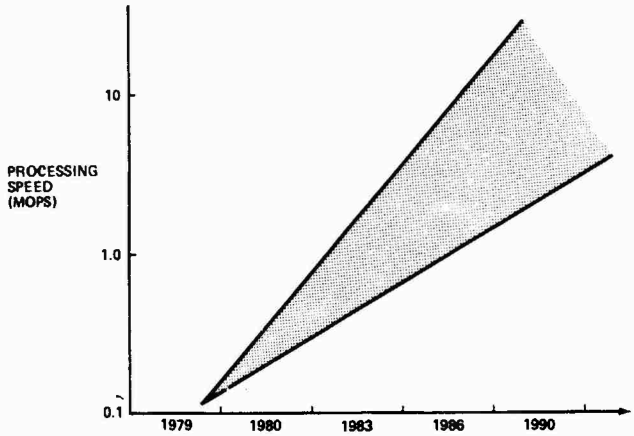


Figure 10 — Projected Microprocessor Speeds

tion. The only way we can effectively use the increased analytical capability is to reduce the time flow and people involved in the design process. I can visualize analytical capacity such that there will be no need for the separation of the analysis and design functions. The design could be done in one computational process. The input would be the concept and operating constraints and the standard design parameters would be stored in the computer. Output can be drawings if needed or more likely go directly to the manufacturing tapes necessary for automated production. We are in the first, limited stages of this process today with the computer-aided design and computer-aided manufacturing.

Figure 10 shows in the solid area those computerized activities in the flow of the hardware from analysis to design to manufacture which are in use today, in some cases in limited applications. The computer capability which is coming is going to make possible the tieing together of the rest of the elements into a composite approach with major reduction in time and cost. One of the problems we have today is the retention of knowledge; the answers to the past analyses, the errors we have made in the past and the resulting corrections. Today that knowledge exists primarily in the minds of our engineers, the analysts and the designers or, at best, in some document or a loose-leaf notebook which, with time, becomes lost or stored. With the capability we will have in the future, the total corporate design knowledge of a company or the industry in total can be stored in the computer or in off-line storage available for immediate application to the problem at hand.

In all this change, and driving for more cost-effective production and utilization of the computer, we must consider the most important resource—the people involved. The roles and responsibilities of the analyst, designer and test engineer will change. There will be greater reliance on the analysis and therefore a greater need for confidence in the analytical results. The design and analysis functions will merge inside the computer. There will be less testing because of the cost and it will be done primarily to support the analysis. Final verification and qualification will be mostly by analysis. Under these conditions the most important individuals will be those who can provide understanding and confidence in the process to the program management. These will be the designer of the computer program and the analyst who inputs and interprets the results and provides the verification. This will mean new organizational concepts. The development of the people to accomplish these new responsibilities must be considered the same as we would consider the development of the analytical tools.

I have attempted to summarize my remarks in Figure 11. The chart depicts, for the areas of analytical capability, the design process and the organizational structure, a view of the past, where we are generally today, and my prediction of what the future holds. First, it shows at the top the degree of dynamic analysis capability from a few degrees of freedom to our three to four orders of magnitude improvement today, to what I believe will be unlimited capability in the future.

Next, it shows the role of analysis and test in the design process. In the past the testing was an integral part of the design with analysis being a means of understanding what happened. Today the analysis and design are being done concurrently with testing supporting the analysis and being used for qualification. For the future, I anticipate the analysis and design being an integrated activity in which the final verification is analytical and testing is primarily supporting the analysis effort. There is, of course, not a clear-cut separation of approaches in time. Examples of all three approaches exist today. However, the majority of the more complex designs are following this path because of test costs and the increased computer capability. This leads then to the final area, that of organization to do the design and produce the product.

In the past the organizations were completely separate entities with specific responsibilities, and with much data being generated and passed back and forth — drawings, documents, test requirements, etc. Today there is significant interaction between the analysts and designers. The organizations are co-located. In some cases we are going directly from the designer to the manufacturing machine by computer with no need for intermediate drawings. For the future, because of the computer capability, the organizations we recognize today will merge. The roles of analysts and designers may disappear as we know them and be replaced by a team which progresses with the design completely within the computer all the way to the machines which fabricate the hardware. I have concerns with our ability to deal with these predictions of the future and they form the basis for the challenge facing us.

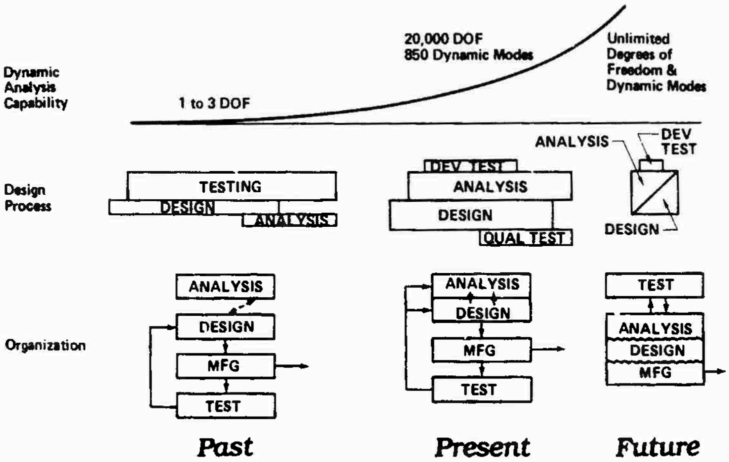


Figure 11 — Analysis Design Process

First, we must understand the tremendous potential we are going to have in computational capability. This is the responsibility of the analysts and management. As managers we must listen to the analysts and recognize the capability they are developing. As I said earlier, we tend to think years behind the current capability because of our detail experience. We mustn't let that constrain our planning for the future. It will require a change in attitude for us to plan for a level and method of analysis and design beyond our experience and an organization to do the job which is as radical as the change in the capability to do the analysis.

I challenge the analysts and the designers to think beyond the constraints we have today and communicate the future possibilities to the planners and management. I challenge management to listen to the young, new experts we have and what they can do. Don't be limited by how we personally have done the analysis and design in the past. If the techniques are needed and are cost-effective, support the necessary investment. Challenge the analysts to provide the verification that is necessary to have confidence in the computer results. Of course we could take an easier path. We could say that we have reached the reasonable limit of dynamic analysis and design, understand and more effectively use the level of analysis we have today and not strive to increase that level of understanding or to optimize the designs. I'm not ready to settle for that path. We must continually strive for those improvements which will increase our productivity across the spectrum in our industries or we will stagnate and fall behind.

I have raised some questions and concerns this morning with the hope of challenging you to help with the solutions. I can assure you that the need for high confidence, cost-effective, rapid dynamic analysis and design is here now and it will grow as we move into the future. I believe the computational capability will outstrip our ability to effectively use it unless we begin now to prepare the trained personnel and develop the techniques and organization to use the computer capability effectively in the design process. The future of dynamic analysis and design looks bright but we are going to have to devote our energies and research funds, not only to doing the design and solving today's problems, but to preparing and planning for the new capabilities. This is the challenge which I wish to leave with you this morning.

# SHOCK IN SOLIDS: ARMY MATERIALS RESEARCH AND APPLICATIONS

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## INTRODUCTION

The Army is vitally concerned with the structural integrity and durability of its equipment, much of which is required to operate in severe dynamic environments. The US Army Material Development and Readiness Command (DARCOM) is responsible for the acquisition and fielding of this equipment, and is well aware of the difficulties in dealing with these adverse environments.

As DARCOM's staff laboratory for materials research and development, the US Army Materials and Mechanics Research Center (AMMRC) is therefore vitally concerned with the response of structural materials in such environments. Accordingly AMMRC's program, to a large extent, deals with the realm of shock and vibration. This involvement ranges from structural response, in the millisecond-time regime to shock in solids, in the nano-second-time regime.

Because of the major emphasis we see today in the development of fragmenting warheads, high density penetrators and armor to defeat high density penetrators, we would like to concentrate this presentation principally on the behavior of materials in time-and-pressure regimes associated with these applications. Specifically, this equates to times of up to 20 or 30 microseconds, and pressures on the order of tens of kilobars.

Before getting into some of AMMRC's current research program in shock in solids, we would like to set the stage by describing AMMRC, its mission and a little about its technology-base program, with emphasis on the solid mechanics part of that program, which we feel would be of greater, direct interest to this symposium.

## AMMRC AND ITS MISSIONS

AMMRC is one of two laboratories reporting directly to DARCOM, the other being the Human Engineering Laboratory. The remaining DARCOM laboratories report to commodity-oriented research and development commands, which make up the development side of the DARCOM complex. AMMRC, therefore, has an across-the-board mission, not directed to a particular type of system.

Stated succinctly, AMMRC's mission is to manage the Army's research and development program in structural materials and solid mechanics. AMMRC is chartered as the lead laboratory within DARCOM for those technologies, as well as for materials testing. The technology-base program is executed not only within AMMRC, but at other DARCOM laboratories, where the requisite skills exist, and on contract.

While AMMRC reports to DARCOM, we really work for the research and development commands in the sense that our program must be responsive to their needs. In fact, besides having responsibility for the materials and mechanics technology-base program which has longer range goals, we are expected to, and do, provide short term, direct support to these commands, project managers (most of whom are within these commands) and to the readiness commands (which comprise the other side of DARCOM). Figure 1 illustrates this role and shows some of these direct support activities, which apply to systems under development, in production or even in the field.

A good illustration of this direct support has been, and continues to be, the development of nuclear shell. For almost two decades the armament R&D Command (ARADCOM) has used AMMRC as an integral part of its team in the development of these shells. AMMRC's role has been in the materials selection and processing area, in assuring the structural integrity of the shell bodies and in the manufacture of the structural components.

Since AMMRC's mission requires that we serve as the focal point for materials research and development, and materials in this context applies to Army systems across the board, we have structured our program along the lines of the DARCOM research and development commands. For example, we break the program out into Materials for Armament, Materials for Aircraft, etc., corresponding to materials requirements of ARRADCOM, the Aviation R&D Command (AVRADCOM), etc. Since DARCOM's readiness commands are organized along those same lines, we are able to focus our program in a responsive way to the needs of DARCOM. As an aside, the research and development commands are responsible for the systems development and acquisition process up to the initial buy, at which point the readiness commands take over.

