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Proceedings

5th JOINT MILITARY—INDUSTRY GUIDED MISSILE RELIABILITY

Symposium

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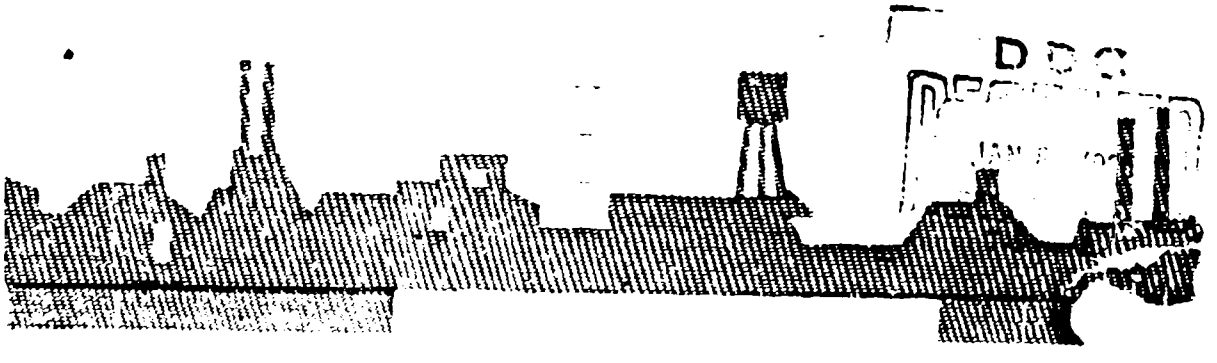
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Volume 1



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FOREWORD

The Sixth Joint Military - Industry Guided Missile Reliability Symposium, sponsored by the Department of Defense, was conducted by the Department of Army under the supervision of the U. S. Army Ordnance Missile Command.

Due to the length of the material presented, it was necessary to publish the technical papers presented in three volumes. The first two volumes contain the unclassified papers and Volume 3 the classified ones.

To prevent delays in publishing, discussions following each paper are omitted from these proceedings.

Additional copies of these proceedings can be obtained by request directed to Commanding General, Army Rocket and Guided Missile Agency, Redstone Arsenal, Alabama, ATTN: Technical Library.

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WELCOMING ADDRESS

By: Major General Sam C. Russell
Commanding General, U. S. Army Air Defense Center
Fort Bliss, Texas

It is a pleasure to welcome you to the Army Air Defense Center. This area is a particularly appropriate location for this symposium because of our extensive activities in the missile field. Including the initial Ajax troop firing in 1953, over 4,700 missiles have been fired under Fort Bliss control by using troops. In addition, there have been some 8,500 research and development firings conducted by our good friends and neighbors at White Sands.

During this period, the annual percentage of successful Ajax rounds in troop firings has increased from 40% to 84%, and Hercules, after a rather unfortunate start, averaged 75% for calendar year 1959.

While certainly some of this improvement in the percentage of successful missiles can be attributed to improved training and improved procedures, a great deal must be credited to the improvement in the reliability of the systems and their components. For example, there have been almost 400 modifications to the Ajax system, resulting largely from experience gained in live firings.

There has been some discussion of eliminating the annual service practice of surface-to-air missile units, primarily because of the cost involved. In my opinion, this would be the falsest kind of economy. Without going into the training, morale, troop confidence, and public relations benefits gained from live firings, and they are many, I believe the firings have justified themselves from the product improvement aspect alone.

Gentlemen, I wish you a most successful symposium. The complete resources of this center are available to support this very worthwhile get-together.

KEYNOTE ADDRESS

BY: Dr. E. G. Witting
Deputy Director of Research and Development
Department of the Army

General Russell, Mr. DeWitt, members of the Symposium, it is indeed a pleasure and honor for me to deliver this keynote address at the 6th Joint Military Industry Guided Missile Reliability Symposium. As you know from your programs, I am filling the shoes of Mr. Morse, our Director of Research and Development for Department of the Army. Unfortunately, he is a casualty of the budget battle in Congress. Mr. Morse has asked me to express his regret in being unable to be here with you. You see we, too, in the Army have our reliability problems in getting our speakers to fulfill their commitments.

Before getting into my subject, I want to express appreciation for the Department of Defense to General Russell and members of the Fort Bliss Center for permission to use these facilities, and to the members of the Army Ordnance Missile Command who have contributed so much to arranging the symposium. I know a lot of work has gone into the preparation for this symposium, and I feel certain you will all reap benefits from their labors.

Reliability is a word which, in the vocabulary of many, has become common place and trite. Too often it has received much lip-service and little action. This kind of thinking must be radically changed. I can assure you that the Department of Defense is aware of this and is doing its utmost to insure that the solution of reliability problems is increasingly stressed in the services.

In talking here, I do not expect to tell you how to do your job. I may not tell you many things you do not already know. I hope, however, I can impart to you the conviction that your problems can and must be solved. The cost of reliability failures has already conservatively been estimated in the billions of dollars. These costs are rising each day.

There may be some of you in the audience who, along with myself, can remember the good old days when automobiles were considered rather unreliable instruments of locomotion. I can remember taking short trips over the muddy roads. In those days we used to carry extra gasoline, pick axe, shovels, and certainly no one would be

without extra rope to help pull stalled vehicles out of muddy holes. The expression, "get out and get under" often applied to motorists jokingly may have been coined frivolously but not without basis. Reliability of automobiles increased with experience.

Up-dating ourselves a few years, let's look at the beginnings of air travel. In the early days of airplanes, each pilot who survived an air crash told what he could remember concerning the cause of the accident. This was the only method available for determining what went wrong. When the Germans were building V-2's during the Second World War, they, too, were going through the same experiences of learning reliability from the accidents that took place. Today in missiles we have come a long way from the beginnings just as we have with the aircraft of yesteryear.

As an illustration, I would like to tell you of my first commercial airplane trip. It was in a bi-plane. At each stop the pilot and copilot got out of the aircraft and pulled and pushed on every strut. While refueling they checked the wings, the undercarriage, the ailerons, the elevators. In essence, neither they nor I considered that aircraft very reliable. The story is considerably different today. Through trial and tribulation, we have learned reliability in aircraft.

In the missile business today, we have neither the time nor can we pay the price for learning reliability through such trial and tribulation methods. What then have we been doing and what more can we do to improve reliability in missiles? I have several convictions which I should like to discuss with you today.

First of all, I am convinced that we must build reliability into our components. Some missiles have been flown without adequate returns. Development missiles cost so much money that we cannot afford to fire them into the air just to see if the components function properly. In many cases where failures result, the exact cause of failure is not known; in fact, the specific component that failed is unidentifiable. The only justification of first flight tests is to measure the system environmental and stress conditions.

In the past, too much attention has been given flight tests to the detriment of laboratory testing. I realize that much bench testing and functional testing has been done, but the importance of other aspects such as testing to failure has been largely neglected to the detriment of reliability. An important part of any reliability program is to insure that samples of development hardware be produced or otherwise procured for test to failure in your laboratories. It is

essential that this be done so that no unreliable component finds its way into the missile system. We must know accurately the conditions of environment into which the particular component is to function. Only then can we insure obtaining an adequate margin of safety.

I feel strongly that we should push the state of the art and advanced technology in the making of all components. When these components have been proven reliable, then, and only then, should they be put into a system. By way of illustration, this is the philosophy that was used in the development of NIKE AJAX system. No major scientific breakthroughs were to be counted upon for the successful completion of the designs. Too often, systems are brought well along into the development cycle without adequately paying attention to these considerations. Then quick, and generally costly, "fixes" are needed to mend the situation.

My second conviction is that you cannot inspect quality into a product. You have to design it into the product and build it into the product. Inspection may remove all the items that are beyond a particular specification limit. However the uncertainties of inspection and deterioration with time and use may give early high failure rates. This implies that to achieve reliability dependence must be placed strongly on trends of particular critical characteristics as determined by measurements or samples of the product so as to get warning of decreasing margin with respect to the rejection points. To insure reliability, we must start with the raw materials and check the product all through its processing.

This brings me to my third conviction -- that is, once adequate reliability is designed into a system, quality control programs must be instituted to insure maintenance of inherent reliability throughout development and production. In the development cycle, the emphasis on reliability must be adhered to throughout the testing program. The entire test program should be closely correlated with actual service conditions. Furthermore, increased emphasis must be placed on determining the cause of failures.

I can well imagine some of you in the audience thinking that here I am pulling some good pilots out of their crashed airplanes again to interrogate them. This is only too true, but at least today we have much better equipment to give us much better information without the loss of human lives during a development program.

When I talk of pushing reliability through development of missile systems, axiomatically I am placing greater responsibility

and reliance on producers of these systems. Because of the complexity of the systems being developed today, the producer must assume increasing responsibility with regard to testing and adjustment of missiles prior to firing. An important factor in this regard is to have contract arrangements which centralize responsibility in an unmistakable way. The same organization should, preferably, be responsible for both the design and first production of new complex devices and systems. It would be most beneficial if that same organization should be responsible for production through evaluation and early service use for incorporation into the design of the changes found desirable and necessary by such experience both in use and in production. With a design in performance so established, the matter of multiple sources of production can then be approached on a sound basis.

The stress which has been put upon reliability in atomic warheads is impressive. These warheads are now being designed to require a minimum amount of monitoring and testing both in storage and prior to use. We should stress the same goal for our missile systems so that they may be fired like artillery rounds with a much higher reliability.

The final conviction which I will discuss today is that the problem of reliability is one about which personnel at all levels and through all phases of development, production, and use must be motivated to emphasize and to solve. This problem of motivating personnel and of educating them in the importance of reliability is the same for the armed services and contractors alike. During the second World War in many of the aircraft factories, large and colorful signs stressed the need for reliability in the production line. These signs read to the effect that "Some day your brother may be in the aircraft you are building."

Now I have told you how important I think reliability is. I have given you a few of my convictions on the subject. Before concluding, however, I should like to bring out three factors which illustrate not only the problems that must be faced but the goals that must be achieved. These three factors are <u>cost</u>, <u>complexity</u>, and <u>time</u>.

How much does reliability cost us? This question has never been, nor will it ever be, adequately answered. We know that our systems are becoming more and more expensive and, hence, the cost of failure mounts continually. For instance, the NIKE AJAX air defense system now has a per missile production cost of approximately $25,000

while its successor, the NIKE HERCULES, cost is $66,000 per missile round. The dollar figure for the production round cost of a NIKE ZEUS missile will be about an order of magnitude greater than the cost of NIKE AJAX. From a dollar point alone, the costs of unreliability are alarming. Not only is there the cost of the missile lost during an abort, there is the cost of the operation and maintenance of ground support equipment during the firing and during the development program and training program there is the added cost of drone targets for air defense missiles.

Another measure of the cost of unreliability may be gained by looking at our satellite programs. Few figures have been released to show the overall costs of programs of this nature. One program, whose cost figures were released, showed that the total program cost the government $111 million, or $10 million per attempted firing. Because of several failures, the cost per successful firing rose to $34 million. That's one heck of a lot of money in any man's book. In addition to the dollar cost with relation to satellite programs, soon a man's life may well be added to the cost of an abort during MERCURY shots.

Missile system complexity may be measured by numerous parameters. I will use only one to give you an illustration of how our missile systems are becoming increasingly complex. Using the number of engineering drawings as a parameter, the NIKE AJAX system required 100 thousand, while the NIKE HERCULES system requires 120 thousand. Yet, today, before development is completed on the NIKE ZEUS system, it will be necessary for approximately 450 thousand engineering drawings to be made.

Turning now to time, there are no adequate time data available in unclassified literature. Even if there were, these data would vary greatly considering such factors in air defense work as the type of target, altitude and course of target, defense missile capabilities, use of decoys, etc. It is apparent, however, as the missile threat increases, seconds of time will become increasingly important and could determine the fate of a city or nation. It is for this reason that reliability goals of 99 percent are necessary.

In conclusion, the attainment of reliability in combat involves many things and many people. We must be sure that we are aware of all of them and that proper measures are taken with respect to them. Reliability involves the development and design engineer; it may be affected by the specification writer, by the purchasing agent, by the contracting officer, by the inspector, and by the quality control organization. It is affected by the responsibilities set up by the contract. Everyone has to do a job right to get reliability. Its achievement calls for a proper attitude on the part of everyone. Conversely, the failure of any link can break the chain. Reliability is everybody's business.

TACTICAL RELIABILITY OF FIELD ARMY GUIDED MISSILE SYSTEMS

Colonel Keith H. Ewbank — Hq, USCONARC

Gentlemen:

For the next few days reliability will be discussed from every possible aspect. Maybe we should start by defining reliability, and of course this depends on who you are. If you are a statistician - it means pure numbers. To some engineers, it may mean performance limits of specific materiels or devices. To one who writes dictionaries it means "suitable or fit to be relied on," "worthy of dependence or reliance," "trustworthy" and of course, more.

I am a soldier, so I am going to give you, in broad terms, the concept as the soldier in the field sees it; of tactical reliability, and I'm not speaking of the soldier in a warm barracks or a theater. I mean the young private living in cold, rough combat conditions with survival as one of his prime objectives.

Field Army missiles can be divided into two general classes - Air Defense and Artillery ground support or SSM - and as you can imagine, in many ways reliability has a different meaning to the Air Defense Artilleryman than it does to the field Artilleryman. They have in common, the requirement that a system place effective fire on a target at the proper time.

Tactical Reliability in Air Defense is characterized by continuous preparedness for action and effective response to the reaction time available. In certain instances, the required reaction time is of the utmost importance and can be achieved only if tactical reliability closely approaches design reliability. A brief comment on the present and future Field Army Air Defense Systems will illustrate the user's perspective.

In Forward Area Air Defense weapons, minimum reaction time considerations assume prime importance. This type system must be capable of almost instantaneous reaction under the worst possible environmental conditions. An obvious corollary is the requirement for an absolute minimum of maintenance.

The REDEYE, a man-transportable, air defense guided missile system, is being developed to meet these criteria. Design reliability must be attained through weapon simplification and ruggedization. However, the fact that an individual soldier, upon detecting an enemy target, aims and fires the missile, introduces overriding factors of the human element into the system. A design reliability approaching 100% is

therefore necessary in order to minimize the degrading effects of the human factors involved and thus maximize the final tactical reliability of the system. Obviously, a weapon of this type must have an extremely rapid reaction time, or it is not "tactically" reliable.

In MAULER, a mobile, division-support air defense guided missile system, an almost opposite approach will be taken to meet the requirements of the forward battle area. Almost full automation will be utilized in order to reduce the human factor. Automation, invariably introduces equipment complexity and its attendant maintenance problems. Experience has shown that user personnel have difficulties with equipment complexity and resultant maintenance requirements under stringent tactical conditions expected in the forward area. It is evident, therefore, that acceptable tactical reliability in the MAULER system must result from maximum component reliability and unsophisticated maintenance procedures.

As the demands upon system reaction time become less severe, we can tolerate a transition from full automation to the semi-automatic design exemplified by the HAWK system. It is evident though, since operational manning levels and functions are intentionally at a minimum, that the reliability of unattended, remotely-controlled equipment must continue to reflect full automation standards. Even with semi-automatic design, the problems of maintaining personnel efficiency are outweighed by the need for reliable equipment performance for extended periods of readiness under conditions when little or no maintenance may be performed. Tactical reliability starts with maximized design reliability which can be supported in the field by quick, simple, and reliable maintenance procedures.

Longer-Range Air Defense systems do not require the extreme fast reaction [illegible] of their low altitude, shorter range counterpart, nor are they subjected to the extremes of rough handling and environmental stress. The emphasis must be placed upon achieving and maintaining a satisfactory degree of tactical readiness. With the generally larger and more complex equipment associated with long range, air defense systems, the maintenance problem tends to become acute. The ratio of maintenance time to operational time is a critical factor. The required tactical reliability can be achieved only by incorporating a design reliability such that operation for extended periods can be expected with little maintenance and few unacceptable losses in operating time.

Now for SSM or field artillery systems. Although we have the equally important requirements for effectiveness, operator training and timeliness, the parameters are not the same as Air Defense weapons because of different priorities of characteristics.

To the field artilleryman reliability is the level of assurance that the system, will effectively accomplish the assigned mission,

that is, place effective fire on the target at the proper time. This effectiveness is the tactical reliability of the system and the technical reliability of the components of the system.

By tactical reliability we mean the ability of the system - under the required tactical and field environmental conditions - (1) to place effective fire on the target, and (2) to be operated by artillery soldiers with average training.

Effective fire is that which is accurately placed on the designated target at the desired time to produce the desired effect. It is both accurate and timely.

Lest someone accuse me of confusing accuracy and reliability, remember that to the tactical commander it matters little whether a mission fails because of an unreliable assembly or inaccurate flight. The fact that the system has not placed accurate and timely fire on the target has demonstrated its unreliability for that particular mission.

In addition, the system must be capable of being operated by average soldiers. Remember that the apparent or design reliability of a system can be materially increased if skilled technicians, specialized test and maintenance equipment and a sufficient level of replacement components are used in the firing area. However, our wartime turnover due to casualties, sickness, accident, and rotation is such that we cannot perform R&D type firings in combat. Also, considering the mobility expected of our future missile systems, we cannot expect immediate contractor or even Ordnance support. Therefore, when you are designing a tactically reliable system, ask yourself these two questions:

Do the prefiring adjustments or replacements require a skill level higher than that possessed by average Artillery soldiers?

Do the prefiring adjustments or replacements require equipment or spares which would not normally be employed by the Artillery battery?

Technical reliability may be considered broadly as the composite reliability of the components of the missile system. This must include all ground and test equipment, as well as the missile itself. We are interested in the whole sequence of operations, not just in the in-flight reliability of the missile. In this respect, oversophisticated systems are particularly to be avoided.