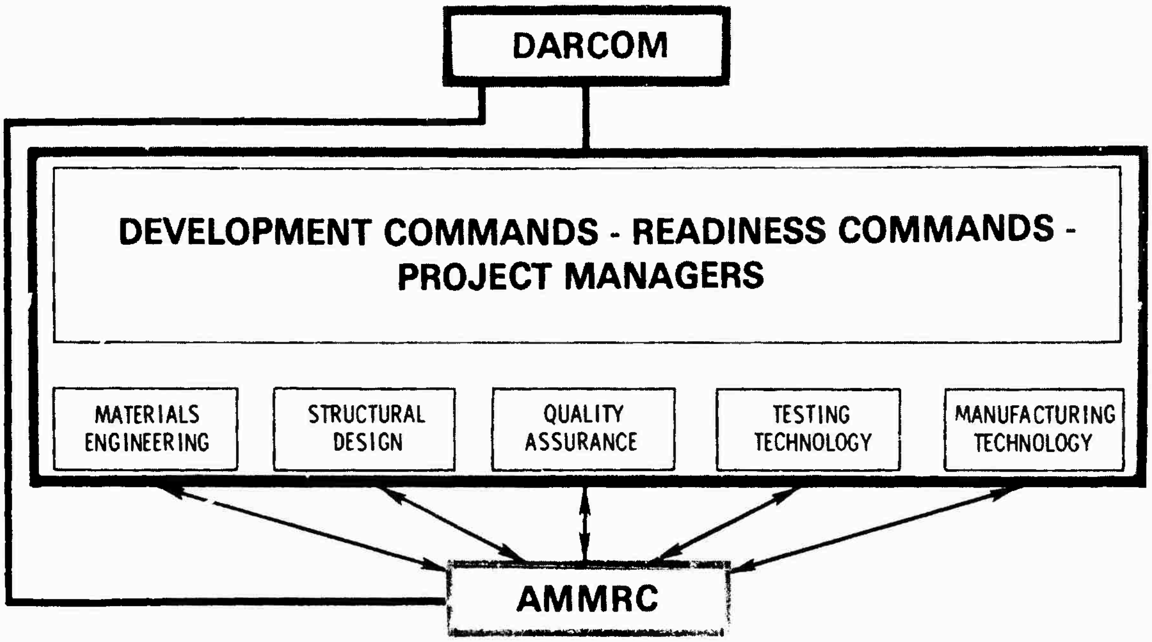


Figure 1 — AMMRC Support Relationship

By structuring our program this way, you can be sure we get into many areas where the dynamic response of materials and structures are key issues. Figure 2 shows some of the areas our technology-base program is currently emphasizing. We will not attempt to cover all of these. In fact we will be concentrating principally on the mechanics aspects of only a few. Besides discussing the shock mechanics aspects of fragmentation, armor and penetrator materials, we will briefly mention mechanics of composite materials and life prediction/reliability mechanics.

AMMRC is located at the site of the former Watertown Arsenal, about six miles west of Boston (Figure 3). In fact AMMRC was formed by the merger of the Watertown Arsenal Laboratories and the Ordnance Materials Research Office, a tenant activity. We are literally surrounded by centers of higher education and research, which facilitates strong interactions. Off the map, but less than an hour's drive to the south, is Brown University which has a very active program in dynamic behavior of materials.

The aerial view of AMMRC (Figure 4) was taken from over the Charles River, looking from the southeast to the northwest. What is now AMMRC comprises the westernmost third of the old Watertown Arsenal grounds. The arsenal was founded in 1816, and was disestablished in 1967. The buildings on the eastern side date to the period from right after the Civil War to the end of the nineteenth century. The oldest of these is the Commanding Officer's Quarters, built in 1865 at a reported cost of less than $65,000. The building is toward the lower right-hand corner nestled among the trees. The newest of this group is Building 36, the low building, with the white facade, running east and west in the center of the picture. Building 36 was completed in 1900 as a gun carriage storehouse; it now houses AMMRC's photo laboratory, technical reports office, library, auditorium, and supply center. Just to the right, in a north-south orientation is Building 312, built in 1894 as a gun carriage assembly shop.

In spite of its venerable exterior, the old gun carriage assembly shop now serves as a modern laboratory facility; much of AMMRC's dynamic testing is conducted within Building 312. For example, a computer controlled testing system (Figure 5) which is used to characterize metals, ceramics, polymers, and composite materials at strain rates from about $10^{-4}$ per second to 50 per second, is located there. Many other dynamic testing facilities are there also, covering higher strain rate ranges. Included are a penetration research facility, used to evaluate armor and penetrator materials, and a light-gas gun facility which can generate shocks in solids up to about 500 kilobars, and measure responses in the nanosecond range.

## SOLID MECHANICS

Perhaps the easiest way to describe AMMRC's solid mechanics technology-base program is to say that its goal is to obtain a quantitative understanding of how materials fail, and with such understanding develop predictive techniques. Although the overall program is structured along systems-oriented lines, AMMRC is organized along discipline-oriented lines. Within the mechanics side of AMMRC this translates to life prediction/reliability mechanics, mechanics of advanced materials, and shock-impact mechanics/dynamics. Regardless of which way it is viewed, mechanics of failure processes is the common thread of the program.

- CHARACTERIZATION OF ORGANIC COMPOSITES
- ELECTROSLAG REMELTED STEELS
- HIGH DENSITY PENETRATORS
- ENVIRONMENTAL PROTECTION/DURABILITY OF MATERIALS
- BALLISTIC MISSILE DEFENSE MATERIALS
- GUN BARREL EROSION
- METAL-MATRIX COMPOSITES
- GEAR MATERIALS
- BRIDGING MATERIALS/CONCEPTS
- CERAMICS FOR DIESEL ENGINES
- FLAMMABILITY/FIRE PROTECTION
- FRAGMENTING MUNITION MATERIALS
- ARMOR TO DEFEAT LONG ROD PENETRATORS
- LIFE PREDICTION RELIABILITY MECHANICS

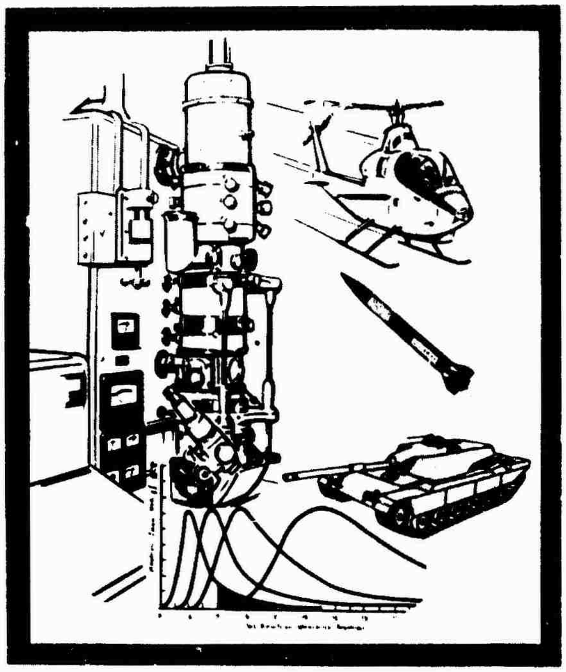

Figure 2 — Current Areas of Emphasis

*Life prediction/reliability mechanics* has as its objective the merging of fracture mechanics with probabilistic-based considerations. We have a number of concerns in this area, which have led to a strong commitment. Because Army systems must operate in increasingly severe environments, we are pushing our materials much harder, and are using materials that are much less forgiving than was the case in the past. As General Baer pointed out, the Army now employs a high-fragmentation steel in the warhead of its 155-mm rocket-assisted high-explosive round. This material is extremely effective on target, but is inherently brittle, posing difficult design issues to insure safety and reliability during rough handling and launching. Obviously, the use of such materials, particularly when employed in more severe environments, dramatically taxes our ability to predict failure.

There are other issues bearing on this area which demand attention. For example, linear-elastic-fracture mechanics is inadequate in its present state; elastic-plastic behavior needs much additional effort as does shear and mixed-mode fracture analysis. From AMMRC's point of view, we feel that even though the current state is not adequate, continuing emphasis on using what is now available is essential.

Another concern relates to the availability of an ever increasing number of structural mechanics computer codes; conservative estimates are that there are now more than 1000 such codes, both general and special purposes, in use in the United States. Many of these are used as "black-boxes," with no understanding of the details of what the codes are doing. A classic example of what can happen if this approach is followed was the shutdown of five nuclear power plants several weeks before the Three-Mile Island incident, when it was discovered that a nonconservative programming error existed in the stress analysis code which had been used ten years earlier in the design of the piping system. We were fortunate in *that* instance!

From a broader perspective than life prediction, the real issue is structural integrity! We have seen too many system development programs in which insufficient attention was paid to structural integrity — until problems developed, sometimes not until after the system had been fielded for a number of years. We suspect that the reason for this is that some high-technology area often drives the development programs, and that the "old line" technologies of shock and vibration, and materials and mechanics are taken for granted. Collectively, we as a community, must make our cries heard! We must constantly carry the message that structural integrity of equipment, particularly under the environments of shock and vibration, can not be taken for granted. It must be an integral part of any development program from inception.