Most of you are familiar with military characteristics, a statement of the capabilities of a missile system which enable it to fulfill the Qualitative Material Requirement.

I would like to give some examples of how we in Materiel Developments interpret these statements to provide you with a better feel for the levels of reliability and time limits required for field artillery guided missile systems. Suppose we require - and this is typical - of CSM systems - that 90 percent of the missiles removed from six months storage pass all prefiring checkout tests with only minor adjustments or component replacements by battalion or battery personnel. We emphasize that these prefiring checks are those performed in the battery area after the missile has been carried or stored as part of the artillery unit basic load. They are not the tests performed when the ammunition is issued at the ammunition supply point, nor tests performed by the Ordnance direct support company. The adjustments and component replacements must be done by Artillery soldiers in the unit without the assistance of Ordnance personnel and without the use of special equipment other than that issued to the Artillery unit. Also, the time required for the performance of these functions must not cause the system to fail to fire at, or reasonably close to, the desired time.

Next, we might require - again typical - that of the missiles which pass prefiring checkout tests, not more than 5 percent may fail to fire at the designated time due to system malfunction throughout a 72-hour period following checkout.

Another typical requirement is that those missiles which launch must have an in-flight reliability of 95 percent. This is the degree of assurance that, after firing, the missile will not abort due to missile failure but will deliver its payload accurately and that the warhead operates as intended. In battle we would not treat in-flight reliability independently of tactical reliability.

Our missile systems are prime battlefield targets and cannot be left in position for long periods of time - particularly nuclear delivery systems. Consequently, we may require that only a short time shall be required to emplace the system and to fire the first missile. This time must include the prefiring checkout of the missile system. Though we would like to treat missiles as we do rounds of cannon artillery ammunition, experience indicates that at the present we definitely need this checkout just prior to firing.

Let's review our required characteristics. The Artillery expects to receive an operable missile at the ammunition supply point. We expect to be able to store and transport this ammunition as part of our basic load. Using our typical percentages, 90 percent of these missiles must pass prefiring checkout tests using standard army procedures and average soldiers with no Ordnance support in the firing area. 95 percent of the checked out missiles must launch on time throughout a 72-hour period after checkout. Then, 95 percent of these missiles must not abort, and must deliver their payloads on target within the normal dispersion limits and function properly upon arrival.

The reliability at checkout, firing, and in-flight must be successively realized in a tactical situation. A missile system which cannot successively pass each requirement is not tactically effective, since it cannot complete its fire mission.

The user can accept no relaxation of requirements pertaining to timeliness of fire or of infiring checkouts. However, if such requirements impose unacceptable limitations such as excessive basic load of spare components, or missiles, or requirements for excessive personnel to perform the prefiring checkout, we must be informed so that we can consider what requirements may be relaxed.

It would appear that a great increase in overall reliability can be accomplished in the area of prefiring checkout. The prefiring checkout reliability may be increased by the provision of a level of spares, based on design and experience, immediately available to the using unit. This will enable us to receive a fire order a reasonable time before firing, make the necessary component replacements without delaying for Ordnance support, and complete the fire mission. To do this, the missile system must be designed so that average soldiers with average training can determine malfunctions and replace components with little difficulty.

To summarize,

1. Tactical reliability can only be defined after operational requirements are known for a particular system. Priorities of characteristics play a major role in this regard.

2. The designer must consider the users "time to repair" and "equipment required to repair" in the developing system reliability.

3. Average soldiers with considerable variety in background and training will operate our systems.

4. Tactical reliability must include prefiring checkout requirements and maintenance requirements as well as the usual "in-flight" reliability.

WHAT RELIABILITY MEANS TO SAC

Lt. Colonel J. W. Anderson, Jr. -- Headquarters SAC

The reliability of strategic weapon systems, including missiles, of the Strategic Air Command is of great concern to the Commander in Chief and planners. It is not enough to just say that it is desirable to have reliable equipment. Neither is a design goal of high reliability just an objective or number; it must eventually be demonstrated and become a valid planning factor upon which we can depend. We have these planning factors available from the hundreds of thousands of aircraft sorties, but the missile systems pose an entirely different proposition. In spite of the difficulties in forecasting missile capability, the numbers, types, basing, and the targeting of the missile force is dependent upon such a forecast. Therefore, it is not only necessary to have a reliability factor, but it must be sufficiently demonstrated to establish proven confidence levels.

Confidence can be more vital than basic reliability. To oversimplify this; for targeting you would prefer a 100% confidence level in low reliability to a low confidence in 100% reliability. Whatever the reliability, you must know it, take it into consideration in your plans, and then set about bringing it to the level of effectiveness required. Improvement of reliability after a system is in the field is usually a most expensive complicated program. The ECP and mod-program costs for limited improvement to be gained have to be weighed against the effort necessary to obtain a whole new issue. It is usually more practical to initiate system development with a proper emphasis on an "Optimum allocation of funds for reliability programs of guided missiles." That last phrase, by the way, is the title of a paper by Dr. Pieruschka (with the Redstone Arsenal) back in 1955.

In large ballistic missiles you have faced problems of precise control, timing, metering, and other factors that lead to integrated system complexity. This was initially accompanied by a general lack of experience and reliability data. There have been many studies and papers on the subject of reliability programs necessary to develop the weapon systems, and there will be some fine presentations by individuals during this symposium as well. But if we are ever to know what our military capability is, we must exercise the full system in the field and eventually fire the missiles. While a launch from an operational site is desirable, as yet SAC has not had the approval to do this. At present flight demonstrations must be

conducted at Vandenberg Air Force Base into the Pacific Missile Range, or at Patrick Air Force Base on the Atlantic Missile Range. When discussing the minimum number of each type to be exercised, we must consider statistical validity, and of course, some of these must be launched each year. Spending too little for reliability demonstrations is a false economy; failure to establish precisely correct confidence levels is militarily dangerous.

Now, if we would discuss specific factors, some definitions are probably in order. Some you will recognize, but where the connotation differs, the user's ideas will be presented.

Overall Operational Reliability of a missile weapon system is the probability that once the execution order is received, and the commit sequence button pressed, the missile will be launched and its warhead will explode with design yield on the specified target, within the CEP definition. This may vary somewhat from R&D reliability, for performance within a designed reaction time is also measured, automatic sequencing replaces manual operation, and the environment is different. This probability is expressed by a decimal number between zero and one. Zero probability means, of course, no chance of the event happening; 0.5 probability means a 50% chance of the event happening; and a probability of 1.0 means the event is certain to happen.

Measured Reliability is the "success ratio" obtained in a series of tests; in other words, the number of successful tests divided by the total number of tests.

Confidence Level is the probability that the true reliability lies between two limiting values, or somewhere above a certain value. A confidence level may be thought of as a probability of a probability.

Confidence Limits are the limiting values between which the true reliability will be for a given confidence level. These limits depend on the number of measurements, or sample size.

The overall operational reliability factor used by the Strategic Air Command for a particular missile weapon system is not easily ascertained. It is recognized that flight reliability of the missile depends on reliabilities of the many individual sub-systems, such as propulsion, flight-control, guidance and re-entry sub-systems. These, in turn, are affected by the many component reliabilities. In addition, the propellant loading systems, erectors, shelter doors, operating consoles, cabling, etc., are all involved. Overall reliability then, is influenced by many individual probabilities,

including those subject to personnel factors, ground support equipment (GSE) and the missile itself.

The complexity of the problem to determine the reliability of a missile weapon system is further complicated by the difficulty of making measurements under actual operating conditions. For instance, a system developed in Florida and demonstrated in California, does not necessarily give SAC a true measure for a Wyoming based missile. In some instances, there is a tendency to make gross extrapolations from reliability factors determined under research and development conditions to use as operational planning factors. It should be realized that we must endeavor to get test results under conditions as near to actual operating conditions as possible, not only geographic, but climatic as well. By conducting some tests on a "No notice" basis the pressures on personnel and equipment that are likely to occur in time of conflict, may be duplicated in order to obtain useful and valid data.

The number used for overall operational reliability of a missile weapon system is not simply the product of all applicable measured success ratios. Nor can a theoretical extrapolation of the product of these measures values be used to obtain a realistic success ratio to be expected under anticipated operating conditions. In arriving at the value for the overall operational reliability of a weapon system, confidence limits associated with measured success ratios must be taken into consideration. These confidence limits are based on an assumed binominal distribution for test results. To illustrate confidence limits, consider the following example: Suppose a measured reliability, or success ratio, of 0.50 was obtained in testing 10 missiles fired under as realistic operating conditions as possible. The true reliability of similar missiles fired under the same conditions would be somewhere between 27% and 73%, at the 80% confidence level. The true reliability would lie between 19% and 41%, at the 95% confidence level. If the 0.50 measured success ratio had been obtained in testing 20 missiles instead of 10, the true reliability would lie between 0.34 and 0.64 at the 80% confidence level, and between 0.27 and 0.73 at the 95% confidence level. The interrelation of demonstrated reliability, confidence factors and sample size is familiar to all of you.

A realization of what effect reliability has on force size may be realized by noting that we will not receive authority to expend our missile force until after an enemy strike has been initiated. It would seem reasonable that this strike would have been planned for 90 or 95% probability of success. This leaves us in the position of attempting deterrence with those surviving, maybe 5 or 10% of the total force. This remaining force is further degraded by in-commission rate reliability.

As an example of what reliability then means in terms of surviving missiles after an enemy attack, let us assume that we require 95% probability of destruction of 200 separate enemy targets. Let us further assume for simplicity's sake, that we have missiles of a type that one delivered warhead would destroy a target. Then, 400 surviving missiles with 80% overall operational reliability would do the job. But if the reliability was only 40%, 1200 surviving missiles would be required to destroy the 200 targets. This is a difference of 800 surviving missiles, or several thousand additional missiles of the less reliable type required for original inventory that must be manned and maintained.

The importance of reliability of missile weapon systems is perhaps most striking in a situation where it is of utmost importance that particular aiming points be destroyed, and the measured reliability is based on a small number of firings. Assume our missiles to have 5-MT yield, and 1-NM CEP. (CEP is defined as the radius of a circle about the aiming point in which half of the missiles are expected to fall.) Now, consider a situation where our missiles are targeted against weapon systems so protected that 10 psi overpressure would be required to destroy them. Let us assume again that a 95% probability of destruction is desired. A delivered warhead will destroy its target in this example, but the lack of confidence in measured reliability of our missiles requires more than one missile per target. Consider two cases: the measured reliability is 0.40 in one case, and 0.80 in the other, each determination being based on 20 firings of missiles in as nearly an operational environment as possible. With 90% confidence, we know that the true reliability is equal to or greater than some value lower than the measured one. In the first case this lower limit is 0.25, and in the second case, 0.65. Using these lower limits of reliability as planning factors, 10 of the less reliable missiles per aiming point are required; while only 3 per aiming point are required of the more reliable missiles.

The effects of missile reliability and the confidence with which it is known are even more pronounced for hardened targets. In the preceding example, had the target been able to withstand overpressures up to 100 psi, one could not assume that one of the same delivered weapons would destroy that target. Now it would require 25 of the missiles of 0.40 reliability to have a 95% probability of destruction, while 9 of the missiles of 0.80 reliability would suffice for the specified 90% confidence in both cases. This is a difference of 16 missiles per aiming point scheduled in the targeting plan. Please realize that the examples I have used are not indicative of any true capability or plan; they are for illustration only.

Having posed the user's problem of determining reliability and confidence, and the importance of this determination in his planning factors, we should look at the solution to the problem. Air Force Regulation 80-14 defines three categories of weapon system testing:

Category I - Subsystem Test. This is the shake - rattle - roll, hot-blowing fungus, etc., with which the manufacturers are all familiar.

Category II - Integrated System Test. In missile weapon systems this should include the GSE and facility as well. A military capability is also implicit in this phase. This is usually met by integrating the using command unit personnel into the test program in ever increasing numbers and with increasingly greater responsibilities.

Category III - Operational System Test. This is the user's responsibility, though hewill be joined by the commands responsible for the various inputs to the whole system. ARDC As the developer, AMC as logistic support manager, and ATC as the personnel pipeline manager. This may be likened to an Inspector General giving the new commander a report on the unit he has just inherited.

In addition to participation in test and evaluation of the system as it has been issued, the user has another fine source of data to help him "figure" his capability. This source is his exercise of the system during unit training (we call this integrated weapon system training, IWST), during the ORI (operational readiness inspection), normal SAC "No-notice" alerts, and the recurring combat training launches each year. Youwill remember that we do not now have permission to launch from all operational sites, and therefore the validity of the data must be adjusted somewhat.

Gentlemen, we have looked at the user's requirement for high confidence in a known reliability and the effect on his force size, desires for mod-programs, basing, manning and operational planning. The Air Force has a user reliability program in effect, so that he may have confidence in a demonstrated reliability. I am sure the manufacturers and developers will have some interesting things to tell us in the next two and a half days about how to meet those requirements in the most efficient way. This symposium has promise of being a very interesting experience.

INTERSERVICE DATA EXCHANGE PROGRAM
(IDEP)

J. H. Draughon, ABMA

In this age of budget-buster missile and space programs, the majority of which are proceeding on a crash basis and all of which are pushing the state of the art, it was inevitable that the constant search for components of higher quality and greater reliability would lead to much duplication in test programs throughout the Armed Forces and industry. The program I shall outline to you presently has as its primary objective the reduction of that duplication of effort in the ballistic missile and space programs, so that those dollars and those scientific and technical manhours saved may be more effectively applied. The program is known as "IDEP" - Interservice Data Exchange Program.

I do not think IDEP will necessarily reduce the cost of testing. I do believe it will result in broader and better test programs for the same dollars and in an enhancement of ballistic missile and space vehicle reliability. If the exchange of these data results in the detection and replacement of a single unreliable or marginal component, and just one large ballistic missile or space vehicle is saved, the program will not have been in vain.

IDEP had its inception as a result of the airing of mutual problems in quality control and reliability in a series of meetings among representatives of the three Armed Services -- Army, Navy and Air Force. The first of these meetings, in early 1958, was sponsored by the Air Force Ballistic Missile Center at Inglewood, California. A second meeting in December 1958, sponsored by what was then the Navy Bureau of Ordnance Special Projects Office, was held at Lockheed's Sunnyvale, Calif., plant. In July 1959, Chrysler Corp. Missile Division in Detroit was host to a meeting sponsored by the Army Ballistic Missile Agency.

From these and other interim meetings, a Coordination Group was formed, composed of one member each from the Air Force Ballistic Missile Division, the Air Force Ballistic Missiles Center, the Navy Bureau of Ordnance Special Projects Office, and the Army Ballistic Missile Agency. This group, of which I am presently the Chairman, generated a proposal for the exchange of user component test data among ballistic missile contractors of the AFBMD, AFBMC, Navy Special Projects Office, and ABMA. (See Figure 1 - Flow of Information to Data Centers and out to Contractors, etc.)

Now, the exchange of data among the Services is not a new idea. In fact, there has been a constant exchange of test data among the Air Force, Army and Navy on an "as requested" basis. This proposal is unique in that it goes several steps further and provides for an automatic exchange of user component test data among selected contractors without the necessity to publish lists, make official formal requests, staff approval of such requests, and finally mail the requested data.

Before we go any further, let me define this word "component". As I will use it, a component is defined as a part or piece not normally subjected to further disassembly, e.g., capacitors, resistors, relays, etc.

The importance of and the urgent need for a better means of exchanging information and data in the missile and space business has been recognized by various public and private management officials and by Congressional committees, not the least of which is the House Appropriations Committee.

Since there can be no question of the desirability of such a program, let us examine the problem. Among other things, investigation has shown that in one specific instance eight different organizations had performed certain controlled laboratory tests on components of the same manufacture and part number. As it turned out, the results from any one of the tests would probably have satisfied the requirements of the other seven if they had been aware of the test results. If such duplication of effort can be stopped, we will save not only the test setup costs but also the time of the test and design engineers and technicians. With the application of the saved effort to other urgent problems, an acceleration of development programs should be realized.

Further, broader and more prompt access to controlled laboratory test data will undoubtedly point the way to better manufacturing and quality control procedures which, in turn, should result in a higher level of quality being maintained within the design specification.

Now, there may be those who feel that when component quality is improved, system reliability is also improved. This is not necessarily true. If a wrong part is specified by the system designer, no amount of diligence by the manufacturer nor by his quality control organization will make the missile system any more reliable than that part is reliable in its particular environment. However, if we can make available to the system designer component performance or failure data which points up the need for a change to a component of higher reliability, enhanced system reliability should result. The need for higher quality and more reliable components cannot be overemphasized.

If a transistor fails in an automobile radio, at most the owner is irked and maybe a little inconvenienced while it is being repaired.

But if a transistor fails in a missile or space vehicle, a multimillion dollar loss may be incurred. We could lose the whole vehicle, or we could lose a part or all of the information the vehicle was launched to secure. In any event, the loss is considerable.

Now, let's take a look at the different types of information which might be exchanged. Some of these are:

1. User component qualification test data, i.e., laboratory-controlled test results;

2. Quality control test results;

3. Reliability test results;

4. Exaggerated stress test results; and

5. Flight test results.

You will recall that I stated earlier that a proposal had been generated for the exchange of user component test data. This element of the various existing types of data was selected because it appeared that this type of data would lend itself more readily to immediate exchange and the benefits would be immediate and extensive. Such test reports will specify that a given component has been tested under controlled environmental conditions, and that the results of such tests are as stated in the report. If a designer has need for such a component for a given environment and he has available to him the results of user tests run under the same or similar environment, he should be able to make a selection with reasonable assurance and without further testing, or at least with a minimum of additional testing. If the tests to which he has access supply only a part of the information which he requires, we are still ahead of the game inasmuch as only partial tests need be run to prove the component for his particular application.

In the case of the exchange of quality control test data, since the volume of such information is extremely large, individual test results would not be exchanged. We contemplate that periodically an analysis of quality control tests would be made and the results of the analysis would be incorporated in the data exchange system.

Now, flight test results pose quite a different problem. There is such a wide difference in the environment encountered in the flight of the same component in different missile systems (in many instances the exact environment is not known or may vary from flight test to flight test), that it becomes almost impossible to make any analysis of the given component which would be meaningful to other missile systems. For example, a given relay might encounter a vibration

characteristic in Missile A of 350 cycles per second. The same component if used in Missile B might encounter a vibration characteristic of half this value. While in still another missile it might encounter a characteristic of twice that factor. Even at different locations within the same missile, the vibration characteristic is apt to be different. So, to earmark a given component as unfit for missile use because of a failure in one missile, is completely unrealistic. However, if failures are such that a significant pattern is formed, these data will be exchanged.

Experience has shown that we can say that a given component is satisfactory or unsatisfactory for use in a given missile only when the environment in which the component will function is known. It, therefore, follows that the only meaningful measure of a component is its ability to perform within its design characteristics under specific environmental conditions. We will attempt to see that the data exchanged under this program meet this requirement.

Needless to say, one of the most difficult hurdles to a meaningful exchange of technical test data is a common language which is understandable to all. By this, I mean some sort of coding so that a given environment is always expressed the same, or that a given type of failure is always expressed in the same terms. Much work has been done by the group working on this proposal for the exchange of data on such a language. As the takeoff point, the coding which had been worked out for the TITAN missile system was used. This has been supplemented, and we feel that we have at least the beginnings of a language which could be used and would be understandable to all. (See Figure 2 - Sample of Coding)

Probably the greatest single problem in this exchange program is the method of transmitting the data from one point to another in such a manner that it is readily retrievable. As you all know, there are masses and masses of data which have been generated. I would not even hazard a guess as to the tons of recorded information which has been generated. In fact, the major question becomes one of how can we take a mass of information and reduce it to proportions which can be handled, and at the same time make that information easily available or retrievable to the engineer who needs it? This problem has been the basis of many EAM and computer program studies.

For IDEP application, we believe that the answer is contained in the Military "D" double-aperture microfilm card. (See Figure 3 - EAM Card) At a reduction ratio of 22-to-1, two pieces of 35 mm microfilm affixed to the two apertures can record eighteen (18) pages of written text. By making a survey of a substantial number of test reports, we have found that 18 pages would cover about 90% of all the

user component tests conducted under controlled laboratory conditions. The remaining 10% can be covered by a second or third follower card. Tests using Military "D" double-aperture cards have shown that no modification to standard machinery is required for satisfactory machine processing.

Now, with the means of reducing the large mass of data to proportions which can be handled, the next question becomes one of who does the handling? It has been decided that this could best be done by establishing what we call Control Centers, or Data Distribution Centers, at three different points. One will be at AEMA in Huntsville, another will be at the AFBMD complex in the Los Angeles area, and the other will be at the Naval Ordnance Laboratories at Corona, California. All AEMA ballistic missile contractors will feed laboratory test reports, coded to the common language, to the AEMA Data Distribution Center, where they will be microfilmed and the film placed in the aperture cards which have been keypunched to permit machine sorting. The required number of copies will be made from the master card by a card-to-card duplicating process. The aperture cards will then be distributed directly to the Air Force and Navy Data Distribution Centers, their designated contractors, and other AEMA contractors. The Air Force and Navy Centers will operate on the same basis. All information will not flow to all contractors; in other words, the designation of contractors will be on a specified area-of-interest basis by the Services concerned. Information in a given contractor's particular area of interest will flow to that contractor, but he will not receive other information which is not pertinent to his particular area of interest. Copies will also go to the Armed Services Technical Information Agency. Qualified contractors and other agencies not a part of IDEP can thus secure the same information by proper request to ASTIA. At the same time the aperture card is prepared, a 5"x8" printed summary card will be prepared from a summary page contained in each test report. (See Figure 3 - Report Summary Card) This summary card will give pertinent summarized information on the test so that a designer can determine applicability of the test without having to study the entire report. These summary cards will be distributed along with the aperture cards. An index of all reports distributed will be prepared and distributed on a monthly basis.

Of course, this i all very nice to have a lot of cards in a Data Distribution Center and other cards sent out to various contractors, but the big question is, what happens to them after they get there?

The objective is to put these cards immediately before the engineers needing the information. Obviously, we can't put all cards before all engineers, but with a little judicious organization we can establish, at specific strategic points within each contractor's plant and within our own service laboratories, decks of these cards which carry test results pertaining to the specific area of interest of the

group. At these strategic locations will be located viewers. After a selection is made from the 5x8 summary cards, the aperture card is placed in the viewer, and one can read the text of the report blown back to the original letter size. This gives the engineer the capability of a quick look at the report. If he needs to make a detailed study of the elements of the report, he may then call for a hard copy. This can be accomplished by one of the high-speed duplicating processes now on the market. These are capable of reproducing in letter-size six cards per minute per aperture at a cost of approximately 15¢ per aperture, including labor to cut reports, etc. I have a hard copy made by one of the processes after a card had undergone 1000 passes through machine sorters, collators, etc. The text is perfectly legible. If the contractor does not have high-speed duplicating equipment, any photographic shop can blow the microfilm back to legible size.

The scope of this program has been held to ballistic missile contractors of the Army, Air Force, and Navy, in order to work out the bugs in what we believe to be a good system. If the trial run is as successful as we have reason to believe it will be, we will propose that IDEP be expanded to embrace other areas.

Now, what about costs? I won't say, "Nothing," because I don't know of anything that is free in this day and age. I will, however, point out certain pertinent facts:

a. The equipment for doing this job is the same as that which will be required in the Department of Defense drawing microfilming program which applies to all Armed Services. It will be available in most large contractors plants.

b. The missile business is a multi-billion dollar business, of which testing to determine suitable components for a given environment is no small part. If we can reduce the multiple testing of the same components, we will gain many engineering manhours which can be applied to advancement of the state of the art. In view of the recent Russian successes, I think there can be little doubt of the necessity of using every asset at our disposal to expedite our own missile and space efforts.

c. If this data exchange program results in the change of a component which saves even one TITAN, ATLAS, THOR, POLARIS or JUPITER missile, to say nothing of a SATURN Space Vehicle, the cost of the program will have been paid for years to come.

Now, let me leave you with one parting thought. An ultimate objective of this program is to work out a system of environmental coding and a computer program so that a designer can query the computer and receive from the computer the top components which have been tested

to the specific environmental limits required. When this can be done, even more time and, consequently, manhours of effort will be saved. It is no small undertaking, but we have every reason to believe it can be done.

The status of IDEP is as follows:

On September 11, 1959, Brigadier General Barclay, Commander of ABMA, approved and forwarded to Rear Admiral Raborn, Chief of the Special Projects Office, Navy Bureau of Ordnance.

On September 25th, Admiral Raborn approved and forwarded to Major General Funk, Commander of Air Force Ballistic Missile Center.

On October 2nd, General Funk approved and forwarded to Major General Ritland, Commander of the Air Force Ballistic Missile Division.

On October 14th, Major General Ritland approved. (See Figure 4)

Since that date, draft manuals of instruction and of the Generic Code have been prepared for the operation of the Data Distribution Centers and for the guidance of participating contractors. Meetings have been held to go over the drafts, and publication of the manuals is imminent. An approach to orient the selected contractors and distribution of manuals to those contractors is in progress and will be considerably expedited in the immediate future. Many of you who are represented here today are among those who either have been or will be called upon in the near future. By the next meeting of this Symposium, a definite evaluation of IDEP will be available.

Members of the IDEP Coordination Group are:

Mr. J. H. Draughon, ABMA	Chairman
Mr. E. J. Lancaster, AFBMC	Secretary
LCDR R. Smiley, INSORD	Member
Major V. Bracha, AFBMD	Member.

Members of the Sub-Group on Mechanics of Interchange are:

Mr. S. Pollock, NOL-Corona
Mr. C. A. Guthrie, ABMA
Mr. M. Barbe, STL, for BMD

* * *

TEST DATA FLOW

INTER-SERVICE COMPONENT TEST DATA EXCHANGE

REPORTS SUBMITTED BY CONTRACTORS

INDEX STRUCTURE

000 00 00 00 00 00

SEQUENCE OF REPORT
CONTRACTOR INITIATING REPORT
COMPONENT & PART CLASSIFICATION CODE

EXAMPLE

601.95.40 20-9R-01

REPORT NO
ABMA
DPST
HERMETICALLY SEALED ARMATURE
TIME DELAY
RELAY

DATA CENTER

1 SCREEN REPORT
2 VERIFY INDEX NO.
3 REPRODUCE SUMMARY
4 PUNCH CARD & ATTACH MICROFILM
5 DISTRIBUTE

ASTIA

MASTER FILE AT DATA CENTER

APPLICABLE CONTRACTORS

OTHER CENTERS

ABMA LABORATORIES

→ ALL REPORTS

ALL SUBJECT CONTRACTOR REPORTS ONLY)

INTERSERVICE DATA EXCHANGE PROGRAM

REPORTING ACTIVITY CODES
(SAMPLE)

A1	General Electric, Syracuse, N.Y.
A2	General Electric, Philadelphia
A3	Bell Telephone Labs, Whippany, N.J.
A4	A.C. Spark Plug, Milwaukee, Wisc.
A5	Avco, Lawrence, Mass.
A6	Martin, Denver, Colo.
A7	AMF, Pacoima, Calif.
A8	Rocketdyne (North-American), Canoga Park, Calif.
A9	Convair, San Diego, Calif.
B1	Douglas, Santa Monica, Calif.
B2	Aerojet, Sacramento, Calif.
B3	Arma, Garden City, N.Y.
B4	Burroughs, Paoli, Pa.
B5	Remington-Rand Univac, St. Paul, Minn.
B6	Aerojet, Azusa, Calif.
B7	Western Electric, Whippany, N.J.
B8	Sycamore Test Site
B9	Santa Susana Test Site
C1	Martin Denver Test Site
C7	AMF, Greenwich, Conn.
7A	Edwards Air Force Base
7B	Patrick Air Force Base
7C	Holloman Air Force Base
7D	Cooke Air Force Base
8N	NOL, Corona
9R	ABMA (Redstone Arsenal)
9S	Martin, Orlando, Fla.
9T	Chrysler, Detroit, Mich.
9U	Ford Inst. Co., New York City, N.Y.
9V	Bendix, Los Angeles, Calif.

Figure 2 (Part I of III)

INTERSERVICE DATA EXCHANGE PROGRAM

COMPONENT AND PART CLASSIFICATION CODE INDEX

(SAMPLE)

025	Accumulators
038	Aircraft Electronic Control Equip.
051	Amplifiers
061	Antennae
091	Audio Accessories
101	Batteries
115	Bellows
121	Blowers and Fans
141	Boards, Printed Circuit
151	Capacitors, Fixed
161	Capacitors, Variable
181	Coils, Inductance
191	Computer Elements
201	Connectors, Electrical, AF & Power
211	Connectors, Electrical, RF & Coax.
241	Crystals, Frequency Determining
301	Electron Tubes
305	Electronic Equipment
318	Environmental Simulation Equip.
321	Filters, Electrical
325	Filters, Non-Electrical
335	Fittings, Pipe
341	Fuses, Circuit Protection, Non-Reset.
345	Gaskets and Packings
358	Gyroscopes
361	Hardware, Electro-Mechanical (Current Carrying)
371	Hardware, Electro-Mechanical (Non-Current Carrying)
381	Hardware, Mechanical
391	Heaters and Coolers, Electrical
405	Hydraulic & Pneumatic Parts & Comp.
411	Identification Devices
415	Ignition Parts and Pyrotechnics
428	Instruments, Gen. Lab., Controlling
438	Instruments, Gen. Lab., Test
448	Instruments, Gen. Lab., Recording
451	Instruments, Indicating (Comp. Pts. only)
461	Light Sources, Electrical
491	Magnets, Permanent
501	Materials
531	Motors, Control & Generators, Precision
541	Mounts, Shock & Vibration Isolation
544	Oscillators, Electrical
551	Power Supplies
565	Propulsion Components & Parts
575	Pumps and Turbines
588	Receivers, RF
601	Relays
651	Resistors, Fixed
661	Resistors, Variable
701	Rotating Machinery (Power Output)
751	Semiconductors, Diodes and Transistors
771	Solenoids (Mechanical Output)
791	Switches, Electric, Automatic
801	Switches, Electric, Manual
805	Tanks and Tank Parts
808	Telemetry Components & Systems
811	Timers and Counters
851	Transducers
901	Transformers
925	Valves and Valve Parts
941	Waveguided and Microwave Plumbing
951	Wire, Cable, and Harnesses

Figure 2 (Part II of III)

COMPONENT AND PART CLASSIFICATION CODE
(SAMPLE)

141 Boards, Printed Circuit

141.00	Construction
.10	Double Sided (Plain)
.15	" " (Printed Component Parts)
.25	Eyleted Holed
.65	Plated Holes
.75	Single Sided (Plain)
.80	" " (Printed Component Parts)

151 Capacitors, Fixed

151.00	Material
.05	Ceramic, General Purpose
.07	" , Temperature Compensating
.10	Electrolytic, Aluminum
.15	" , Tantalum, Foil, Etched, Non-Polarized
.16	" " " " , Polarized
.23	" " , General
.25	" " , Sintered Slug, Non-Polarized
.26	" " " " , Polarized
.40	Glass
.45	Mica, Foil
.47	" , Silvered
.65	Paper, Foil
.70	" , Metallized
.75	Paper - Plastic, Foil
.75	" " , Metallized
.80	Plastic, Foil
.81	" , Metallized
.95	Vitreous Enamel

151.00.00	Construction
.10	Encapsulated
.30	Hermetically Sealed, Can
.35	" " , Rectangular
.40	" " , Tubular
.50	Molded
.70	Rectangular
.90	Tubular

Figure 2 (Part III of III)

DATA EXCHANGE CARDS
INTER-SERVICE COMPONENT TEST DATA EXCHANGE



ENGINEERS MICROFILM CARD

SUBJECT
REPORT NO
DATE
QTY TESTED
TITLE
PART TYPE
SIZE
RATING
INTERNAL SPECS OR PROCEDURES IMPORTANT TO PROPER INTERPRETATION OF THIS TEST OR REPORT:
PART MFR.
MFR'S PART NO.
TEST WAS ABOVE MFR SPECS: YES NO
NAME & NO OF ASSOCIATED TESTS
SIGNIFICANT MODES OF FAILURE, IF ANY:

ENVIRONMENT	TEST LEVELS, DURATION, DETAILS, SPECS
VIBRATION	
SHOCK	
HIGH TEMP	
LOW TEMP	
HUMIDITY	
LIFE	
ALTITUDE	
OTHER	
OTHER	
OTHER	

ADDITIONAL REMARKS:

REPORT SUMMARY CARD

IDEP

INTERSERVICE DATA EXCHANGE PROGRAM

FOR BALLISTIC MISSILES AND SPACE SYSTEMS

The recommendations made by the Coordination Group for the Inter-Service Exchange of Ballistic Missile Component Test Data have been examined and appear to be reasonable, desirable, and to the best interests of the Government.

Approval of the recommendations and authority to implement in my Command is evidenced by signature affixed hereto.

O. J. RITLAND
Major General, USAF
Commander, AFBMD

BEN I. FUNK
Major General, USAF
Commander, BMC

W. F. RABORN, JR.
RADM, USN
Director, Special Projects Office
BUORD

J. A. BARCLAY
Brigadier General, USA
Commander, ABMA

Figure 4

MANAGEMENT POLICIES FOR ASSIGNING DEPARTMENTAL RELIABILITY RESPONSIBILITIES

by Leslie W. Ball

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STATUS OF RELIABILITY ENGINEERING

About ten years ago, reliability engineering entered its first phase. The name "conceptual" would be appropriate to this phase because at that time the greatest need was to formulate and propagate concepts such as the Product Rule. After the efforts of the pioneers, such as Robert Lusser, had drawn attention to the problem and events in Korea had emphasized its importance, reliability engineering entered the "fact finding" phase. Service failure data gathered by AIRinc. Research Corporation and others confirmed the pessimistic opinions of a growing band of reliabilitlity specialists. It was recognised that new methods were required to deal with the so called "early" and "random" types of failures. Consequently, reliability engineering entered the "technical methods research" phase.

In this year 1960 conceptual, fact finding and technical methods research efforts continue to be important but technical knowledge has advanced to a point where the most urgent need is now for "management methods research". This is not an academic opinion. Its validity is being demonstrated by current BMC/STL experience on the Minuteman Intercontinental Ballistic Missile Program. In this program achievement of overall weapons system cost effectiveness through reliability improvement is the principle objective. We must and will achieve two orders of magnitude improvement in the failure rates of electronic and electro-mechanical parts, but to do so it has become necessary to concentrate our reliability efforts in the area of management methods research in general and parts supplier control in particular.

In brief, we may say that in the year 1960 retention of our military superiority depends upon achieving superior reliability in complex weapon systems and that in turn this superiority depends upon the ability and dedication with which we attack the problem of reliability management methods research.

UNDERLYING CAUSES OF UNRELIABILITY

Mere concepts or even undigested facts are not a satisfactory base for management action. It is necessary to work out a simple but fundamental understanding of the underlying causes of unreliability and to express this understanding in management terms.