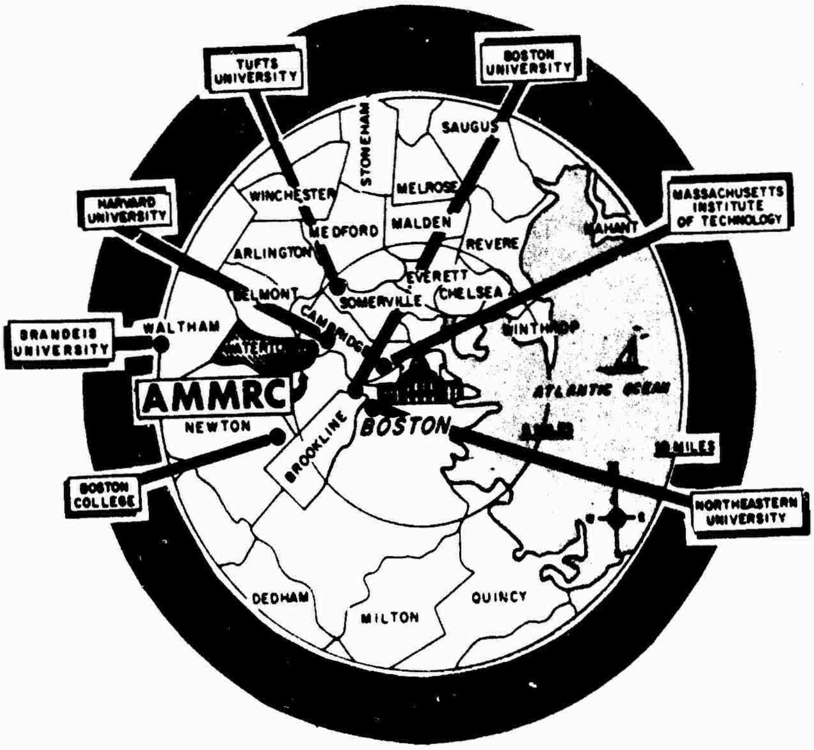


Figure 3 – AMMRC Location

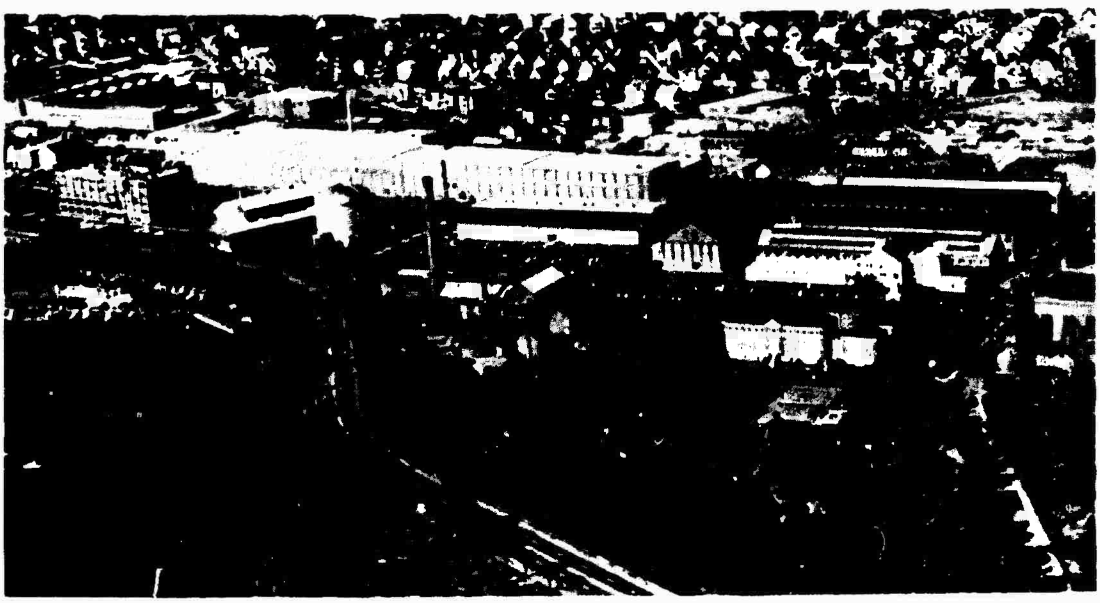

Figure 4 – Aerial View of AMMRC

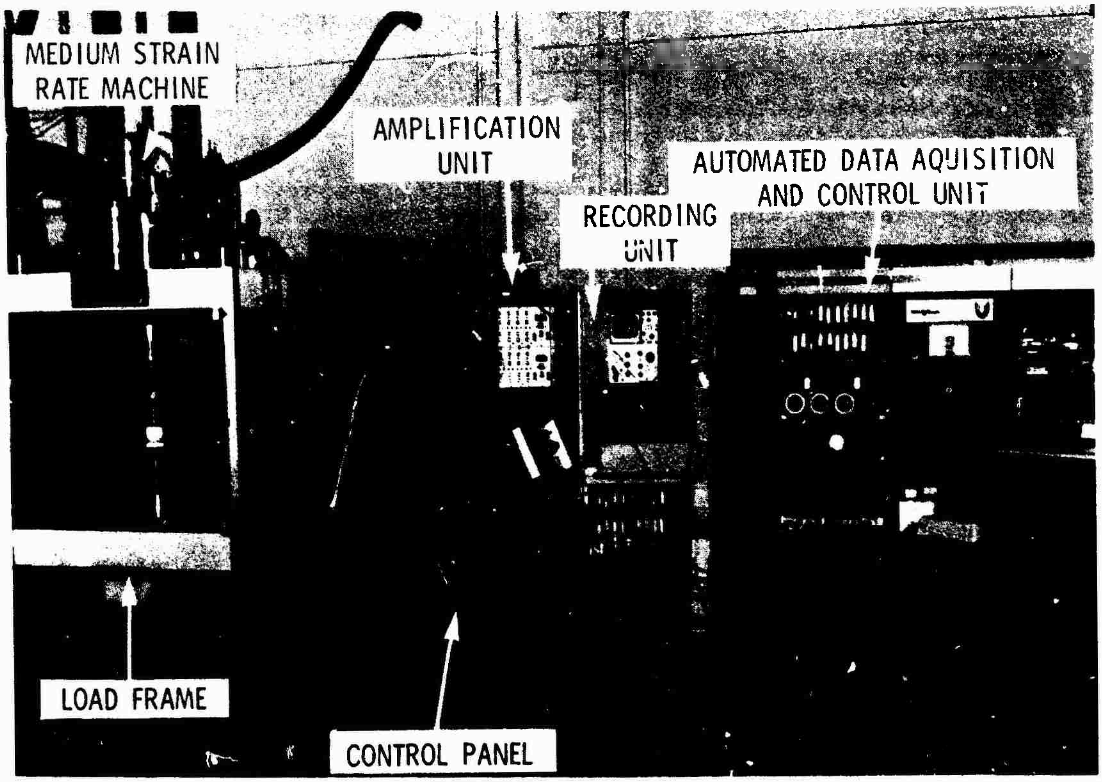


Figure 5 — Automated Materials Characterization Facility

Our goals in *mechanics of advanced materials* are really not too different. Here we are concerned with the behavior of ceramic materials and composite materials. One area of considerable importance relates to devising joint design methods. Of course, this is really a subset of our general concern for obtaining an understanding of how these materials fail.

Composite materials, for example, are finding their way into many Army systems, as are structural ceramics. However, they are not being used to their potential, primarily for two reasons, which are closely related. First, these materials are more difficult to characterize than are metals; hence our data base is woefully sparse. Second, we simply do not understand enough of how and why these complex materials fail, and are therefore not able to fully exploit them.

The obvious advantage of composite materials is that they offer high specific strength and stiffness, which means we should be able to develop lighter, and therefore higher performance or more efficient systems. Moreover, by judicious application of these materials it is possible to reduce life-cycle costs. A good example of where both weight and money can be saved appears to be in Army tent frames. The US Army Natick Research and Development Command (NARADCOM) and AMMRC are conducting a program with the objective of replacing aluminum frames with glass-polyester in one of the Army's tent systems. (NARADCOM is the only one of DARCOM's research and development commands named for its location, rather than commodity for which it is responsible. They have the responsibility for troop support systems.) It now looks like a composite frame will be lighter, less expensive, and even more durable than its aluminum counterpart.

Another apparently good application of composites is mobile assault bridging. In his keynote address, General Baer mentioned the demonstration project for metal matrix composites in vehicular-launched bridging components. That is a high risk, high-potential payoff venture that will not come to fruition for at least several years. However, the US Army Mobility Equipment Command (MERADCOM) and AMMRC are carrying out a collaborative effort to introduce organic matrix composites into bridging right now. The motivation is to save weight and thus save emplacement time.

All in all, composite materials and structural ceramics are here now, but we will certainly be seeing much more of them in the future. There is certainly much work needed in the shock and vibration arena to overcome the deficiencies in characterization data and failure prediction techniques.

Within *shock-impact mechanics/dynamics* we are principally concerned with how better to use available materials, and with defining the characteristics that better materials should have for use in applications such as fragmentation devices, high density penetrators, and advanced armor systems. While AMMRC does not have the responsibility for developing such systems, these are areas in which materials performance is almost indistinguishable from systems performance.

The most powerful tools available for analysis of the response of materials in these applications are the so-called "hydrocodes," which were originally developed by the

Atomic Energy Commission for the design of nuclear devices. AMMRC principally uses the HEMP (Hydrodynamic-Elastic-Magneto-Plastic) code, developed by Wilkins at Lawrence Livermore Laboratory (Reference 1). These computer codes, which we will be discussing in more detail later, now have provisions for including material strength in the analysis. So the term "hydrocode" is misleading, in that it is possible to do much more than simply hydrodynamic analysis.

In effect, these codes provide an excellent means of modeling shock events in solid materials, as far as predicting wave propagation events, stresses or pressures and strains is concerned. However, lacking are the *details* of how materials behave in these severe environments, particularly the details of dynamic fracture. These are a necessity, if we are to affect improvements in materials for these applications.

It is not that the codes are lackir ; rather it is the case that we do not understand dynamic fracture well enough to formulate criteria for the codes. Existing dynamic fracture criteria are, in general, too simplistic to be realistic, or too complex to be practical. This situation is not as dire in nuclear applications, since then the pressures that result are so great that considerations of the details of material strength are insignificant. In the penetration and fragmentation applications, pressures (and stresses) are an order of magnitude lower, at least at times of importance in these latter events. Hence, the material strength and dynamic fracture are overriding issues.

This dynamic environment is one in which there are few nonmilitary applications, so that the data base is also sparse here. As a result we feel it essential that we make a maj . commitment in this area.

General Ward expressed his concern with the potential for development of high-energy laser weapons by the Soviets. We share that concern; in fact the DOD materials and structures community have an ongoing, well-coordinated tri-service effort directed toward understanding the interactions of high-energy laser beams with structural materials. This is simply one more dimension of our interest in dynamic response.

Before turning to some of our current activities in shock-impact mechanics, and in particular the fracture aspects, we would like to cite one example in which a fairly simple dynamic failure model was used successfully. This example pertains to the use of a mechanical means of wave shaping to enhance fragmentation. In a conventional fragmentation device a cylinder, or other shell, is filled with high explosive. The explosive is detonated at the center of one end. The ensuing shock wave, traveling down the shell, results in a radial expansion of the shell. The fracture, or fragmentation process, is via shear cracks at about 45° from a radial direction, either singly or in combination with tensile cracks oriented radially, which originate near the outer surface of the shell.