The authors choice of underlying causes is based on failure analysis. The results of each analysis have been expressed in tabular form using the following four column titles: (1) Item, (2) Failure Phenomenon, (3) Controllable Human Error and (4) Recurrence Control Action.

The first column names the part that failed. This is justified because every failure is the failure of a part even though the system produces the stresses and performance requirement that cause failures.

The second column gives a description in engineering terms of what actually happened.

The third column "Controllable Human Error" is absolutely essential to paving the way for management action to prevent recurrence, because management can not control the law of physics but can control the actions of their employees.

The fourth column "Recurrence Control Action" provides an answer to the question, "What specific discipline or practice could management require and enforce to reduce the probability of recurrence of this same failure?".

Failure analyses performed in accordance with the above pattern have led to the conclusion that the underlying causes of unreliability are:

(1) Variance in Materials and Processes. Customer demands for extreme performance combined with a national tendency to grab the novel have led to the use of materials and processes that have associated with them variances that cause myriads of infrequently occurring modes of failure.

(2) Lack of Organized Knowledge. Organized knowledge of "normal" modes of failure is available to design and manufacturing engineers in handbook form but knowledge required for the prediction, control and measurement of infrequently occurring modes of failure has not been adequate.

(3) Breakdown of Management Discipline. In structural engineering

absolute reliability has been achieved by management enforcement of the discipline of stress analysis, qualification testing, process control and conformance inspection. In the missile electronics and even in the missile mechanical industry failure analyses show that these disciplines have deteriorated. For example, in the case of electronics the discipline of stress analysis was hardly recognised until a few years ago.

Because it is not possible to achieve the performance required of missiles without the use of materials and processes that carry with them myriads of infrequently occurring modes of failure it is not possible to restore absolute reliability. However, it is possible to provide through reliability research the data and methods required to predict and control failure rates and to provide reliability assurance methods for ensuring that the disciplines necessary to controlling failure rates are followed.

GENERAL RELIABILITY POLICY STATEMENT

It is totally unsatisfactory for the general manager of a missile company to meet a customer demand for a reliability program merely by creating a reliability engineering group. Reliability achievement requires a positive series of actions at all levels of the organization. This series of actions must start at the top and be generated down with the full weight of line organization authority.

A general manager can discharge his responsibility by issuing a "General Reliability Policy Statement" provided that this statement is specific and comprehensive enough to cover (1) Purpose, (2) Organization, (3) Practices, (4) Personnel and (5) Audit. Each of these items will be discussed in the following sections of this paper.

RELIABILITY POLICY STATEMENT-PURPOSE

The general reliability policy statement of purpose should be derived from the above list of underlying causes. The following is a model statement:

I. PURPOSE

The John Doe Company will maintain a company-wide reliability program. The purpose of this program is to attain maximum systems effectiveness within available funds by providing organized knowledge and by enforcing effectiveness disciplines for prediction, control, measurement, and reporting of both normal and infrequently occurring modes of failure.

RELIABILITY POLICY STATEMENT-ORGANIZATION

The policy statement on organisation should not deal with organization chart details. Such details may result from expediency and be subject to change. It should deal with those aspects of organization that are vitally important to reliability achievement and fundamental enough to have long term stability.

The question "Who is responsible for reliability?" does not lend itself to a helpful answer because reliability activities are so widespread throughout an organization that only the general manager can be responsible for all aspects.

Much more useful answers can be generated by asking four questions. "Who is responsible for reliability research, who is responsible for reliability creation, who is responsible for reliability assurance and who is responsible for project reliability management?". The following model general reliability policy statement follows this pattern.

II. ORGANIZATION

(a) Reliability Creation. The design departments are and will continue to be responsible for building reliability into their designs The purchasing and manufacturing departments are and will continue to be responsible for building reliability into production hardware.

(b) Reliability Research and Assurance. A reliability director reporting directly to the general manager will be responsible for ensuring that the knowledge, practices and skills required for reliability creation and reliability assurance are developed and made available as needed throughout the organization.

(c) Reliability Assurance. Design reliability assurance and pro duction reliability assurance groups will be established either within the engineering and quality departments or reporting directly to the reliability director.

(d) Project Reliability Management. For each project for which a reliability program is established a reliability project manager will be appointed to ensure the coordination and effectiveness of all aspects of the project reliability program.

It should be noted that the above statement of policy permits but does not enforce gathering all the reliability research and assurance groups

together into one line organization under a reliability director. The essential organization requirements are (1) that these groups be established and (2) that the reliability director have centralized functional control over them. Decentralized location and line administration are not incompatible with centralized functional responsibility and control. Table I. illustrates this organizational principle.

RELIABILITY POLICY STATEMENT-PRACTICES

The reliability program must control the detailed activities of every drawing board designer, buyer, manufacturing floor or bench worker, inspector and service support technician. There are two major aspects to accomplishing this requirement.

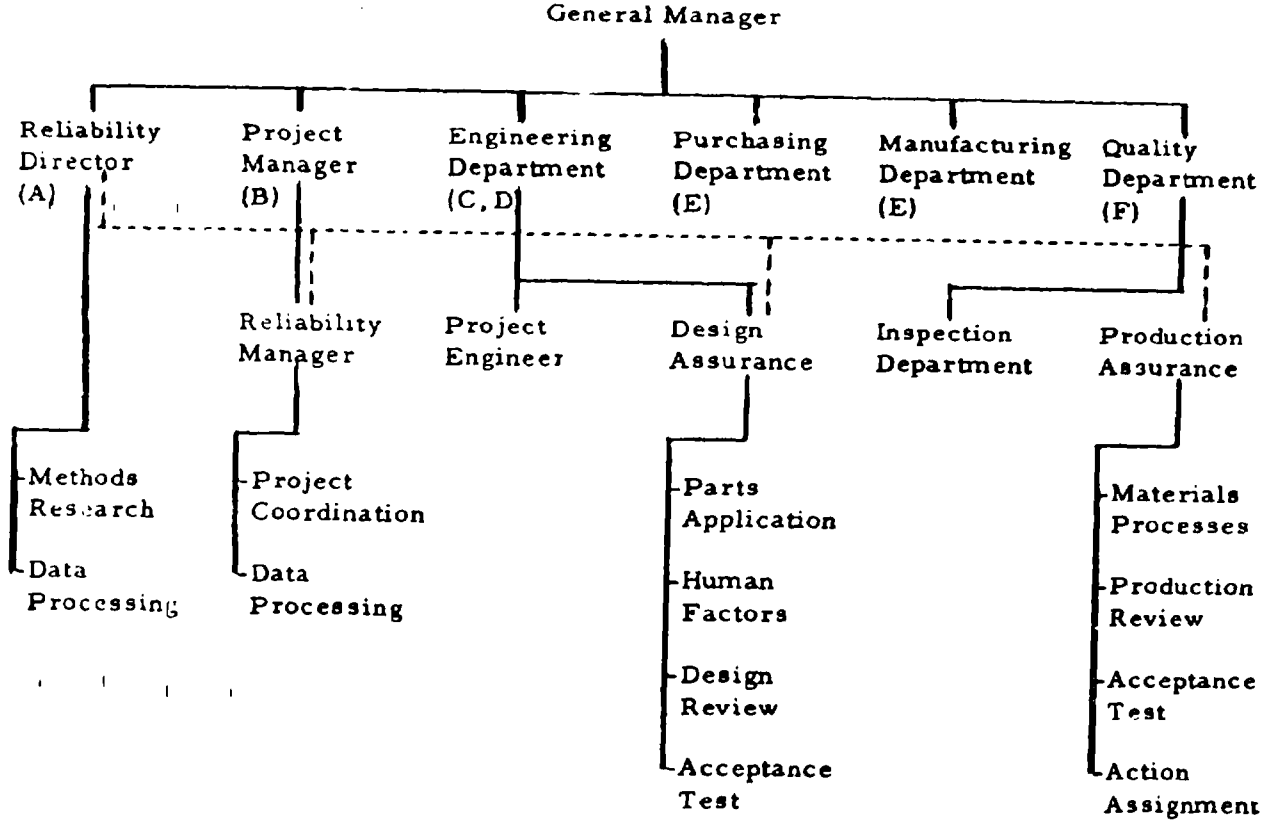
First, every activity that affects equipment reliability must be identified and within each activity required procedures must be catalogued. Table II. presents a list of thirty activities. This list has evolved from the failure analysis process in answer to the question "What specific activity or discipline could management require to prevent recurrence of this failure in the future?". In addition, every Department of Defense specification, policy or contractual requirement for reliability has been checked to ensure that the list of activities was complete. Of course, Table II. shows only brief titles that are subject to misinterpretation as to meaning and scope. The author has completed an "Activities Policy Manual" which includes a model policy statement for each activity and a list of applicable principles that are so fundamental that they apply to all types of organization and product. A book now under preparation further elucidates the nature and scope of each of these activities.

The second requirement is that management discipline within the company must provide for a continuum of documented authority from the general reliability policy statement down to the actual operating instructions used by the bench worker. Both the requirement for identification of activities and the continuum of authority are covered in the following model policy statement.

III. PRACTICES

A continuum of management control over reliability practices will be established and maintained by the following sequence of authoritative documents:

(a) Reliability Policies Manual. The Reliability Director will issue and maintain a Reliability Policies Manual that will,



Note.
For correlation of Skill Groups with Reliability Activities see Table 2.

Table I. Centralized Functional Control by a Reliability Director

RELIABILITY ACTIVITY	RESPONSIBLE SKILL GROUP
A. Reliability Research & Services	Reliability Research Engineers
1. Data, Methods & Failure Cause Research	1. -Materials & Processes
2. Organization of Information, Guides & Data	2. -Parts Application
3. Provision of Skills, Training & Motivation	3. -Human Factors
4. Company Policy & Basic Program Report	4. -Methods Research
B. Project Reliability Management	Reliability Management Engineers
5. Contractual Commitments & Financing	5. -Project Coordination
6. Project Program Plan Preparation & Liaison	6. -Data Processing
7 Task Audits, Reviews & Status Reports	
8. Data Center & Failure Rate Surveillance	
9. Failure Recurrence Control Surveillance	
C. Design Reliability Creation	Design Engineers
10. Design Procedures & Instructions	Consultation by Sub-groups
11. User Requirement & Environment Studies	1, 2, 3, 4, 7 and 8
12. Studies to Allocate, Predict & Improve	
13. Part & Circuit Selection & Stress Analysis	
14. Tests to Failure & Safety Margin Adjusting	
15. Reports, Specifications, Test Plans & Criteria	
16. Failure Recurrence Control by Design Change	
D. Design Reliability Assurance	Design Assurance Engineers
17. Continuous Design Document Reviews	7. -Design Review
18. Monitoring Point Design Reviews & Meetings	8. -Design Acceptance Test
19. Functional & Environmental Proof Tests	
20. Field Analysis of Design & of User Manuals	

E. Production Reliability Creation	Purchasing & Manufacturing
21. Production Procedure Documentation	Consultation by Sub-groups
22. Supplier Selection & Control	9 and 10
23. Manufacturing Self & Supervisory Controls	
24. Parts Screening & Manufacturing Self-Tests	
25. Recurrence Control by Production Change	

F. Production Reliability Assurance	Production Assurance Engineers
26. Production Document Reviews	9. -Production Review
27. In-Process & document Compliance Inspection	10. -Production Acceptance Test
28. Acceptance, & Quality Verification Tests	11. -Failure Action Assignment
29. Factory Failure Reports & Action Assignment	
30. Field Data Recording & Action Assignment	

CORRELATION OF SKILL SUB-GROUPS WITH ACTIVITIES

1. -Materials & Processes	1, 2	7. -Design Review	17, 18, 20
2. -Parts Application	1, 2	8. -Design Acceptance Test	19
3. -Human Factors	1, 2	9. -Production Review	26, 27
4. -Methods Research	1, 2, 3, 4	10. -Production Acceptance Test	28
5. -Project Coordination	5, 6, 7	11. -Failure Action Assignment	29, 30
6. -Data Processing			

Table 2. Reliability Research, Project Management, Creation & Assurance Activities

(1) identify specific activities essential to achieving the above purpose, (2) provide policy guidance for each activity, (3) define departmental responsibilites for each activity.

(b) Reliability Procedure Guides. The Reliability Director will identify all the procedures that must be written by each functional department to implement the Policies Manual and will provide a guide for each such procedure.

(c) Department Procedures and Instructions. Each functional department will issue Department Procedures as required to implement the Reliability Policies Manual and such further Operating Instructions as are required to control each practice.

RELIABILITY POLICY STATEMENT-PERSONNEL

During the phase in which the principle job of the reliability engineer was to spread concepts and to gain attention to reliability from his colleagues, reliability groups could be staffed by "generalists". Now that reliability program implementation requires very specific activities, staffing by generalists is proving to be chronically ineffective. The time as come when extremely serious attention must be paid to the specific skills and training required to make reliability engineering personnel effective. An essential aspect of this study must be to provide long term career growth possibilities for motivation of on-board personnel and for recruiting of new talent.

Table I. lists eleven types of reliability engineering skill and correlates these skills with the reliability activities list. Again, the brief titles used for the skill groups are subject to misinterpretation unless model position descriptions are provided for each. The scope of this paper is limited to emphasizing the extreme importance of having the skill groups well defined rather than providing the position descriptions.

A model general reliability policy statement on personnel is as follows.

IV. PERSONNEL

The specialized skills required for implementation of reliability practices will be identified and job categories established. The Reliability Director will ensure the professional adequacy of these skill groups.

RELIABILITY POLICY STATEMENT-AUDIT

It is extremely important to management understanding to recognise that for procurement of high reliability parts and equipment a traditional relationship between buyer and seller has broken down. Traditionally, the buyer would write a specification describing the performance characteristics that had to be met and the buyer and seller would agree on a test program that would be satisfactory for demonstration of contract fulfillment. For procurement of high reliability the principle of specifying a quantitative value is fundamental but its application is not simple. It is complicated partly by the fact that reliability is a growth characteristic and can best be represented by a curve relating reliability to calendar time. The initial reliability of the prototype is only one point on this curve. It is complicated further by the fact that, with the exception of electronic equipment for which the requirement is a mean time between failure of less than 100 hours, demonstration by testing alone is prohibitively expensive, time consuming and inconclusive. Even if reliability could be demonstrated by testing with reasonable cost and accuracy this demonstration often would come so late in a program that by the time that failure to meet the reliability requirement was recognised the loss of lead time would be catastrophic.

Because the buyer cannot contract for reliability simply by requirements for testing the sellers output, it is absolutely essential to contract for control and visibility of the reliability that the seller builds into his design, purchasing and manufacturing work. It is to be expected that the sellers first reaction to demands for extreme visibility of his internal operations will be resentment. This resentment will be increased if the buyer is not clear on just what type of visibility is needed and proposes to use an excessive number of resident buyer engineers.

This type of problem has been a major factor in BMC/STL development of management methods for the Minuteman Reliability Program. It has been found helpful to convince suppliers that every scrap of information that the buyer is seeking is essential to their own management control over their reliability programs.

Attempts to achieve both management visibility and project control by means of a single "Project Reliability Program Report" covering both the contractors basic practices and the particular project have proved to be unsatisfactory. Major improvements are being gained by requiring a "Company Basic Program Report" and a separate "Project Program Plan". The former document summarizes all the policies, practices and experience of the company that are available for

application to any project. The second document then can be restricted to a catalogue of specific tasks for each of which there is a definite objective, fund allocation and time phasing.

The following is a model general reliability policy statement on audit:

V. AUDIT

Management visibility of the status of reliability practices, skills and project programs will be provided by:

(a) Basic Reliability Program Report. The Reliability Director will issue and maintain a Basic Reliability Program Report. This document will summarize the current status of the policies, procedures, instruction and skill groups that have been developed for implementing any project reliability program.

(b) Project Reliability Program Plans. Each customer requirement for a Project Reliability Program will be met by establishment and execution of a Project Reliability Program Plan. Each such plan will consist of clearly defined tasks prepared in accordance with the Reliability Policy Manual and the Basic Reliability Program Report. Progress reports on each task will be specific and will be distributed to project managers, company management and to the customer.

SUMMARY

In this year 1960, the most urgent aspect of reliability engineering is the need for management methods research and for implementation of methods already developed. Enough work has been done for the reliability engineering profession to offer to management a clear path for constructive action. General management can fulfill their responsibilities and provide effective delegation to the next organizational level by issuing a General Reliability Policy Statement covering Purpose, Organization, Practices, Personnel and Audit and by backing implementation of the policy statement after it has been issued. This symposium can contribute to improved management of reliability programs by spreading understanding among the engineering attendees and by clarifying a course of action for more effective contract requirements among the Department of Defense attendees.

HIGH RELIABILITY REQUIREMENTS PRESENT CHALLENGE TO THE ELECTRONICS INDUSTRY

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Introduction

The task of designing and building reliable electronic equipment is rapidly becoming one of the most important problems in the electronics industry. Reliability has been brought to the attention of everyone in a very vivid manner during the last two years by some spectacular failures in attempts to launch satellites and missiles. The Defense Department is now writing reliability requirements into all contracts for weapons systems. These requirements are already having repercussions throughout the whole electronics industry from component manufacturers and their suppliers to system designers and fabricators. The impact will be felt increasingly within the next few years.

Reliability problems are not restricted to the manufacture of military systems alone. The importance of reliability for industrial applications is becoming increasingly apparent as more and more large scale computers and other complex electronic equipment are being employed by industry. The problems will become increasingly acute as automation with its myriads of components and equipment comes into more widespread use.

Inasmuch as reliability has come to be a major problem, it is desirable to examine the whole subject. What is reliability? What makes the problem so difficult? What is being done and what can be done to design and build reliable equipment? We shall investigate these points very briefly in what follows.

Reliability - An Old Problem in New Form

In order to discuss reliability, it is first necessary to define what is meant by the term. Basically we mean that whatever we are considering is reliable if it almost always works when we want it to. The term almost always suggests that reliability is somehow associated with probability. That is correct. We can never be 100% certain that something will work when we want it to. However, it may be possible to build a system which is likely to work almost 100% of the time. We say, then, the system has a probability of .9999 or .95 or some other positive number less than one. It is sometimes convenient to define reliability as the probability that whatever we are discussing will operate in a satisfactory way when we want it to.

Time usually enters into discussions of reliability. It is not sufficient that everything works in a satisfactory way at the instant a missile is launched. The equipment must continue to operate for a length of time necessary to assure the success of the launching, however long this may be. Thus, when one states reliability requirements, time often appears in the specification, i.e., with probability .98 a computer must operate without a failure for 100 hours. The .98 is called the reliability index of the system.

The reliability problem is not a new one. It has been met and solved with some success in a large number of industries. For example, the manufacturers of light bulbs, electron tubes, and automobile batteries have been concerned with turning out reliable parts for many years. The task facing the electronics industry is of a different order of magnitude, however. Many electronic systems have 50,000 or more electronic components in them. The task of getting all these parts to perform properly is quite different from that needed to be reasonably sure that a single light bulb will operate. In addition, the reliability requirements are often much higher on these complex systems than they are for, say, automobile batteries. If a missile fails on launching, several million dollars are lost. Even worse, national security is dependent in part on reliable systems. When a car battery fails it is only necessary to replace the battery. The only unfortunate result may be a dissatisfied customer.

At the present time, the reliability requirements for very complex electronic systems are often for very short times, of the order of hours or less. These have been very difficult to meet. However, the trends both for military and civilian applications are toward high reliability requirements for very long operating times without maintenance. For example, a successful unmanned flight to Venus or Mars would require the electronic equipment to operate for thousands of hours without maintenance and without a failure. Similarly it is becoming desirable to have missiles sit in readiness for firing for years with little or no maintenance. Equally well it is becoming a requirement that large scale digital computers in industry operate for long periods without failures. The same requirements will have to be met by the electronic equipment in automated factories.

It should be clear that the task of making a very complex piece of electronic equipment operate for long periods without failure is not an easy one. A program of major proportions will be needed in the entire electronics industry to produce such systems.

Facets of Reliability

The manufacture of complex electronic systems which meet certain high reliability requirements is what might tritely be called a cradle to the grave operation. The responsibility extends far beyond the company which designs and builds the system. It begins with the component manufacturers and the suppliers of the component manufacturers. Reliable systems require reliable components and components designed to meet the specific reliability requirements of the system as well as to meet performance

requirements. Next, reliability must be part of the design specifications. Circuits must be designed with reliability as one of the most important requirements to be met. Of course, the manufacturer's process and manufacturing techniques must also be geared to the production of reliable systems. The emphasis on reliability does not even cease when the systems have been produced. It is necessary to record the behavior of these systems during actual operation in the field. When failures do occur, careful analysis must be made to ascertain what caused the failure. Was it a poor component, faulty design, or what? This information must then be fed back to the proper departments as an aid in improving the reliability of future systems.

The management task of assuring the production of reliable systems requires special organizational structures which are seldom found in present day organizations. Reliability requirements extend beyond engineering only, manufacturing only, or purchasing only. The organizational structure must be such that the reliability activities in all areas can be coordinated so that all work toward the final objective rather than having each department work toward its own objectives which may be incompatible with producing reliable systems.

The technical and administrative aspects of producing reliable systems will next be investigated. As we shall see, there are a number of areas in which techniques are not now available.

TECHNICAL ASPECTS OF RELIABILITY

Reliability Apportionment

Reliability requirements for complete systems are now being specified in military contracts. For industrial applications there will be certain minimum reliability requirements if the system is to be feasible. The determination of the actual reliability specification in such a case requires a trade-off study between cost, performance, reliability, and customer satisfaction.

Assuming that a reliability requirement is given for the entire system, it then becomes necessary to break down this requirement into reliability requirements for subsystems, then circuits, and also components. In other words, it is necessary to break down the over-all reliability requirement into something which circuit designers can use and something which can be used to write specifications for component parts.

At the present time, there is no general procedure available for making such a reliability breakdown. The reliability breakdown must be such that in addition to the reliability requirements, restrictions on weight, volume, etc., as well as the performance characteristics, can be met. In order to talk about making an optimal breakdown of the over-all reliability requirement one must have some objective -- such as minimizing the total system cost. The breakdown cannot really be made optimally independent of the circuit design since the design has a marked influence on reliability. In reality the circuit design should be established

simultaneously with the reliability allocation if a true optimal solution is desired. This would include selection of the proper components to be used in the circuit. Here one encounters additional difficulties because the components will often need to be designed specifically to meet the reliability requirements. Any general model for opportioning the reliability must then also consider the probabilities and costs for developing components.

The above discussion points out that the development of a model for optimal apportionment of the system reliability appears to be difficult to develop. A great deal of work must be devoted to finding good ways to break down the system reliability requirement to the circuit and component levels. It is not exactly clear what analytical tools are in use today for this. In reality it appears that most reliability breakdowns are based more upon intuitive judgment rather than upon analytical methods. Whether this is good or bad depends upon how good is the intuitive judgment of the individual making the breakdown.

The Sacred Exponential Distribution

Most of the statistics associated with reliability computations are based upon what is known as the exponential failure distribution. If P(t) is the probability that a system or component which began operation at time zero survives up to time t, then according to the exponential distribution

$$P(t) = e^{-\lambda t} \tag{1}$$

where λ is a constant independent of time, called the failure rate. The probability that the system will have failed at some time between 0 and t is then

$$Q(t) = 1-P(t) = 1-e^{-\lambda t} \tag{2}$$

This is the cumulative probability of failure. The curve is shown in Figure 1.

Differentiation gives the failure density function f(t)

$$f(t) = \lambda e^{-\lambda t} \tag{3}$$

The apriori probability that the system will fail between time t and t+dt is f(t)dt. The mean of this distribution is

$$\bar{t} = \lambda \int_0^\infty te^{-\lambda t}\, dt = 1/\lambda \tag{4}$$

Consequently $1/\lambda$, the reciprocal of the failure rate, is called the mean time to failure. When $t = 1/\lambda$ we see from (1) the probability that the system is still operating is $e^{-1} = .36$ (see Figure 1).

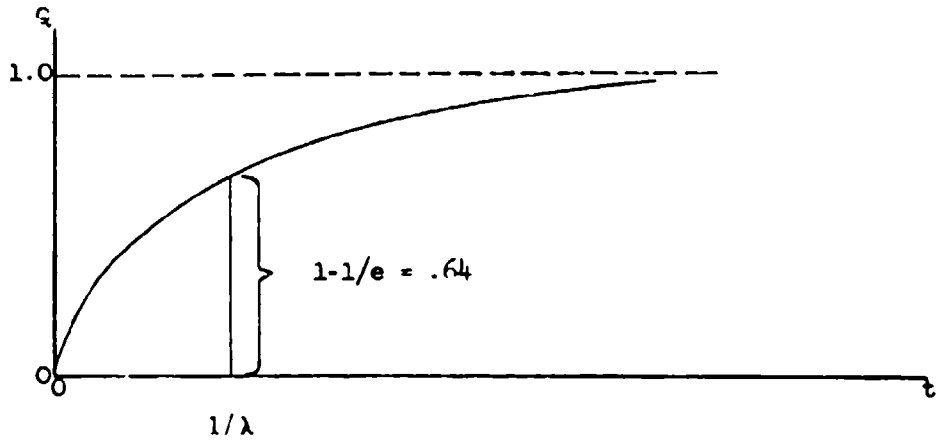


Figure 1. Cumulative Probability of Failure

To compute the probability that the system will fail in the interval t to t + dt given that it has survived to time t, we use the general conditional probability formula (assuming A and B independent)

$$P(A) = P(A|B)\ P(B). \tag{5}$$

Where $P(A)$ is the apriori probability of event A, $P(A|B)$ is the conditional probability of A given that the event B has occurred; and $P(B)$ is the apriori probability of event B; but

$$P(A) = f(t)dt = \lambda e^{-\lambda t}\ dt;\ P(B) = e^{-\lambda t}$$

Thus the probability that system fails between time t and t + dt, $P(A|B)$, given that it has survived to time t is λdt. This is a very interesting result because it says that the probability that a failure will occur in the time interval t to t + dt is independent of how long the system has been operating. This also explains why λ is referred to as a failure rate.

The exponential distribution has some other very convenient properties in addition to those mentioned above. Suppose we imagine a system be formed from a number of parts, each of which obeys the exponential failure rate distribution. Let the failure rate of part i be λ_i. Then if a failure of any one component is independent of the others, the probability $P(T)$ that the system will survive from time 0 to t is the product of the probabilities that each component will survive. Thus if there are n components

$$P(t) = (\exp -\lambda_1 t)(\exp -\lambda_2 t) \ldots\ldots (\exp -\lambda_n t) = \exp -(\Sigma_i \lambda_i)t \qquad (6)$$

Equation (6) shows that the system also obeys an exponential failure rate law, and the failure rate λ for the whole system is just

$$\lambda = \Sigma \lambda_i$$

All these properties of the exponential distribution indicate that it is quite easy to make reliability computations if the assumption is made that everything obeys the exponential failure rate law.

Although the exponential distribution has very desirable mathematical properties, the real question which must be answered is how well does it represent failures of components and systems. The answer to this question does not seem to be available today. Although there is some evidence that failures of certain components obey the exponential distribution, it is not clear (and almost certainly not true) that all components do. Even less can be said about the distributions of failures for complex systems. It is quite important to learn something about these distributions because realistic reliability computations cannot be made without some knowledge of these matters.

It is worthwhile to keep in mind some properties of the exponential distribution. First it can be noted that it does not account for wear out. If a system has survived up to time t, the probability that it will fail in the next time interval is independent of how long the system has been in operation. The probability is the same immediately after the system has been started as it is after the system has been operating for 1000 hours. Ultimately any system will wear out. The exponential distribution also ignores particular failure mechanisms. Essentially what it assumes is that there are a very large number of ways in which a system can fail. The number is so large that failures can be considered to occur at random.

The specification of a mean time to failure can be very misleading if one is not careful. For example, a system which is to operate for one year with high reliability may require a mean time to failure of perhaps 25 years if one uses the exponential distribution to perform the computations. There is no implication here that the system must last 25 years. It may be worn out completely in a year and one day. However, if the systems obey the exponential failure law during the one year of operation, this distribution must have $1/\lambda = 25$ years. The mean time to failure is the only parameter in the exponential distribution, and hence when λ is fixed, the distribution is determined.

For the system discussed above, it may be necessary for one of the components going into the system to have a mean time to failure of 100,000 years. Clearly this number has nothing to do with the length of time over which the component must operate. It is only necessary

that the component operate for one year in the system. The value $1/\lambda$ = 100,000 years determines the exponential distribution for this type of component and thus determines the probability that a component will fail within a year.

Reliability and Circuit Design

One of the most important ways of improving reliability is through circuit design. Unfortunately, however, very few techniques have been developed to aid the designer to devise reliable circuits. Part of the task is to have circuits which will not overload the components under normal operating conditions, thus causing a failure. This problem appears to be reasonably straight forward, involving little more than using suitable deratings on components. Things are not always quite this simple in practice either because performance cannot be sacrificed or because suitable components are not available.

To decrease the likelihood of system failure due to a complete collapse of some component for reasons which lie outside the circuit, it has often been suggested that redundancy in components be used. This has not been found to be too helpful in many cases because the complexity of the switching circuits reduces the reliability to a point where little is gained from redundancy and quite a bit is lost in the parameters of cost, weight, and volume.

Often a system fails, not because a component has failed completely, but rather because some characteristic of the component has drifted with time outside of the tolerances which allow the circuit to perform in a satisfactory way. In order to know if a circuit is reliable, the designer must know how sensitive the circuit is to drift, because nearly all components will drift with time. Essentially no techniques are available at present for performing such analyses although work is underway to develop them. The problem is very complicated if all parts are allowed to drift simultaneously. However, it is quite likely that sufficient information can be obtained by allowing a small number of parameters to vary simultaneously.

In addition to the type of circuit analysis described above, it is also of interest to be able to have some way of computing the possible behavior of systems constructed using components having known probability distributions for the nominal values of the parameter and known distributions for drift as a function of time. In other words, if components are chosen at random from inventory to build a system, what sort of variations can be expected in the system performance due to normal variations in the components. This problem is important from the reliability point of view and for the associated problems involved with interchanging and mating subsystems. Monte Carlo analysis will quite likely be a very useful technique in studying this type of problem.

Individual Component Reliability

The reliability of a complex system depends strongly on the use of extremely reliable components. We must begin by asking what a reliable component is. A reliable component is one which will operate and have all pertinent parameters remain within tolerance for a long enough time and with a high enough probability that the entire system will meet the reliability specifications. The production of such parts requires much more than improved quality control on the production line and better testing procedures. Reliability must be designed into the parts.

In order to design parts which are reliable it is necessary to understand the physical processes which control the manufacture and operation of the component. It is impossible to design a reliable part if one does not know what to do to make it reliable. Unfortunately, with many devices such as transistors, it seems that not enough is known about modes of failure. Only after a considerable understanding of the nature of failures modes and wear-out has been accumulated is it possible to design with confidence a part and production process to obtain the desired reliability. Many things are known today which, if used, could improve the reliability of such devices considerably.

The production process itself is very important in obtaining high reliability parts. A production process which gives wide variability is not satisfactory even though some of the parts may be very reliable. The reason for this is that it appears to be very difficult to determine whether or not a part will be reliable just by making some simple tests on it immediately after it is produced. One cannot rely solely on a testing program to choose reliable parts from a population with considerable variance.

Quality control is needed at each important step in the production process. It is much easier to catch something going wrong at some intermediate step then it is in testing finished parts because a very large number of finished parts may need to be tested to find defects which could be caught by making relatively few tests at an intermediate stage.

In order to obtain components with the desired reliability (no wear-out or drift out of tolerance for given time) the purchaser must be able to write suitable specifications for the component manufacturer. To be able to do this requires the ability to perform the tasks outlined in the previous sections. In addition, there must be a close working relationship between the component manufacturer and the system manufacturer. The most important contribution of this relationship would be better definitions of tolerances. For many technical and other reasons, nearly all tolerances are not reasonable or practical.

Reliability Testing

Reliability testing is an important facet in the manufacture of reliable systems. Many problems arise in reliability testing, however. We shall consider two aspects of the testing problem here: (1) testing of component parts, (2) testing of final systems. It seems to be a quite popular philosophy today to believe that the reliability of a component part of system will be verified by some sort of testing procedure.

Consider first the problem of testing component parts. After these parts have been designed and manufactured, how do we know that they actually meet the reliability specifications? Usually the procedure taken is to place enough units on test in order to estimate if mean time to failure of the component distribution is within a given interval with some degree of confidence. For a component which is supposed to operate successfully with a high probability for a long period, such as five years, several problems are encountered in developing a testing program. First there is generally not enough time available to test any single component for a five year period. Facing this fact, the argument is often developed that an estimate of the mean time to failure with the required degree of confidence can be obtained by testing much larger quantities of parts for much shorter periods of time. This argument is valid if the component actually follows the exponential failure distribution. If the failures are completely random, then a trade-off between the number of parts tested and time is possible. Suppose, however, that a wear out mechanism sets in after three years and every part will fail after four years. This would never be determined by testing parts for only six months or a year. It is a very dangerous procedure to try to compress the time scale on testing without sufficient evidence that this is valid.

Let us assume that the component does obey the exponential failure distribution and that we can test for a shorter period by placing more units on test. A simple computation shows that if components which are supposed to have a very long mean time to failure are to be tested for times not long compared to the mean time to failure, and it is desired to obtain an accurate estimate of the mean time to failure, the number of units which must be tested can easily run into tens of thousands or even hundreds of thousands depending on how accurately one desires the estimate to be. Clearly the amount of money required to carry out such a testing program on a number of components is huge. Furthermore, if the components cannot be made on a high production basis, it may take the manufacturer years to make enough parts for the test program alone.

Finally, let us ask what useful information is gained from the type of test program outlined above. Provided all the assumptions made are valid, we do indeed obtain an estimate of the mean time to failure. However, it tells us nothing about the variability in the manufacturing process with time. It does not follow that the manufacturing process

will always yield such good parts. The process may get out of control and the components will not be as reliable as necessary. When such huge testing programs are required, it is practically impossible to carry out the test once, let alone periodically, to make sure the production process is under control. Hence, it would appear that one must face the fact that it will be extremely difficult to be sure the component vendor's production process is under control simply by using statistical testing procedures.

Let us next examine the system test problems. How do we know that the systems meet the reliability specifications? In many instances it is impossible to devise tests which will simulate actual operating conditions and which will not destroy the systems. Even when it is possible to realistically simulate operating conditions, the number of systems which must be tested and the length of time over which they would need to be tested make the task of demonstrating that the systems have the desired reliability practically impossible. This is especially true when only a very small number of systems are to be built. For example, if two guidance and control systems were manufactured for use on two space vehicles, it is not possible to prove ahead of time much of anything about whether or not these two systems meet the reliability requirements. The final proof is in their operational behavior. It seems to be a property of many systems that we cannot really say much about their reliability until they get into operational use.

The above discussion suggests that the normal statistical experiments become hopelessly costly and time consuming or are otherwise impractical when they are used to attempt to demonstrate the reliability of components or systems. It appears that it will be economically impossible to statistically demonstrate the reliability of components and systems with any high degree of confidence or regularity. Therefore, some other more certain and practical procedure must be used. This assurance should perhaps come from careful design and manufacture with an emphasis on extra systems for functional tests of physical and electronic phenomenon considered critical, unique, or advanced.