In the conduct of a basic study involving computer modeling of exploding wire experiments, which were used to characterize the dynamic spall strength of aluminum, by discharging a capacitor across a wire in the center of the cylindrical test specimen, the thought occurred that perhaps this could be extended to enhance fragmentation. From this, the SLAPPER concept evolved (Figure 6). By using two cylinders with a space between them, the shock wave, on detonation of the high explosive, accelerates the inner cylinder (or SLAPPER) across the void, impacting the outer cylinder. By varying the radii and thicknesses of the cylinders, the rarefaction occurring after passage of the shock, caused by the impact, can be "tuned" to produce radial tensile stresses large enough to result in spall failure in the outer cylinder. This spallation, or tensile fracture in the circumferential direction, produces another mode of fracture in the fragmentation process.

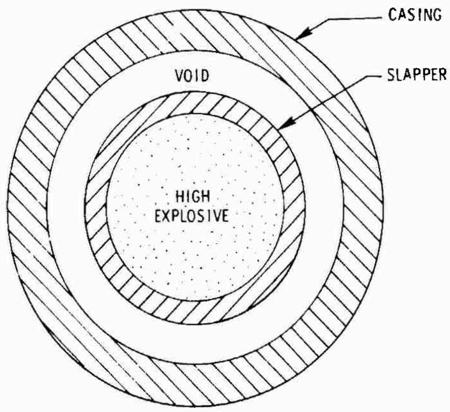


Figure 6 — The SLAPPER Fragmentation Concept

The method used to "tune" the configuration was based on the fracture criterion suggested by Butcher and Tuler of Sandia Laboratories. This model simply uses the integral under the stress-time curve as a failure criterion. The integral can be maximized by adjusting or "tuning" the configuration.

Table I shows the results of an experimental verification. A relatively ductile material, 1026, cold-rolled steel was compared with the high fragmentation steel, HF-1, we mentioned earlier. In the conventional configuration the HF-1 yields almost three times as many fragments as the 1026-CR. This is because the HF-1 is inherently brittle.

With the SLAPPER, a dramatic increase in the number of fragments results in both materials. But the main point is, that by using this approach, significantly more fragments can be obtained with the relatively ductile 1026-CR than with the brittle HF-1 using a conventional approach. This implies that the increased launch safety associated with the 1026 steel can successfully be married to the required fracture behavior at detonation time which is required for increased lethality.

TABLE I
Effect of Slapper on Fragment Count

| Fragments Larger Than 1/2 Grain | | |
|---|---|---|
| | Conventional | Slapper |
| HF-1 | 1200 | 2400 |
| 1026-CR | 430 | 2120 |

## PENETRATION MECHANICS/FRAGMENTATION MECHANICS

At this point in the discussion it is appropriate to provide more specific details as to the scope of AMMRC's program in the area of shock-wave propagation in solids under explosive loading or ballistic impact conditions. Our general concern is with what happens when a long-rod type of penetrator impacts an armor plate at velocities up to 5000 feet per second, or what happens when one fills a steel cylinder with high explosive and detonates the latter. Our specific concern at AMMRC is in the role played by material properties of the solids in these extreme loading environments. How does the dynamic yield strength influence the interaction of penetrator, armor or fragmentation device? Does the fracture toughness concept of static materials behavior have any meaning in this context?

Naturally, full-scale testing of such weaponry is expensive, so for purposes of screening candidate materials for these applications small-scale ballistic ranges and detonics facilities are employed. Orthogonal X-ray observations are made of both ballistic and explosive events. In addition to kinematic variables such as residual velocity and residual mass of fragments when penetration does take place, we are particularly interested in the patterns of the fracturing process and the timing of these events.

As indispensable as experimental observations are in this arena, the extreme pressures and short-time frames involved make it difficult to obtain specific measurements at the most interesting locations. Transducers attached to specimens tend to be destroyed too early; photographic or X-ray observations do not discriminate in a satisfactory manner between designs whose primary difference is in material selection. (Two notable exceptions to this comment are: (a) some recent ultrahigh energy X-ray observations of the penetration process at Los Alamos using PHERMEX and (b) some instrumented long-rod penetration experiments by Hauer at BRL.) On the other hand evidence abounds in post-mortem examinations to show that for many applications, material selection is of critical importance.

In this context computer simulations of these ordnance applications have proven extremely useful in interpreting experimental results. The specific contribution of such calculations is to provide reliable and quantitative details of the stress-and-strain fields which prevail in the interior of such hostile environments.

When such calculations are done carefully and then correlated with experimental observations, the result can be a significant enhancement of our understanding of the requirements for material properties in ordnance applications.

To describe the formulation behind such simulations as succinctly as possible, we might say that one begins with the conservation laws (mass, momentum, and energy), couples to these an equation of state which is realistic for the high pressures and short-time frames involved, casts the entire assembly into a finite difference formulation and then integrates step-by-step in time. Output is a detailed history in time of the physical variables of interest.

We shall not list the governing differential equations themselves since they vary somewhat in form depending upon whether a Lagrangian or an Eulerian formulation is used. They are readily available in References 1 and 2. We shall instead focus in this brief exposé on the details of the equation of state employed.

In the early development of such computer codes for the simulation of explosive events, attention was focused upon the hydrodynamic mode of behavior, appropriate for pressures on the order of bundreds of kilobars (i.e., an order of magnitude above strength of material considerations). For such applications a pressure-volume relationship (the Hugoniot curve in Figure 7) is determined in a series of plate-slap experiments which involve conditions of uniaxial strain. The rear surface of a target plate is monitored with a laser-interferometer technique and, from the fine detail of the observed motion, inferences can be drawn as to the material response under very high pressures and in microsecond-time frames. As more and more experimental evidence accumulated it became clear that there was a sub-structure associated with the stress-wave patterns generated under shock-loading conditions. For stress amplitudes on the order of the strength level of metals (tens of kilobars) an elastic-plastic behavior was observed to be superimposed on the Hugoniot curve, Figure 7. In this model of material behavior, the stress trajectory followed by a material point is

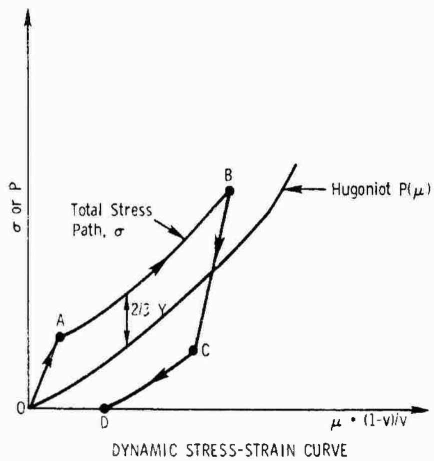


Figure 7 — Dynamic Stress-Strain Curve

as follows: Elastic response along OA (up to the Hugoniot-Elastic-Limit) plastic deformation from A to B (where the amplitude of B is determined by impact velocity, e.g.); then as relief waves propagate into the interior, relaxation of stress at the point in question is attained by initial elastic relief along the path BC, and finally, plastic relaxation along CD. Actual stress states in ordnance applications are more complex because of the location of free surfaces and multidimensional characteristics. However, the essential point to be made here is that for stress states in the tens of kilobars, strength of material considerations become significant and are treated as a superposition on the Hugoniot P-V curve.

In scenarios involving explosive pressures or very high impact velocities, stress levels on the order of several hundred kilobars are obtained initially. For such states it is found that the total stress path collapses onto the Hugoniot, and the strength of materials issues are not dominant. However, the primary point to be made in this paper is that such conditions form only the early and very short-lived first phase of the entire scenario, that in fact most of the time of interest is spent in a second stage with which much lower stress levels are associated. It is also true that very little plastic deformation is done during the first stage, but massive plastic deformation is accomplished during the second stage when strength of materials issues are paramount.

It should be stressed that at this point we are discussing plastic flow of materials and not, as yet, fracture.

As an example of the kind of results obtainable from computer simulations of shock-wave propagation in solids, Figure 8 shows some details of the detonation wave propagating down the axis of steel cylinder which contains a core of high explosive. Initiation of detonation occurred 4 microseconds earlier at the left-hand edge of the axis of symmetry. Figure 9 shows details of the propagation at 8 microseconds after detonation.

As shown in Figure 8, pressures on the order of 200 kilobars are generated in the explosive (the Chapman-Joguet pressure characteristic of the explosive) and these are transmitted onto the steel casing. As is also clear from Figure 8, relief waves propagate into the pressurized zones very quickly. Figure 9 shows details of the initial outward expansion of the steel casing, further propagation of the detonation wave (peak pressures have not quite reached the right-hand side of the cylinder), and the effect of the rarefaction waves. Of special interest is the fact that the outwardly moving left side of the steel casing is subjected to very low values of internal pressure from the explosive gas products, and in fact the internal stress states in this region of the steel is actually in a tension field of modest amplitude (10 kbar tension is indicated by the heavier contour lines).

An indicator of the credibility of these internal details of stress and deformation is the fact that the velocities predicted by the calculations for the metal parts are within five percent of the experimentally observed velocities.