One of the most promising areas for testing seems to be in the area of identifying defective parts or systems with a relatively short test. The objective is to test every component and system and to eliminate those which are defective without harming the others. Such tests are often referred to as "burn-in" tests. To develop such tests it is necessary to have a thorough understanding of the modes of failure for the component or system and the types of defects which are most likely to occur. Today not too much is known about suitable burn-in tests either for components or systems.

Another area which is receiving considerable attention is that of accelerated life tests. Attempts are being made to develop tests which increase the severity of some conditions such as temperature, and thereby introduce a failure in a much shorter time than under normal conditions. The whole idea is to be able to develop accelerated tests

which will correlate with failures under normal conditions. The job of developing accelerated tests is a very touchy one, especially if there is to be a very large contraction in the time scale. The difficulty lies in the fact that the accelerated and normal life tests cannot be conducted on one and the same component. For the accelerated life tests to be meaningful at all, the failure mechanism under accelerated conditions must not differ from those under normal conditions. Even if this condition is not (and the task of demonstrating it is met, can be very difficult), the tests are often not practical. This is because extremely large samples must be tested to obtain an accurate estimate of the reliability of the components under normal conditions when the time contraction is very large.

MANAGEMENT ASPECTS

The company confronted with meeting a stringent reliability requirement for the first time faces many management problems. There are financial problems caused by increased costs in rather obscure and intangible areas. There are, of course, engineering, manufacturing and quality problems as outlined above. In addition, questions arise in purchasing concerning vendor-vendee relationships; in industrial relations on the always important questions of skill, training, seniority; and in administration on how to organize for reliability. In short, all areas of activity are affected.

The challenge of reliability, to date, has been met primarily by engineering and quality control. However, some companies, recognizing the more general nature of the problem, have focused attention on organization and the placing of responsibility for reliability. When such responsibility has been delegated it may be found in a variety of places. Some of these appear to be more political rather than practical expedients. In certain instances quality control is charged with the entire responsibility for reliability. In others, the reliability function is to be found completely within engineering; or a committee consisting of members from many departments attempts to advise someone in higher management on what actions should be taken. None of these seems to be very effective. Quality control cannot effectively supervise reliability activities in engineering. Equally well, engineering usually cannot implement a reliability program in manufacturing. There is a further difficulty in having the reliability responsibility lie in a single organization. In such cases it is quite possible that the reliability function will be used to serve the objectives of that particular department and will not be effective. For example, in many companies salary levels are based upon numbers of persons supervised. A zealous manager may tenaciously maintain control over the Reliability Group for this reason although it might be more effective in some other department.

The management aspects of reliability will be discussed in two parts; (1) the short range requirements, and (2) the long range requirements. These tend to be quite different because of the existing nature of the

electronics industry. The transition from one type of management to the other will, no doubt, be slow and gradual.

The Reliability Organization Today

We shall begin with a discussion of the type of reliability organization which might effectively meet the challenge of today. Such an organization must be strong and its manager must have the power to make decisions and to enforce these in any area where the need arises. In many respects reliability people are in the same state today that quality control was some years ago before it really obtained authority to stop production when quality was poor. Until the reliability organization has the authority to make changes, it will be unable to make an effective contribution.

Clearly no reliability program can succeed unless the top management is convinced of the need for it. When the management becomes so convinced, as ultimately it must be if the organization it directs is to survive, the way is open to develop a valuable reliability program. Its first task will be to delegate to some group or groups the primary responsibility for protecting the company's interests in meeting reliability specifications. The responsibility for reliability cannot be suitably delegated, per se, to any one line organization, especially since it must deal with almost all departments. Organizationally, it might be better to have a staff group responsible for reliability assigned to the office of the Chief Executive who operates the Company or Division. Perhaps in some cases, even at a higher level. The proper jurisdiction of this group is the most controversial subject in reliability today. It even transcends the technical discussions revolving about the mathematical concepts of testing and assurance.

Regardless of the above, for present day management structures, it is best for the reliability group to report to some line organization. If management were sufficiently aware of the importance of this group, as pointed out above, it would no doubt report to the Chief Executive. However, since this enlightenment will be some years in coming, the reliability group should report to the first level of management in the Company or Division. Because of the responsibilities involved it should not report at any lower level. The choice of line functions lies between Engineering and Quality Control. This, of course, assumes an independent Quality Control Department which reports to the Chief Executive of the Company.

The state-of-the-art or sophistication of the company's products and management structure will dictate the final selection. For crash programs of significant size and complexity, engineering is the most likely choice. This is mainly because quality control needs technical upgrading and education as well as all other departments. However, for programs incorporated into company activities under normal conditions, quality control should be the department selected. The reasons are

that objectivity and efficiency are of prime importance. Quality Control departments are by nature more orientated in these directions than are Engineering departments.

The management of the reliability function should not be delegated to a committee. The committee method is satisfactory for coordination and liaison needs. However, it cannot be relied upon to supply the drive necessary for a successful reliability program. What is needed is an aggressive forceful approach aimed at uniting and educating all functions regarding their duties and responsibilities concerning this new challenge.

Regardless of the function to which it reports, Reliability will be categorized as a staff organization. However, the head of the reliability organization must in reality be able to make decisions and have them enforced. Such an arrangement is not too uncommon. Many so-called staff organizations do in reality make decisions.

The reliability organization has a number of responsibilities extending from development of components to the study of the operational behavior of the final system. Briefly, some of their responsibilities are:

1. Components:

   Set up reliability specifications on components to be supplied by vendors. It was noted above that in many cases it is very difficult to test components to determine their reliability. Thus, the reliability organization must be able to have some control over the way in which the component supplier designs and manufactures these components. The reliability group must also be involved with decisions in packaging, transporting and storing the components. It should have some control over the purchasing department so that a number of standard practices such as buying from a component vendor, simply because it is the lowest bid, will be abolished.

2. Circuit Design:

   The reliability group must monitor the design of the system's circuit. In many places design review is becoming popular. This appears to be necessary at the present time. It will also probably be necessary for the reliability organization to establish a standard parts list and to prevent use of any parts not on the list unless approved by the reliability group. This is necessary in order to concentrate on improving a relatively small number of components. Sometimes there is a certain sacrifice made by restricting the number of parts, but this is more than made up for by the concentrated effort made to improve the reliability of these parts.

3. Manufacturing:

The reliability group must make sure that the manufacturing process yeilds a system with the highest possible reliability. It must also be sure that practices which are detrimental to reliability are not allowed. For example, if manufacturing runs out of inventory on some component, it must not be allowed to go out on its own and purchase locally some similar component which has a much lower reliability. This is much more than a quality control function. Naturally, the quality control organization will be expected to handle the details of testing, etc., to insure that a product of suitable quality is being produced.

4. Failure Reporting and Analysis:

The task of setting up, coordinating and monitoring a failure reporting and failure analysis system rests in large part with the reliability organization. It is desirable to have a procedure such that each time a failure occurs, it is properly recorded and a detailed study of the component or circuit is made to determine why the failure occurred and what can be done to correct it. An integrated failure reporting system which extends all the way from the component manufacturers to operational systems is a most important facet of a reliability program.

5. Education:

As has been noted previously, an understanding of reliability problems is woefully lacking at almost all levels in many companies. Hence one of the most important tasks of the reliability group is that of education. Management must be educated, designers must be educated, and so must manufacturing and purchasing. Even suppliers and customers need education in certain cases. Naturally the type of education required differs somewhat from group to group, viz: from management to designers. Once some of the educational goals have been accomplished, the burden falling on the reliability group should be considerably lightened.

6. Analysis:

It was indicated in the technical discussion that a great deal of work needs to be done in the area of quantitative reliability analysis. In general, designers or engineers normally found in an electronics company do not have the proper background in statistics, numerical analysis, etc., to allow them to work in this area. Consequently the task of developing these analytical techniques falls to a large extent upon the reliability group.

Needless to say, it cannot be expected that all the above tasks can be carried out by the reliability group alone. They must be done in cooperation with other departments. It should be noted, however, that the above tasks require differing types of people. No single individual could be expected to work efficiently upon all of them. Some jobs require a very practical approach, while others require a highly mathematical approach. Thus, one would expect to find a variety of skills within the reliability group. In the long run the areas of responsibility will not change too much. However, it may not be necessary to have a single reliability organization managing all of them.

The Long Range Organization

Reliability is just another quality characteristic. In fact, it only lends the dimension of time to any other dimension or functional characteristic. For this reason, reliability will eventually take its place along with all others in the part or product specifications. It will be dealt with in much the same manner as industry today deals with any other quality characteristic. Engineering will be responsible for its incorporation into the product and processing specifications. Manufacturing will be responsible for the reliability of parts, components, and systems produced. Quality Control will be responsible for the measurement of reliability to assure that the specification was met.

For the long range program, the main change will be in management's attitude toward some of the so-called non-productive functions of the organization. The three areas slated for the most attention are quality control, purchasing, and certain engineering services such as components and materials, and standards groups. The emphasis will be on education and strict adherence to jurisdictional lines for the discharge of responsibilities. Progressive organizations will have extensively supplemented formal education programs with in-plant training programs. For example, in some years to come, all employees in a large electronic company, from the lowest level of supervision up, will have the equivalent of a BSEE today. In addition, they will have had extensive formal training in the technical aspects of quality control, procurement, and industrial relations. Today this need for cross-polonization is very acute. It is the principle reason for "projectizing" such functions as reliability.

With an improvement in the general level of technical understanding for the various functions, lines of responsibility may be more clearly defined. Authority will be delegated to departments which can discharge the responsibility most efficiently. The role of technical personnel will be one more of support rather than action.

For instance, it will be possible to delegate to quality control the responsibility for measuring reliability. Such delegation will penetrate all areas of the company including research and development.

Since the quality control specialists will then be able to understand the scientific explanation of the phenomenan to be measured, the task of making such measurements may be delegated to quality control.

In examples, such as the above, where the very existence of the company or an important project depends upon the accuracy of facts and their analysis, it may be necessary to so divide the tasks. Engineering or research responsible for creation, quality responsible for measuring, testing, and analyzing.

Similarly, with procurement, reliability will present many interesting changes to modes and methods of operation. The improvement of components which are used in advanced electronic systems will affect not only engineering, procurement, manufacturing, and quality control, but also fiscal and legal departments. The task of improving the components which go into electronic systems will fall upon the component manufacturers. However, the funds required for improvement programs may in many cases come to the component manufacturer from the system manufacturer in the form of contracts. This means that the system manufacturer will want to have some control over what the component supplier does. In turn, this implies that the system manufacturer will want to know something about the manufacturing process for the components. The system manufacturer may even wish to go so far as to have its engineers examine the component production process periodically to make sure that high reliability standards are being maintained. Such an arrangement is completely contrary to the present state of affairs where component manufacturers tend to be rather secretive about their manufacturing process or at least parts of it.

Furthermore, in many cases the money for improving components may come from the military -- either in direct contracts to the component manufacturer or indirectly from the system manufacturer. Quite possibly the government will require that a lot more information be released for general use than the component vendor would like.

Because of the above requirements, one can expect that a new relationship will be required between the component vendors and users. One can go on and ask what will happen to those component manufacturers which do not receive large contracts to improve their parts. They will either be forced to use their own money for improvement or be faced with loss of markets. Here again there are many problems to be faced.

SUMMARY

The gist of the above is that organization for reliability in the short range is being done along project lines. This is caused by the present differences in levels of technical ability of the various departments or groups involved. Over the long range, the need for a

special group called "Reliability" will vanish as standard departmental functions become able to absorb their responsibilities. This will become possible as the technical levels of all functions improve until finally all engineers and specialists in purchasing, quality control, and manufacturing are more knowledgeable in electronics methodology. At that future time, organization charts will look much as they do today, and reliability will be another characteristic specified by engineering and measured by quality control.

R AND D ENGINEERING RELIABILITY PROGRAM

AT MOTOROLA'S WESTERN MILITARY ELECTRONICS CENTER

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Scottsdale (Greater Phoenix), Arizona

INTRODUCTION

In the past decade reliability has been properly recognized as one of the major factors that determines the worth of electronic equipment. We are glad to see that reliability is now considered simultaneously with other worth factors such as performance, weight and size, maintainability, cost, operability, and producibility.

Motorola recognizes the importance of reliability in military electronic equipment. We have been increasing reliability through both internal programs and participation in external industry-wide programs. Our approach for achieving an acceptable reliability level within economic limits is detailed in the following discussion.

TOP MANAGEMENT SUPPORT

Top management at Motorola has long recognized the necessity for increasing the reliability of military electronic equipment. Of more significance has been the willingness to finance reliability effort prior to such effort being contractually required.

Dr. Daniel Noble, Executive Vice President of Motorola, is well-known for his speeches and publications on Reliability. Mr. Joseph Chambers, Vice President and General Manager of WMEC, was the original Chairman of the Department of Defense Adhoc Group on Reliability of Electronic Equipment and recently was industry's representative on the Congressional Advisory Committee on Reliability to the House Committee on Appropriations. Several papers on reliability[1] have been presented and published by Dr. Robert Samuelson, Assistant General Manager. Mr. A. S. Hume, Manager of our Communications and Navigation Laboratory, was Task Chairman of Task Group 2 for the Advisory Group on Reliability of Electronic Equipment Report (AGREE), June 4, 1957.

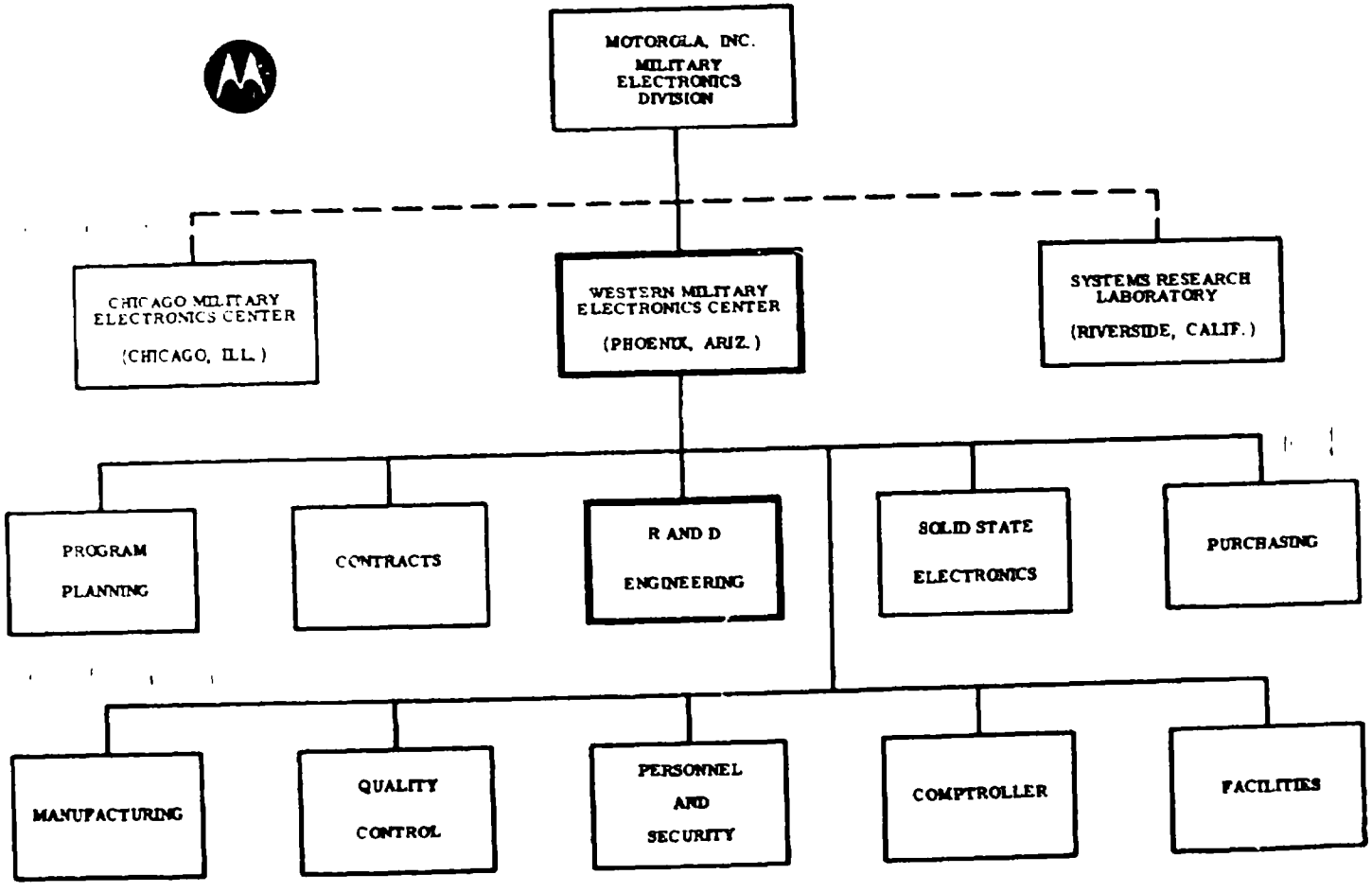
Other Motorola personnel are members of and in some cases the chairmen of various reliability and components committees in the Aerospace Industries Association, Electronics Industries Association, Institute of Radio Engineers, and American Society for Quality Control. Also, many papers on reliability have been presented and published by our Chief Engineer, Reliability and Components Group Head, and several other Reliability and Components Group personnel (See References).