Another interesting illustration of the details provided by computer simulation and of interest to material property evaluation is shown in Figures 10, 11, and 12. The problem simulated is that of a steel cylinder impacting a steel target

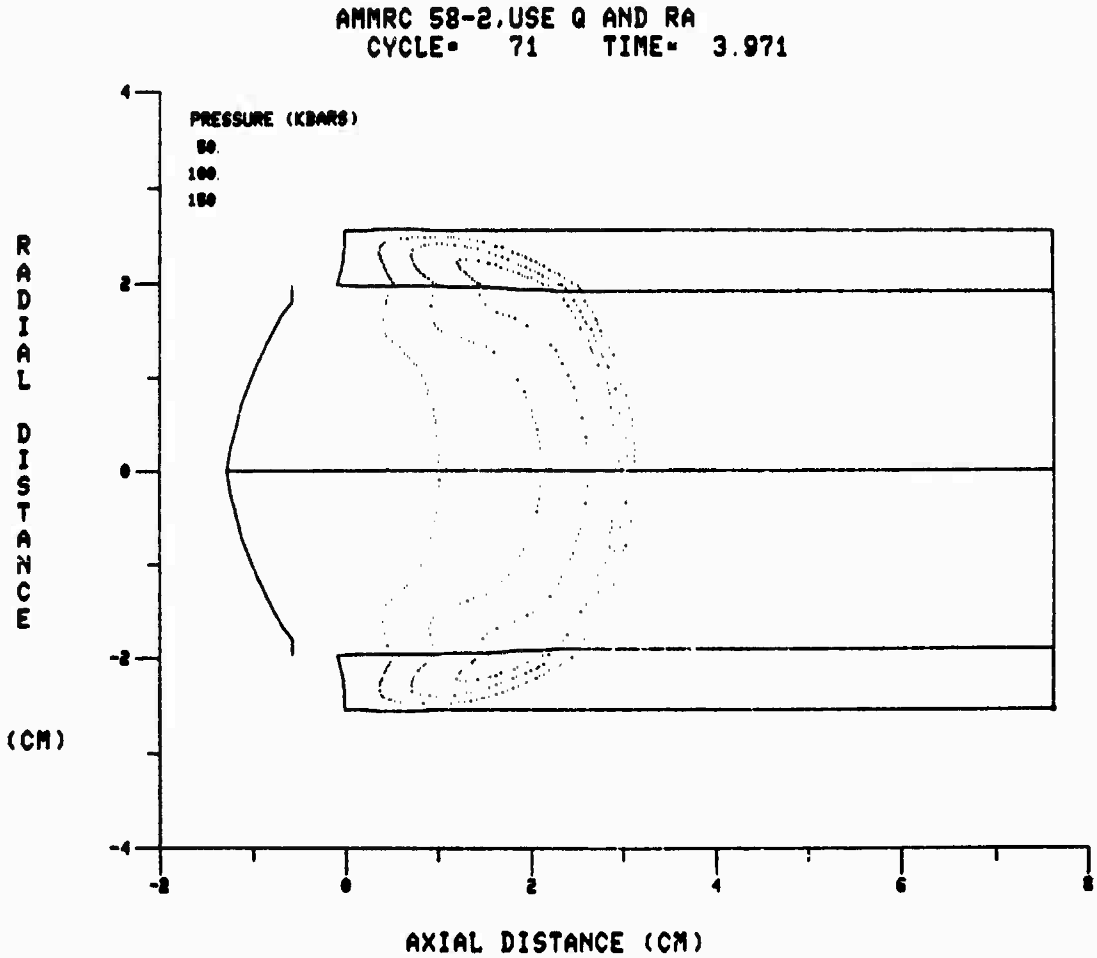


Figure 8 — Computer Simulation of Fragmenting Cylinder, 4 Microseconds after Detonation

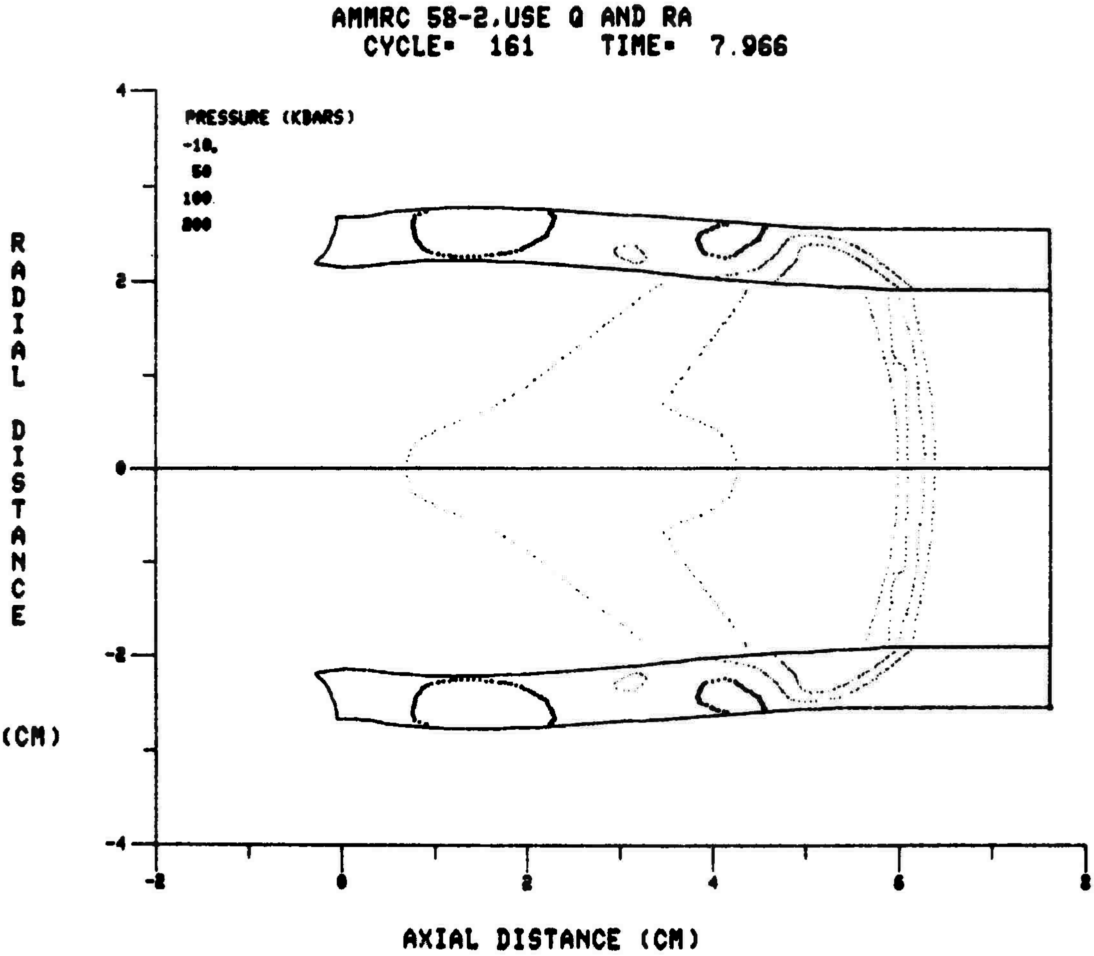


Figure 9 — Computer Simulation of Fragmenting Cylinder, 8 Microseconds after Detonation

at 2500 feet per second. Contour plots of pressure are shown at 1, 2, and 3 μsec after impact. Details of a rarefaction wave can be seen entering both target and projectile from the lateral surfaces of the projectile long before the initial wave reaches the projectile rear surface. These rarefaction waves can produce tensile stress states in both projectile and target at very early times, as shown by the darker contour lines in Figures 11 and 12.

Whether these tensile stresses produce fracture depends largely upon the dynamic tensile strength of the material. Correlation with experimental observations reveals that lower strength steels (those with a hardness of RC 20, e.g.) tend to have low dynamic tensile strengths and are vulnerable to spall mode of fracture, whereas high-strength steels (RC 50 say) are far less vulnerable to spall in the simulation above. See Reference 3 for detailed comparison with experiments.

If the issue of ballistic penetration depended upon tensile mode of failure, one might expect then that the higher strength steel would offer greater ballistic protection. However, because a new mode of fracture intervenes – viz. adiabatic shear – it turns out that the higher strength steel can be penetrated with a lower velocity for the example shown.

In general our level of understanding of the dynamic tensile mode of fracture is far superior to our understanding of the shear mode of failure. This is unfortunate since the latter is by far the more common mode both in armor/penetrator interaction and in fragmentation munitions as well.

Observations of shear bands and the recognition of their importance to ordnance applications are as old as WWII when Holloman and Zener first proposed that a possible explanation of their occurrence was a competition between work-hardening and thermal-softening. Their idea was that as plastic work is done the initial result is an increase in flow stress (the material work-hardens). However most, if not all, of this work is converted to heat and since there is insufficient time for thermal flow to occur, as plastic deformation continues the result is a thermal-softening effect which competes with work-hardening effects. If thermal softening wins out locally, the result is a concentration of further deformation in local regions heading eventually to the observed extremely localized failure patterns.

Until recently there has been no attempt to quantify such a model largely because of a lack of a suitable analytical model to provide sufficient details. With the development of

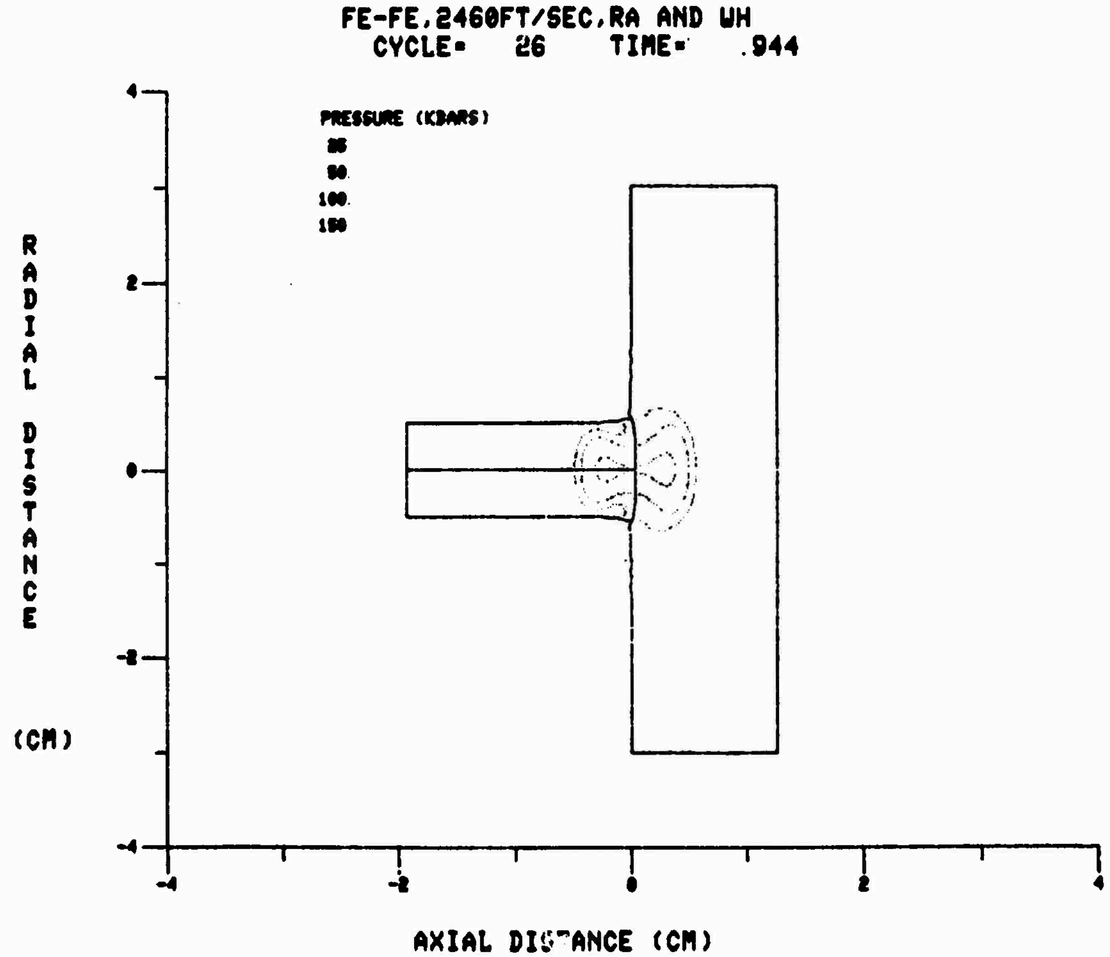


Figure 10 — Computer Simulation of a Cylinder Interacting with a Target 1 Microsecond after Impact

computer codes such as HEMP, however, interest has been revived in modeling the adiabatic shear fracture process.

One such model is outlined below. The central idea is to make the flow stress of the material depend upon both plastic strain $\gamma^p$ and temperature T as in the expression

$$Y = Y_0 (1 + \beta\gamma^p)^n \exp(- aT/(Tm - T)).$$

The effective plastic strain $\gamma^p$ can be computed at each finite difference mesh point for each instant of time. Furthermore, the plastic work effected by a stress state $\sigma_{ij}$ acting through a strain $d\epsilon_{ij}^p$ is

$$\Delta W = S_{ij} \cdot d\epsilon_{ij}^p$$

where $S_{ij}$ is the deviatoric component of total stress. In turn the associated temperature rise is given by

$$\Delta T = k\Delta W/\rho C_v$$

where $\rho$ is the material density and $C_v$ the specific heat.

The first parentheses in the expression for the flow stress Y represents the work hardening contribution, the second that of thermal softening.

There are two problems with this model in practice: (1) It relies on the knowledge of how flow stress depends explicitly on temperature (such data is not readily available and is expensive to generate), (2) Available data for both work-hardening and thermal-softening are generally obtained under isothermal conditions, not adiabatic.

An improvement in this model has recently been suggested in the Olson model which derives an analytical expression for stress-strain behavior under adiabatic conditions. It results in the expression

$$Y = Y_0 (1 + \alpha\epsilon^p) \exp(- \beta\epsilon^p).$$

This expression is very similar in makeup to the prior model but has several advantages. The first is that it is expressed solely in terms of the plastic strain level $\epsilon^p$, thermal-softening effects being embedded in the exponential term. This model exhibits a characteristic instability strain, i.e. a value of strain for which $dY/d\epsilon^p = 0$ and the flow curve reaches a maximum and begins to drop in value as deformation proceeds. This form of the Olson model estimates that plastic instability begins at a strain of

$$\epsilon_i = (\alpha - \beta)/\alpha\beta.$$

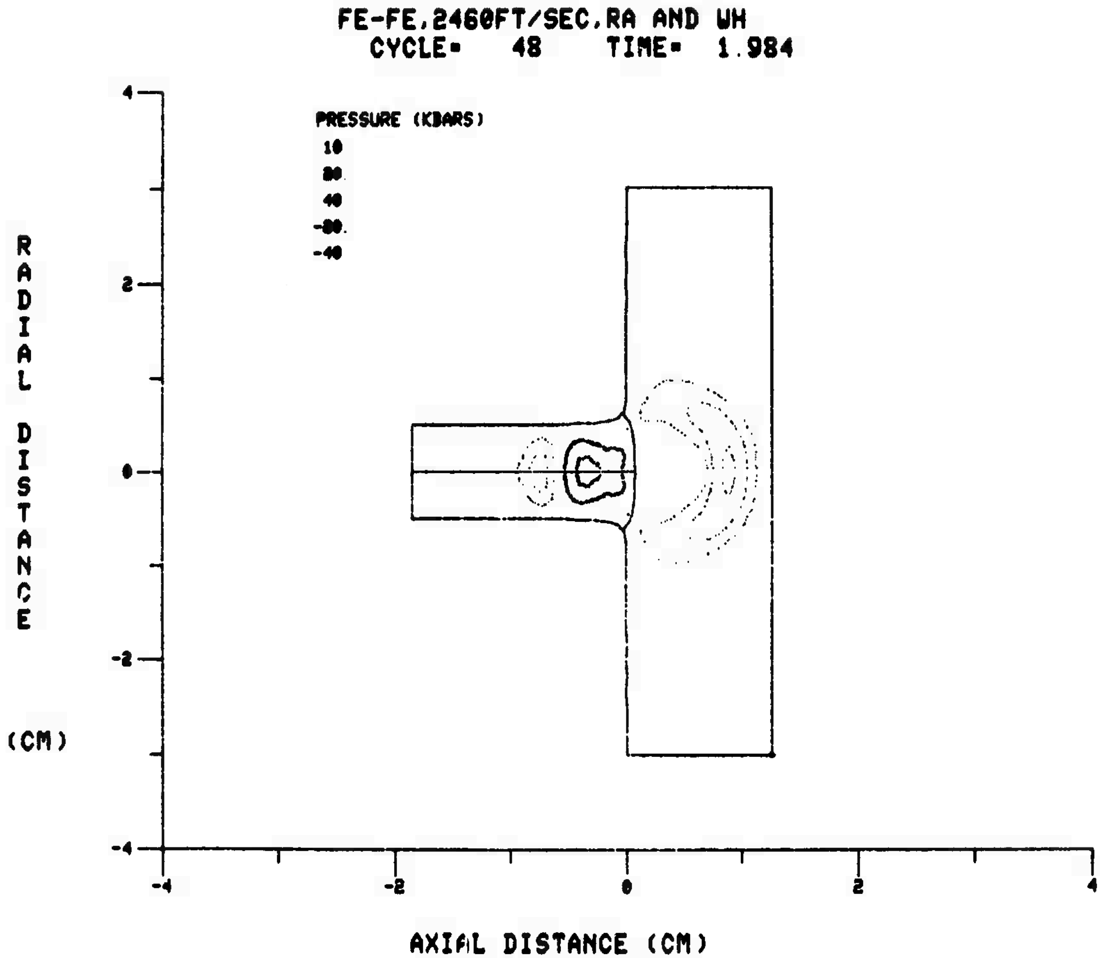


Figure 11 — Computer Simulation of a Cylinder Interacting with a Target 2 Microsecond after Impact

Experimental evidence that such behavior does in fact exist can be found in results of dynamic torsion tests done under sufficiently high nominal strain rates that adiabatic conditions might be expected to persist. In particular, results of Lindholm on a high-strength steel (H4-TUFF) and results of Culver on mild steel (1018) both exhibit the behavior cited and provide estimates for the parameters of the Olson model.

As a test of the suitability of such models for simulating the behavior of steels under ballistic impact conditions, computer simulations were run in which the same projectile was impacted against a "hard" and a "soft" steel. The designation hard and soft refer to values of flow stress used in the calculations as determined by the Lindholm and Culver experimental data fitted to the Olson model.

The gross features of the experimental result were well simulated. For an impact velocity below the penetration limit, the soft target had a large crater at the impact face and a large bulge at the rear. The hard target had a small crater at the impact site and no perceptible bulge at the rear.

Of far more significance is the fact that the softer target showed no tendency toward adiabatic shear localization — material near the impact site was moved gradually out of the region by massive plastic flow — and in fact all the target material continued to work-harden.

By way of contrast, on the hard target a few zones immediately in front of and near the outer perimeter of the projectile had begun to thermally soften, to decrease in strength after a plastic instability had begun. However for the impact conditions studied to date, no dramatic localization or propagation of this behavior was observed in the calculations.

While these results are somewhat tentative, particularly since the data used in the calculations do not correspond precisely to those appropriate for materials for which we have ballistic experimental data, they are nonetheless encouraging and appear to produce far better simulations than do the same calculations with simpler material property descriptions.

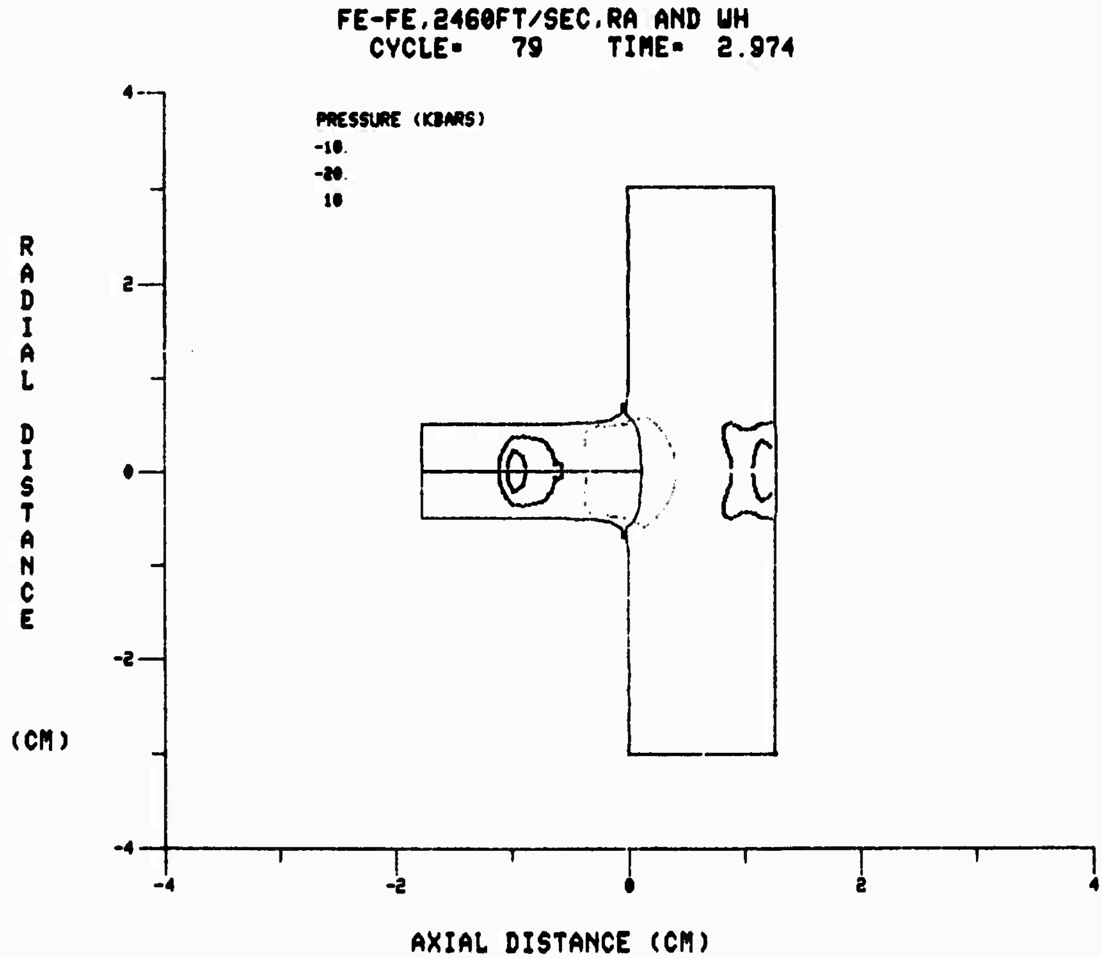


Figure 12 — Computer Simulation of a Cylinder Interacting with a Target 3 Microsecond after Impact