ORGANIZATION

Our particular approach to reliability is designed to blend with our basic organization and with the type of business we seek. Motorola's Western Military Electronics Center (WMEC) at Scottsdale (Greater Phoenix), Arizona is one of 3 primary Motorola Military activities. Other activities are the Chicago Military Electronics Center (CMEC) and at Riverside, California, the Systems Research Laboratory. The Phoenix operation is primarily concerned with electronic equipment for manned and unmanned airborne vehicles, and the associated support equipment. Our customers include all services, either directly or indirectly through other contractors, and Governmental Agencies.

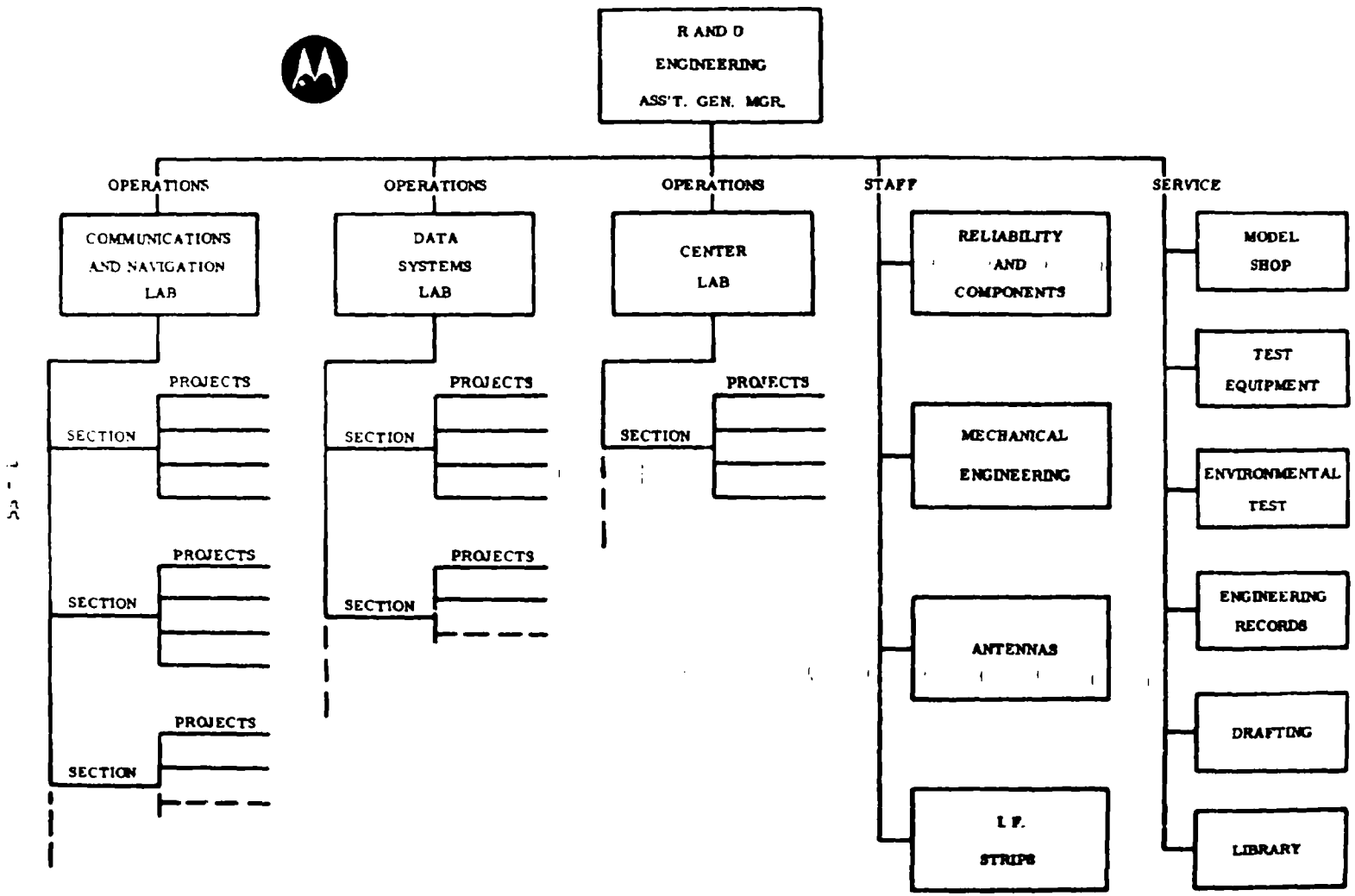
At WMEC we have the departmental breakdown by basic functions into Contracts, R and D Engineering, Purchasing, Manufacturing, Quality Control, and other typical groupings. Figure 1 illustrates this organization. The R and D Engineering Department is fundamentally on a project basis. Current total engineering manpower is around 900. Management firmly believes that a strong project approach with a design team devoted to a single project is optimum. This approach is shown in Figure 2. There are 3 R and D Laboratories, where each Laboratory has 4 or 5 Sections and each Section 4 or 5 Projects. Supporting the R and D Projects are centralized Staff and Service Groups, which have specialists and facilities in areas necessary to sustain the R and D operating projects.

Reliability functions in the R and D Engineering area are centralized in the Reliability and Components Group. Figure 3 illustrates this group's functional organization. The reliability functions of the Reliability and Components Group (as shown in Figure 3) will be discussed subsequently and as pertinent.



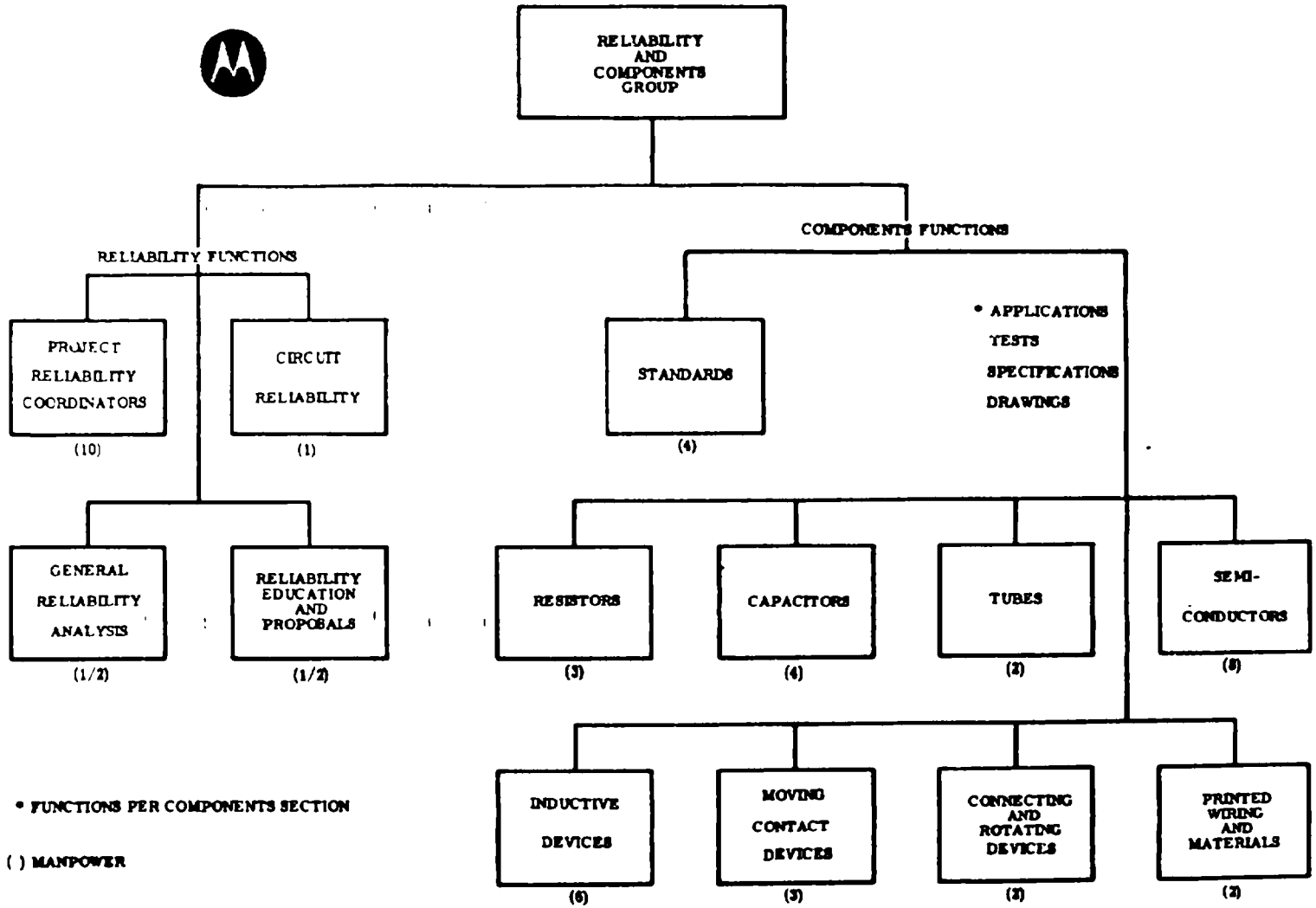
MOTOROLA'S WESTERN MILITARY ELECTRONICS CENTER'S ORGANIZATIONAL PERSPECTIVE

FIGURE 1



MOTOROLA'S WMEC R AND D ENGINEERING DEPARTMENT

FIGURE 2



FUNCTIONAL ORGANIZATION OF THE RELIABILITY AND COMPONENTS GROUP

FIGURE 3

RELIABILITY EXPERIENCE

Motorola's ability in the area of reliability is a result of direct experience as well as management support of general reliability programs. Considerable experience in attaining reliability has been gained from our standard reliability program. This standard reliability program is a basic effort that reaches all projects, and is presented in the following section. Where the customer recognizes the reliability need through additional funding specifically to achieve reliability, further effort above the basic program is applied. Several such programs where additional reliability effort was funded are cited below.

Several years ago we re-engineered an existing electronic control system used in the Navy's Terrier Surface-to-Air missile.[2] The redesign was aimed expressly at higher reliability, and results were significant. During design approval flights at the Naval Ordnance Test Station, China Lake, California, no failure was ever attributed to the Motorola designed control. Concentrated reliability effort is presently being applied on such important efforts as the Guidance Beacon for the Bomarc missile, B-58 IFF equipment, the guidance unit for the Sidewinder missile, and Command Receivers for the Man-in-Space project and the Minuteman.

STANDARD RELIABILITY PROGRAM

A feasible plan for achieving acceptable reliability within economic limits is incorporated in our standard reliability program that is outlined below. The standard reliability program is a minimum effort that directly and indirectly reaches all projects.

Standard Reliability Program

A. Reaches All Projects
B. No Additional Project Funding
C. Basic Reliability Approach
    1. Use Reliable Parts
    2. Design for Reliability
    3. Test to Uncover Weaknesses
D. Reliability Indoctrination Efforts
E. Reliability Control Measures.

Several elementary but fundamental points represent the starting place of the development of our reliability program. The worth of

electronic equipment is determined by several factors--performance, weight, size, cost, operability, maintainability, reliability, producibility, and safety. In each individual equipment the various factors will often be different in importance. For the reliability factor, we have a basic effort that reaches all projects. In addition to this basic effort, reliability efforts are emphasized where the individual situation warrants. Thus reliability takes its proper perspective in the total viewpoint.

In the development era of electronic equipment several elements are highly significant in achieving reliability. Our development reliability program entails the pursuit of these elements, which are:

1. Use reliable component parts,
2. Design electrically and mechanically for reliability,
3. Test early to uncover weaknesses.

In our basic reliability program the project design engineers are made aware of the importance of these elements, and are assisted in properly applying these elements. Each of these elements is discussed below.

The responsibility for achieving reliability, as well as for achieving performance, remains with the individual who can best achieve desired results--the project design engineer. He is supported by company-wide programs for increasing reliability in each of the above elements. Engineering management exerts positive control on project reliability efforts by formally reviewing the reliability elements at periodic project reviews. Reliability educational efforts are significant in our approach, and are discussed in a subsequent section.

Use Reliable Component Parts

Selection of reliable component parts and provisions for ensuring their high quality during subsequent procurement are prime requisites in developing and building reliable electronic equipment. The component parts aspect of our standard reliability program is oulined below. We believe that our systems and circuits engineers should not have to be proficient in component parts, and have specialists in this area. Component parts activity is centralized in the Reliability and Components Group that was formed in 1953 within our Terrier Project and expanded into a service for all projects in 1955. All component parts have been divided among 8 Sections where each is responsible for testing, applica-

tion, procurement documents, and standardization. Eighteen engineers and 20 technicians comprise the component parts specialists staff (see Figure 3).

Use Reliable Parts

A. Centralized Component Part Specialists

1. Application
2. Testing
3. Procurement Documents

B. Determine Best Part Types and Vendors

1. Past Experience
2. Screening Tests
3. Tests to Failure
4. Vendor Facility Surveys

C. Control Vendors with Adequate Procurement Specifications and Perform

1. Qualification Tests
2. Lot Acceptance Tests
3. Requalification Tests

D. Standardization Program

1. MIL for standardization
2. Company (standard specs) where reliability stressed

E. Project Level Implementation

1. Approach Planned at Inception
2. Controlled by Management and Specialists Thru Reviews.

Motorola has supported an extensive centralized parts testing program, including tests to failure, multi-level stress testing, and each of which is methodically documented. In addition, we have participated in various inter-company sponsored tests. Visits to the manufacturing facilities of the various suppliers of component parts have provided important supplemental information. Feedback of part failure information from Incoming

Inspection and the manufacturing process is handled by Quality Control, and represents another input source to our parts specialists. We also report results of the above part information sources to our vendors in an attempt to secure product improvement. Such part information has led to the objective selection of part types and vendors.

Component part types commonly used and vendors selected by the part specialists are presented to our projects through the Motorola Military Division Standard Parts Catalog. Two classes of component parts are included, strict MIL component parts and parts with reliability significantly improved over the MIL level. Strict MIL parts are procured to the MIL documents. We know that many parts are better than the MIL reliability level from the results of our testing program. Motorola has prepared its own specifications for the better than MIL parts.[3] These specifications follow the MIL format, but have more rugged tests and test sequences, require more specimens, allow fewer failures, tighten electrical requirements, and have provisions for periodic reassurance tests, including penalty clauses for failure. We started preparing such specifications in 1957, and now have 36 specifications and 96 associated drawings. As state of the art MIL specifications are issued, we obsolete our company specifications. For the more special parts not suitable to standardization, as a minimum we prepare a drawing with general requirement notes and perform limited evaluative tests. Where reliability and/or high production are pertinent, we prepare a full specification and perform the qualification tests.

Each project's component parts approach is preliminarily planned at the proposal era, and is firmly planned at the project's inception. Project personnel are assisted by the Reliability and Components Group in planning a parts approach. The Standards program having both strict MIL and company high reliability parts allows each project to emphasize standardization through MIL parts or to emphasize reliability through high reliability parts. Several control measures exist with respect to the actual implementation of a project's planned component parts approach. R and D Engineering Management, at the Laboratory Manager level, approves each project's approach. Each project periodically circulates its part type and vendor selection to the Reliability and Components Group, Quality Control, and Purchasing for information and comments. Also, copies of all parts purchase orders are sent to the Reliability and Components Group for information and comments.

Design Electrically and Mechanically for Reliability

Reliable equipments result from thorough electrical and mechanical engineering that provides adequate safety margins for the end-use operating conditions. In our previously discussed component parts efforts, we have learned the capabilities of the parts selected for use. Reliable circuits are the direct result of adequate allowances for the limitations of the basic building blocks, component parts. Following are the outline and discussion of designing for reliability.

Design For Reliability

A. Electrical Design

1. Reliability Estimates
2. Simplicity
3. Proven Good Circuits
4. Derating of Parts
5. Part Variations
6. Redundancy Where Necessary.

B. Mechanical Design

1. Minimize Environmental Effects
2. Balance Among Reliability, Maintainability, Cost, Producibility, Operability, Size and Weight.

C. Project Level Implementation

1. Design Aids Available
2. High ME:EE Ratio
3. Controlled by Management and Specialists Thru Reviews.

Reliability estimates at the paper design stage allow comparison of reliabilities of different approaches and indicate the degree of effort required for various sections of the equipment. In the electrical design area reliability is enhanced by designing circuits that are tolerant to appreciable and realistic variations in part values and supply voltages, using a minimum number of parts adequately electrically and environmentally derated, and coordinating circuit functions to achieve simplicity.[4,5] Whenever feasible, designers make use of available designs which have proven good during field use. Circuit design is the primary responsibility of the project engineers. These designers are

educated to the above electrical design considerations through various mediums subsequently discussed in the section on Reliability Indoctrination Efforts. The project engineer is assisted by being provided, when he starts his paper design, with information on part limitations, parameter variations, recommended deratings, and other application data. As part of our standard reliability program, such guidance information is contained in our Reliability and Components Handbook, and Standards Catalog.

Particular attention is given to mechanical design in order to minimize the effects on component parts caused by the environments of temperature, humidity, vibration, shock, pressure, radiation, and dust. We have a ratio of 1 to 6 for mechanical to electrical engineers, insuring that environmental stresses are adequately considered. Mechanical engineers are assigned to projects, and packaging approaches are coordinated by our Mechanical Engineering Lab Specialists. The Mechanical Engineering Lab consists of Specialists (12) in thermodynamics, structures, shock, vibration, acoustics, and theoretical mechanics. Mechanical design guides are published in the Mechanical Engineering Memoranda Manuals as guidance for project mechanical engineers.

Control measures on actual electrical and mechanical designs are the periodic project reviews. Periodically throughout a project, normally at 6 week intervals, the Laboratory Manager, Chief Engineer, Section Head, and staff groups' representatives review each project. Potential design deficiencies are brought to light for early correction.