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DYNAMIC TESTING — HOW FAR WE'VE COME — HOW MUCH FURTHER TO GO

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## INTRODUCTION

It is a very simple to accept an invitation to address a plenary session such as this one, particularly on the topic of Dynamic Testing with which one has been closely associated for a number of years. It is even easy to write an abstract for the program which has a nice ring to it. Then comes a moment of truth when one realizes:

1. How broad and multi-faceted the topic of "Dynamic Testing" really is;

2. How humbly one should approach the topic;

3. It's too late to back out now; and

4. One best be somewhat selective in the topics to be addressed.

Dynamic test can be categorized by a two by three matrix of field and laboratory viz-a-viz vibration, acoustics and shock. All six types of dynamic tests are the subject of one or more papers at this 50th Symposium. Even if one restricts consideration to laboratory vibration tests, there is still a plethora of tests with differing purposes and, therefore, differing requirements and techniques.

As this is the 50th Symposium, spanning approximately 30 years of very rapid technology development, it is perhaps useful to begin this address with a review of the evolution of dynamic and, in particular, laboratory vibration testing. This will be followed by introduction of test purpose and test condition matrices which may help in understanding why certain tests are or should be performed in certain ways. This will then lead to a discussion, both philosophic and hardware-directed, of a few of the needed developments in this field. One of these developments, namely the very topical area of vibration screens, will be discussed in some detail.

The reader may now have sensed that the paper will be biased towards the vibration testing of avionics. However, the writer believes that with very little change of emphasis, the same techniques, problems, etc., apply equally well to shock testing and acoustic testing of all types of equipment in all types of vehicles as well as to testing the vehicles themselves.

## EVOLUTION OF VIBRATION TESTING

There are close to a dozen vital ingredients in the performance of a vibration test. These are listed in the left hand column of Table I. It is instructive to follow the development of each of these ingredients over the last thirty years. However, it is even more instructive to follow the interplay of these developments as they complemented each other in leading to todays very sophisticated systems. It should be pointed out that with only one or two possible exceptions, every type of hardware listed in Table I is still in use. No exact date can be given for each development, since most evolved from a single specialized facility to general usage over a period of several years. However, key dates are the late Fifties, during which random vibration became viable and acceptable, followed by the early Seventies when the advent of digital control caused somewhat of a revolution.

Starting at the left hand side of Table I, which is the era of propeller driven aircraft, low frequency "somewhat sinusoidal" vibration on mechanical shakers with simple data acquisition was adequate to test the much simpler equipment of the day, especially as it was almost invariably mounted on vibration isolators. As acoustic and vibration environments encountered in jet aircraft, missiles and rockets became quite severe and more complicated, and as the equipment became more complex and could no longer retreat behind the false security of vibration isolation, even the swept sinusoidal vibration to higher frequencies made possible by electrodynamic shakers was found wanting.

Fortunately, concurrent with Morrow and Muchmore's basic paper on the need to perform random vibration, the mathematical theory was available from the field of communications. Also, the crystal accelerometers, the magnetic tape recorders for repeated playback, the audio spectral analyzers and the electronic power amplifiers all became available when needed. (Or did the need spark their development?) Furthermore, we learned that controlling a test with a velocity meter at the end of the armature opposite the test object is not very realistic or safe. Then it became clear that a single arbitrarily chosen location to control the vibration was not much better and the more elaborate control strategies became fairly standard. Most importantly, however, we learned that a human servo equalizing a swept analyzer was

TABLE I
Evolution of Vibration Testing

| | |
|---|---|
| MOTION GENERATOR | MECHANICAL ECCENTRIC, MECHANICAL INERTIAL, ELECTRO-DYNAMIC → (HYDRAULIC ACTIVATOR) → |
| POWER SOURCE | ELECTRIC MOTOR → M/G SET. → ELECTRONIC POWER AMPLIFIER → |
| CONTROL SYSTEM | NONE, NONE, TECHNICIAN → ANALOG SERVO → DIGITAL SERVO → |
| CONTROL TRANSDUCER | VELOCITY METER → CRYSTAL ACCELERATORS → |
| CONTROL STRATEGY | SINGLE PT → AVERAGE, PEAK SEL. → RESPONSE CONTROL → |
| DATA ACQUISITION | OSCILLOGRAPH OSCILLOSCOPE, METER → MAGNETIC TAPE → |
| SPECTRAL CAPABILITY | SWEPT OR FIXED SINE → RANDOM → COMPLEX, UNLIMITED |
| UPPER FREQUENCY | ≈ 60 Hz → ≈ 500 Hz → ≈ 2000 Hz → |
| DATA ANALYSIS | EYEBALL → SWEPT FILTER → COMB FILTER → FFT → |

SEPTEMBER 1979

just inadequate since our customers did not appreciate buying us one test item to destroy during equalization and another to use for tests. So the analog servo control of a comb filter equalizer/analyzer became standard until superseded by the digital control systems. These digital systems not only perform random but also sinusoidal, shock and, in fact, almost any time-history of interest. In addition, they have the inherent capabilities to analyze, process and store the results of the test with almost unbelievable accuracy, repeatability and efficiency.

One development not shown in Table I but which profoundly influenced the performance of shock and vibration tests, was the introduction in 1959 of the "slip-plate" or "slip-table." This not only permitted testing of the test item in its normal orientation for all directions of excitation but enabled three axes of test to be accomplished with one fixture.

## TEST PURPOSE MATRIX

It is all very well to have the capability to perform very sophisticated tests to exacting standards. However, if the purpose of the test is not clearly understood and remembered, a cost-ineffective and maybe even counter-productive test can easily result. It is suggested that the purpose of any test falls into one of three categories. First, the purpose may be only to gain understanding of the structural characteristics of the test item, e.g, a modal test. Second, the purpose may be to determine the adequacy of the design, This may be separated into short term and long term adequacies, which translate into functional performance and fatigue life respectively. Third, the test purpose may be part of the quality assurance program. Again this purpose may be subdivided into the two aspects of reliability and quality. The former attempts to measure the long term failure rate given that the majority of quality flaws have been removed by tests having the latter purpose. Table II is a matrix of these test purposes versus the type of test. The type of test is listed in chronological order, although not all programs will include all tests. With a few exceptions, it is clear which purposes of test are associated with each type of test. However, the recently increasing emphasis on reliability growth and reliability demonstration tests with realistic vibration environments can easily lead to tests with too many and counteracting purposes, as indicated by the several question marks in Table II. It is to be hoped that clear understandings of both the commonalities among and the distinctions between the purposes of design, reliability and quality tests can be achieved in the near future. Experience indicates that the present confusion is particularly acute with respect to Production Sampling Tests.

## TEST CONDITION MATRIX

Once the purpose of the test is established, the test conditions may be selected, in principle at least, in a straight forward manner. In Table III, the same types of tests discussed in the previous section are listed against the four major test parameters which, in a broad sense, determine the test conditions. These parameters are: the assembly level of the test item; the degree to which it is necessary to simulate the operational environment; the use of time-acceleration in the test; and finally, the degree to which the frequency spectrum of the environment need be simulated. It will be seen that production acceptance tests or screens differ from all other tests. These differences are discussed in detail in a later section.

TABLE II
Test Purpose Matrix

| TEST I.D. | STRUCTURAL CHARACTERISTICS | DESIGN ADEQUACY: FUNCTIONAL PERFORMANCE | DESIGN ADEQUACY: FATIQUE LIFE | PRODUCT ASSURANCE: RELIABILITY | PRODUCT ASSURANCE: QUALITY |
|---|---|---|---|---|---|
| DESIGN DEVELOPMENT | √ | √ | — | (RELIABILITY GROWTH) | — |
| FLIGHT WORTHINESS | — | √ | — | — | √ |
| DESIGN VERIFICATION | √ | √ | √ | — | — |
| DESIGN QUALIFICATION | — | √ | √ | (RELIABILITY DEMO) | — |
| PRE-PRODUCTION (FIRST-ARTICLE) | — | √ | (?) | (?) | √ |
| PRODUCTION SAMPLING | — | (?) | (?) | √ | √ |
| PRODUCTION ACCEPTANCE (SCREENING) | — | — | — | (?) | √ |

TABLE III
Test Condition Matrix

| TEST I.D. | PREFERRED ASSEMBLY LEVEL | SIMULATION | ACCELERATION | SPECTRUM SIMULATION |
|---|---|---|---|---|
| DESIGN DEVELOPMENT | COMPONENT | LOOSE | NOT USUALLY | LOOSE |
| FLIGHT WORTHINESS | COMPONENT - MAY BE SYSTEM | PROBABLY NOT | NO | LOOSE |
| DESIGN VERIFICATION | SYSTEM | YES | YES(?) | YES |
| DESIGN QUALIFICATION | SYSTEM | YES | YES | YES |
| PRE-PRODUCTION (FIRST-ARTICLE) | SYSTEM | YES | MAYBE | YES |
| PRODUCTION SAMPLING | SYSTEM OR COMPONENT | YES | NO | YES |
| PRODUCTION ACCEPTANCE SCREENING | COMPONENT | NO | YES, IN ATYPICAL SENSE | NO |

SEPTEMBER 1979

## FUTURE DEVELOPMENT

Having taken a brief view over our shoulder to see from whence we came, it is appropriate to look ahead and try to discern where we should be headed. In other words, what are the most pressing problems to which we should direct our efforts. The following paragraphs discuss three hardware/software developments needed to reduce the costs of testing. These paragraphs are followed by short discussions of four shortcomings of our technology.

In some ways, the control of a vibration test is akin to the flight of an airplane. First comes take-off when the controller is very busy measuring the system transfer function and adjusting for non-linearities, etc., as the test level is increased to its maximum. Once at level, i. e., cruise altitude, it takes little effort to make minor adjustments to the drive signal from time to time. When the test is stopped, for whatever reason, the controller is again busy ensuring a safe shutdown of power. Thus the full capability of digital controllers is used only for a small percentage of most vibration tests. It would appear conceptually feasible to make better use of the controllers by time-sharing one controller to tend several shakers, particularly for long duration tests such as reliability development/demonstration or endurance tests. Of course, only one "take-off" or "landing" can be attempted at any instant.

In somewhat similar vein, digital control systems have the inherent capability to improve the performance of response control tests. At present, digital controllers perform swept-sine response control tests very adeptly. However, for random vibration an iterative procedure is still necessary, as it is with analog systems. Again, it is only a SMOP [Small Matter of Programming] to enable the controller to calculate the frequency location and depth of notches required in the input spectrum and to update these calculations from time to time as the test proceeds. Of course, slower "take-offs" will be required while these notches are calculated initially.

The third and last hardware development to be mentioned can be simply stated. If broadband vibration is to be employed economically as a manufacturing screen on a large scale, it is imperative that low cost alternatives to the present sophisticated "state-of-the-art" systems be developed. It must be emphasized that this statement encompasses the whole process, not just the cost of the vibration facility and the labor cost of the personnel with appropriate skill levels to run and maintain the facility.

Turning now to less specific even though perhaps more profound needs, the time for humility which was mentioned earlier has arrived. Certainly, it is possible to perform complicated tests safely, accurately and reasonably economically. But how well do the results of the test reflect what would have happened in the aircraft or missile or whatever use is intended. Would that failure on the shaker happen in the field? Would it happen again on the shaker? Why are so many failures in the field charged to dynamic environments, rightly or wrongly, even though the equipment passed qualification tests which were based on envelopes of field data? The answers to these questions, if known, would indicate that there is considerable room to improve the state of our particular art and art is used advisedly. Some reflection indicates four areas where improvement is most needed.

First, it is suggested that a broad understanding of the limitations of our knowledge be sought. It is all too easy to yield to pressure to calculate some kind of a number and run some kind of test even though we do not know quite what we are doing or why we are doing it. Then we are willing to draw profound conclusions from the results that a real understanding of the processes involved would rapidly disprove.

Secondly, some progress must be made in the area of undue conservatism and over-specification if we are to aid in the design of functionally adequate, reliable, cost-effective equipment which is not too heavy, too large, too costly to manufacture and too complicated to maintain. Too often, the conservatism of enveloping is readily acknowledged and countered with a plea of lack of data. Of course, more data can never reduce an envelope. An alternative which entails some calculable risk must be sought and embraced.

One facet of the problem of overspecification, and conservatism is the effect of impedance match and/or mismatch. A way must be found to avoid specifying maximum levels as inputs at "fixed-base" natural frequencies when numerous studies have shown that these are just the frequencies where minimum levels occur. Maybe only the overall level is controlled after equalization with a dummy mass. Maybe flexible fixtures must replace the massive super-stiff structures presently used. If the "required" level on the 10 pound test item cannot be obtained with a 40,000 pound shaker, there may be valuable information in that fact.

The three areas for improvement just cited are "old friends" which have faced the audiences of this Symposium for years. However, in the last three to five years, a new challenge has been growing and some progress in its solution can wait no longer. This challenge is for the testing community to effectively adapt and innovate test requirements, test methods and test facilities to accomodate the overall needs for environmental qualification; reliability development and/or demonstration; Mission Profile Testing (CERT); and manufacturing screening. This whole process is presently receiving a great deal of emphasis, not always by those experienced in the discipline. It would be very unfortunate for the community if the end result of a great deal of effort and expenditure of resources was little or no improvement in the field.

## SCREENING VIBRATION REQUIREMENTS

The last few paragraphs have touched on several problem areas, i.e. opportunities, whose mitigation would constitute a significant contribution to vibration testing. To close this address, it may be appropriate to discuss what the writer considers to be the most topical "opportunity" of the day, namely, definition of the requirements for vibration screens.

A vibration screen is a manufacturing process which, along with other screens such as thermal cycling, is applied to each system prior to delivery from the manufacturing plant. Note that this phraseology does not mean the screen must be applied on a system basis, merely that the screen is applied to those parts of the system which can be practically and usefully screened at some level of assembly. Note also that a screen is a process — not a test. Failures generated by screens are good which is opposite to the customary view of a failure during a test.

The sole purpose of the screen is to weed out flaws or defects in the equipment prior to shipment so that these flaws do not become failures in the field. This can be illustrated by Figure 1 which portrays the flaws remaining in a piece of equipment versus time. At any time, the initial flaws less the flaws remaining are the cumulative failures. The curves are exponential, derived from the basic premise that the rate of flaw precipitation, i.e., failure rate, is proportional to the number of flaws remaining in the equipment. The curves have been substantiated by analysis of both field and factory failure data.

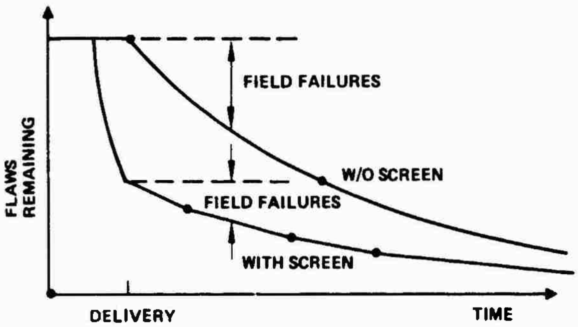

Figure 1 — Flaws remaining versus time

It should be noted that if the screen removes a significant proportion of the initial flaws, the total number of failures which must be repaired in the field is also significantly reduced. However, as field time becomes large, and remembering that the curves shown represent an average over all S/N's of that equipment, the two curves will be almost indistinguishable. In other words, the longterm reliability will not be noticeably improved, particularly if the repair and maintenance processes should create new flaws.

Before returning to the vibration screens, one more concept must be introduced. This is the idea that not all flaws are precipitable by all environments. This is shown in Figure 2 which shows conceptually the degree of coincidence of precipitable flaws in the production environment, $U_P$ and the field environment, $U_F$.

If the above models are accepted, it now becomes possible to make some statements about screening conditions in general, and vibration in particular.

First, it is not necessary and may well be undesirable that the screen simulate the field environment. Figure 2 shows that is necessary to simulate the effects of the field environment so that $U_P$ and $U_F$ are as coincident as possible. However Figure 1 shows that simulating the field environment, i.e., 1 hour of screen equals 1 hour in the field, is inadequate. To be reasonably efficient and economic, the screen must be an environment which precipitates the same population of flaws but at a much faster rate, i.e., an accelerated test, in a special sense.

Even though the field environment is not to be simulated, Figure 2 is most likely satisfied if some of the field characteristics are reproduced. Experience indicates and there is a consensus that broadband vibration excitation is necessary for a screen to be efficient. Note that it was stated as broadband, not necessarily random. The key point seems to be that all modes, or at least, most important modes are excited simultaneously.

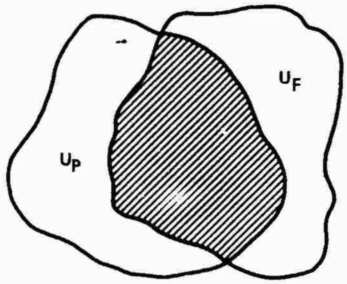

Figure 2 — Degree of coincidence at precipitable flaw populations

One must now consider the spectrum, which is defined by three parameters: 1) the area under the curve, i.e., rms acceleration, 2) the overall bandwidth or frequency range and 3) the actual shape of the spectrum, i.e., is it continuous and how much variation from maximum to minimum.

It is the writer's opinion that the efficiency of the screen will be very tolerant of variations in the spectrum providing:

1. The spectrum is reasonably continuous, with no wide holes, over a frequency range embracing a number of modes of the item being screened.
2. The overall level is appropriate.
3. The spectrum shape is essentially unspecified and uncontrolled.

The above three statements are not likely to make a vibration test engineer (or specification writer) very comfortable. After all, he has spent his career trying to meet tight tolerances on spectral density requirements and/or attempting to build fixtures with identical inputs at a number of attachment points, as required by the specification. Now somebody wants to discard all that and just control the overall level. This will allow the test item to load down the fixture! Of course, it may also avoid overstressing the equipment and using up its fatigue life. And for every valley, a peak must appear at some other frequency if the area is to be preserved. How do we know that peak won't cause a failure? We don't know for sure. But peaks only occur where it is easy to drive the system, which is not at damaging frequencies.

The only other requirements on the conditions are that:

1. The flaws are precipitated rapidly.

2. No inappropriate design failures are induced. Appropriate design failures would be:

   a. Design failures only discernible from testing a large population

   b. Previously detected design failures inadequately corrected

c. Design "improvement" inadequately verified, value engineering changes.

3. An adequate yield of the proper type of flaws is obtained. This can be measured preliminarily before delivery witb final information only obtained from field failure date.

4. No flaws are induced.

Note that the screen conditions are independent of the field environment and the design specification. However, it does seem reasonable that there be some loose correlation. In otber words, the more severe the field environment, the more rugged will be the design which probably means the more severe the screen needed to precipitate the flaws. Conversely, of course, this means that there is no universal screen. It further means that the adequacy of the screen can only be judged by the end results, which unfortunately, is entirely too late.

If tbe above remarks have any merit, it is clear that developing appropriate vibration screens will be a very difficult, ongoing task, probably different for every new project. Some success can only be achieved with only a very flexible approach to their specification and adjustment through analysis of failure types and quantities.