Test Early to Uncover Weaknesses

Careful attention to the design practices just described greatly reduces the number of reliability problems showing up during subsequent manufacturing and use. Exhaustive testing of breadboards, and early and final prototypes uncovers remaining weak areas for corrective action before production release. This aspect of our approach to reliability is outlined and discussed further below.

Test For Reliability

A. Locate Weaknesses for Correction

1. Bench Tests
2. Environmental Tests

B. MTBF or Reliability Test (where reliability emphasized)

C. Project Level Implementation

1. Approach Planned at Inception
2. Controlled by Management and Specialists at Reviews.

Systems breadboards, using the same component parts as planned for the final equipment, are assembled and bench tested early in the program to uncover interaction probems. Critical component part parameters and supply voltages are varied in value during equipment bench tests to help prove adequate performance safety margins. Equipment prototypes are operated at environmental extremes to demonstrate endurance against failure. Equipment performance variations measured during both bench and environmental tests are analyzed with the aid of statistical techniques to establish manufacturing and end use tolerances.

As with reliable design practices, testing of breadboards and prototypes by projects is controlled by periodic project reviews attended by engineering management and staff group representatives.

RELIABILITY INDOCTRINATION EFFORTS

We believe that reliability indoctrination is an important part of a reliability program. Our indoctrination methods include both direct and indirect approaches, as shown in the following outline.

Emphasis on Reliability Indoctrination

A. Reliability and Components Handbook
B. Mechanical Engineering Manual
C. Inplant Reliability Course
D. Project Reliability Coordinators
E. R and C Group Reports
F. Junior Engineering Training Program
G. College Courses
H. Participation in Industry-Wide Reliability Efforts.

Our Reliability and Components Handbook, initially issued in 1955 and periodically revised, is personally issued to every engineer.[6] To date over 700 handbooks have been issued, with around 300 of these going

outside of Motorola. The Table of Contents of our handbook is shown as Appendix B. An extensive transistor circuit design check list recently issued has been well received by our design engineers. Just recently the fourth presentation of our inplant Reliability Short Course was completed. Course content is shown below.

Content of Motorola WMEC's Reliability Short Course

Session 1a.	Introduction to Reliability
Session 1b.	Component Parts Program
Session 2a.	Parts Procurement Documents
Session 2b.	Parts Standards Program
Session 3	Mechanical Aspects
Session 4	Reliability Analysis I, Reliability Models and Measurement
Session 5	Reliability Analysis II, Component Part Value Variations and Appropriate Circuit Design Techniques
Session 6	Reliability Analysis III, Part Derating, Redundancy, and Reliability Estimating.

About one-half of our design engineers have attended the course, and we plan to periodically repeat the course.

Reliability Coordinators (reliability specialists assigned to projects emphasizing reliability, discussed below) and other engineers working in reliability areas meet every 2 weeks for several hours. At these meetings, which are analogous to seminars, pre-selected reliability topics are presented and discussed. These meetings help keep our reliability engineers abreast of the state of the art and allow them to swap notes on their problems and solutions. New junior engineers are assigned to the Reliability and Components Group for 3 to 4 weeks, as well as to other R and D Engineering staff and service groups, Quality Control, and Product Engineering. Engineers completing this sequence of assignments obtain an excellent appreciation of the methods and value of engineering for reliability and producibility. Junior engineers who will be designing circuits attend an extensive 10 week semiconductor circuit design course.

Through several years of correspondence and discussions we have assisted several engineering colleges in introducing reliability concepts into their curriculum.[7] In cooperation with the University of Arizona, our personnel have instructed a graduate-credit course, Reliability and Engineering Statistics. We attend and often present papers at all important reliability symposia and conventions, as well as actively participate in several AIA, IRE/ASQC, and EIA working committees. This keeps us well informed on the state of the art in systems and component part reliability.

PROJECTS EMPHASIZING RELIABILITY

Our standard reliability program enables us to produce more reliable equipment at competitive prices even though reliability has not been emphasized by the customer. Where the customer recognizes the reliability need through additional funding specifically to achieve higher reliability, further emphasis is put on the practices followed in our standard reliability program. Highlights of the emphasis are outlined below.

Project Emphasizing Reliability

A. Project Reliability Coordinator/Staff

B. Emphasis of Same Fundamentals as Standard Program

1. Use Reliable Parts
2. Design for Reliability
3. Test for Reliability

C. Additional Funding.

The exact nature of the reliability emphasis is individually planned for each such project. Emphasis includes providing a reliability coordinator engineer and assistants, if necessary, in the project area. The coordinator monitors those project-engineering activities that primarily affect reliability and provides a liaison between the project and the staff groups. Note that the coordinator is a Reliability and Components Group man attached to the project. As such, he has a line of communication through the Head of the R and C Group to the Manager of R and D Engineering in the event the project is jeopardizing reliability. (See Figure 3.) Detailed duties of our Reliability Coordinators are shown as Appendix A. Currently we have 10 coordinators.

In the component parts area we will usually use the highest reliability parts as covered by our company specifications, and will prepare complete specifications for and qualify special parts. Further, in a project emphasizing reliability, additional manhours will be provided for designers to more thoroughly analyze circuits and packaging. In the testing area a formal Mean Time Between Failure test is performed, as well as more exhaustive bench and environmental testing of equipment models to uncover weaker areas.

Funds for these additional efforts are paid back many times by the maintenance savings during field use, as well as the added availability of the equipment through increased reliability. Additional funds will vary up to 15 per cent of the development funds.

SOME RELIABILITY MEASURES

Reliability measures of our equipment are collected by the Reliability Analysis Section of the Reliability and Components Group. Such reliability measures will serve management in appraising our effectiveness in achieving reliability and are necessary in developing accurate reliability estimating techniques.

Table 1 contains reliability measures t[illegible] have. Obtaining data for such measures is difficult, as in most cases obtaining quantitative reliability measures is not a primary objective of the task that produced the data. However, if the advent of contractual reliability requirements and associated tests continues to grow, we will obtain more such data. Currently we have several contractual reliability requirements and tests that will soon yield more accurate data.

CONCLUSIONS

We believe that our approach to reliability is wisely balanced. Those functions affecting reliability that are best accomplished by a centralized authority are delegated to staff groups. The individual designer is permitted the freedom [illegible] attain necessary equipment reliability commensurate with his project's total requirements. Our reliability effort is based on education and cooperation. Periodic reviews, conducted by engineering management and staff specialists, provide a reasonable number of checks upon the progress of a project's reliability efforts.

Table 1

MTF Measures

Equipment			Data Collection			Estimated MTF (Hrs)	
Description	Design Era	Tubes/ Trans/ Others (Qty's)	Type of Hard-ware/Qty	Conditions	Op Time/ Fail	Direct Data	**Future Operation
Electronic Control, Missile	1953-55	89/0/ 747	Advanced Engr. Model/14	Factory, Some Environ. Test	850/21	41	95
Guidance Beacon, Missile	1955	55/0/ 572	Production/ 22	Pre Flight Test	2479/8	310	---
Data Link, Missile	1955-56	0/97/ 790	Production/ 22	Pre Flight Test	5744/24	240	---
Radio Control AN/MRC-66							
Subscriber	1956-57	63/6/ --	Early Engr Model/32	Field Test	13840/91	152	256

Table 1

MTF Measures (cont)

Equipment			Data Collection			Estimated MTF (Hrs)	
Description	Design Era	Tubes/ Trans/ Others (Qty's)	Type of Hard-ware/Qty	Conditions	Op Time/ Fail	Direct Data	**Future Operation
Central	1956-57	169/18/ --	Early Engr Model/2	Field Test	864/6	144	---
A-G IFF	1956-57	24/41/ 728	Early Pro-duction/15	Pre Flight and Flight	1139/6	190	228
Production* Test, PATE	1957	0/2310/ --	Advanced Engr. Model/1	Factory	12200/7	174	305
Component Tester, B-58	1958	50/619/ 5610	Advanced Breadboard/1	Laboratory	744/1	744	---

*Transistor count and failures for Motorola designed units.

**Discounting 80% of the failures where cause was corrected.

In our approach we do not equate reliability individually to system design or component parts or circuit design or environmental testing or time (MTBF) testing or production. Rather, we equate reliability to the total of such engineering and manufacturing functions. We recognize reliability efforts as a legitimate area of engineering specialization. Our Reliability Group performs the staff functions of keeping abreast of state of the art, advising management, education, and consulting. Where reliability is emphasized on a project, we stress the engineering elements affecting reliability and have a Reliability Coordinator as part of the project.

Thus we treat reliability specialization as a staff function and do not have separate reliability controlling line operations. Perhaps in the furture, the nature of electronic equipment development may be such that it must be controlled in an analogous manner to the typical Quality Control exercising surveillance over Manufacturing. If such becomes the case, we would approach this as total engineering control and reliability would be one part of this total control.

This discussion has been about our reliability approach in the R and D Engineering phase. Reliability considerations are very important in the production and field use phases. Our Product Engineering and Quality Control activities provide continued attention to reliability considerations after the R and D Engineering phase.

Motorola's reliability program is the result of an early appreciation of the importance of reliability by our management and of many years experience in producing reliable equipment. We believe that our tested and efficient program can satisfy Military reliability requirements.

References (some recent publications):

1. "Design for Reliability," R. E. Samuelson, ORDNANCE, January-February, 1959.

2. "Terrier Electronic Reliability," Russ Yost and F. E. Dreste, MISSILES AND ROCKETS, December, 1957.

3. "Guided Missile Reliability Through Improved Component Specifications," R. E. Roberts, PROCEEDINGS OF 5TH NATIONAL JOINT MILITARY-INDUSTRY GUIDED MISSILE RELIABILITY SYMPOSIUM, December 1958.

4. "Improve Circuit Reliability," C. A. Krohn, ELECTRONIC DESIGN, April 1, 1959.

5. "Circuit Design Concepts for High Reliability," F. E. Dreste, PROCEEDINGS OF THE 6TH NATIONAL SYMPOSIUM ON RELIABILITY AND QUALITY CONTROL, January, 1960.

6. "A Reliability Handbook for Design Engineers," F. E. Dreste, ELECTRICAL ENGINEERING, June 1958.

7. "Reliability and Engineering Colleges," C. A. Krohn, 1958 IRE WESCON CONVENTION RECORD - PART 6, August 1958.

APPENDIX A

RELIABILITY COORDINATOR DUTIES

I. Component Parts Area

A. See that part specification and qualification coverage planning meeting per DI 560/12 is conducted.

B. Insure that optimum component parts are used by consultation with parts specialists.

C. Issue project standards (AVL)

D. Insure that adequate procurement documents exist.

E. Have necessary preliminary evaluative testing and qualification to specifications performed.

F. See that failed parts are submitted to R and C for analysis.

G. Issue instructions to incoming inspection.

H. See that parts planned for final use are used in breadboards at earliest time.

II. Design Area

A. Have reliability estimate performed.

B. Issue project derating guide. Follow up with stress analysis.

C. Issue project component part variation guides. Follow up to see if utilized in circuit design.

D. Issue part failure susceptibility guides.

E. See that thermal, vibration, shock, etc. requirements receive adequate consideration through consultation with mechanical specialists.

F. See that producibility requirements receive adequate consideration through consultation with product engineering/ quality control specialists.

APPENDIX A

RELIABILITY COORDINATOR DUTIES (cont)

III. Testing

A. Assist in planning breadboard and prototype performance and environmental testing.

B. Assist in planning formal reliability measurement test and burn in when such are required.

C. Formulate malfunction reporting process on above tests.

D. Follow up on above testing and malfunction reporting.

E. See that running time records are kept on advanced breadboards and prototypes.

F. Follow up on manufacturing malfunctions.

IV. General

A. Assist in the formulation of operational and environmental requirements through spec review, customer contact, etc.

B. Prepare customer required and/or proj. periodic reliability progress report.

C. Participate in periodic project reviews, follow up on.

APPENDIX B

RELIABILITY AND COMPONENTS HANDBOOK
MOTOROLA INC.

Western Military Electronics Center
Scottsdale, Arizona

Contents

1. GENERAL AND PHILOSOPHY

1.1 TWENTY-SEVEN RULES FOR GUIDED MISSILE ENGINEERS
1.2 SOUND ENGINEERING - THE FOUNDATION OF EQUIPMENT RELIABILITY

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2.1 RELIABILITY AND TIME

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2.1.2 Reliability
2.1.3 Derivation Notes

2.2 MATHEMATICS OF RELIABILITY MEASUREMENT

2.2.1 Mean Time to Failure Computation

2.3 RELIABILITY OF COMBINATIONS

2.3.1 Reliability of a Series

3. DESIGN FOR RELIABILITY GROUND RULES

Paper on "Triad for Design Reliability"

3.1 RECOMMENDED APPLICATION OF COMPONENT PARTS FOR HIGHER RELIABILITY

3.1.1 Derating of Electrical Component Parts
3.1.2 Standard Resistance Values
3.1.3 Choice of Resistance Values
3.1.4 Derating of Electron Tubes

3.2 REALISTIC OPERATIONAL TOLERANCES FOR COMPONENT PARTS AND STATISTICAL APPROACH TO CIRCUIT DESIGN

3.2.1 Variation to be Expected in Resistors and Capacitors
3.2.2 Variations to be Expected in Tubes
3.2.3 Variations to be Expected in Semiconductors
3.2.4 Statistical Approach to Circuit Design

3.3 ADEQUATE TESTING AND RELIABILITY RECORDS NEEDED ON EQUIPMENT MODELS

3.3.1 Failure Reports on Tubes and Parts
3.3.2 Equipment Reliability Records and Reliability Measurement
3.3.3 Setting of Production Tolerances Based Upon Measurements on a Few Units

THE DEFINITION AND DETERMINATION OF MISSILE WEAPONS SYSTEMS RELIABILITY

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Introduction

The purposes of this paper are as follows:

a. To define an index of reliability for artillery missile systems.

b. To outline a method of evaluating the index of reliability referred to above.

There is at present no uniform system or theory dealing with the determination of missile systems reliability. Almost every paper and/or conference pertaining to future missile systems deals in some manner with various aspects of something called reliability. The result is some confusion relative to the definition and measurement of reliability. This paper contains a suggested approach to the problems of definition and evaluation of tactical reliability.

From the standpoint of tactical artillerymen, determination of reliability must ultimately be oriented toward tactical performance, which is intimately associated with the commander's ability to perform his mission. Hence, the whole approach outlined in this paper encompasses those factors which have a direct bearing on tactical performance. The general view is directed toward a method of appraising the extent to which a given weapon system meets a specified set of standards.

The particular factors envisioned as being significant are outlined in Part I of this study. Generally, these factors are based on direct statements from military characteristics. In one or two instances the specific factors are based on contemplated statements for future military characteristics formats.

For present considerations, specific factors which enter the evaluation for overall reliability will be mentioned only as examples. Generally, these factors will be referred to here categorically. The method presented here is not limited to any particular number of factors.

The basic concept under consideration revolves around the definition of reliability, together with a specific procedure for evaluation. Missile weapon system reliability is a measure of assurance that the system will function as required under the operational-environmental conditions and time limits specified in the military characteristics.

PART I
TACTICAL RELIABILITY FACTORS FOR MISSILE WEAPONS SYSTEMS

During World War II and the war in Korea, field commanders were not greatly concerned with reliability of weapons systems. On the battlefield, they had the utmost confidence that they could move their cannons into a position, slam a shell in the breech, and fire away at the enemy. When the artilleryman became of missile age, he discovered that there was a term called "countdown" and another one called "hold." He soon learned that these words meant for him procedures that would greatly change his accustomed mode of operation which we may call "charge--shoot--and be damned." He began to hear the cry "hold" all too often, and began to learn only too well that this meant that his equipment had broken down or one of his men had made an error, or both. It was not long before he began to wonder whether he could employ effectively some of the missile systems that were being turned over to him. At any rate, he soon began to think in terms of reliability or rather in terms of: "what are my chances for moving cross-country and arriving at my firing position in an operational status?" He began to wonder: "What are my chances for checking out this missile within the time allowed me so that I can attack this target effectively?" Such thoughts convinced him that he must have a thorough knowledge of reliability factors in order to plan and execute his field operations. What are these factors, and how do they tie in with field operations?

The tactical commander is concerned primarily with the problem of obtaining worthwhile effects on the target. To get this result, he must move his artillery organization into a firing position from some distant area, establish survey and communications, and acquire meteorology data, if needed. The organization will have to emplace and secure equipment, checkout missiles and warheads, receive the fire mission, and launch the missile. This sequence of operations will frequently change its pattern because events on the battlefield will call for changes. There may be long periods during which target intelligence is being developed, or in fact the targets themselves are taking form. There may be delays in moving the weapons systems into a more favorable position or for establishing the maneuvering ground or airborne forces in an attack position. There may be holds while waiting for the target analysis, selection of appropriate warhead, or the decision to fire. It seems then that missile field operations will frequently be discontinuous affairs.

If these field operations can be separated into major significant phases, the artilleryman can determine his chances for success of each phase under the conditions specified. This is the key to our approach on reliability from the user's standpoint; that is, to determine the chances for success in each major phase of a field operation.

After the artilleryman has acquired the numerical figures that spell out the reliability factors, he is able to plan and execute his operations--

again, probably in major phases--so that he knows where he stands at all times and perhaps can make provisions for improving his chances of success. For example, if a battalion commander was to launch a missile of perhaps 0.75 checkout reliability, he might prepare a second missile and have it on standby in order to bolster his chances for successful accomplishment of the mission. In all of his deliberations, and as reflected in the definitions which follow, the element of time is of prime importance. Time must be considered when we speak of success in field operations.

With this concept as a background, we may proceed to define reliability as applied to the major phases, pre-flight and in-flight portions of the field operation. But, first, it is necessary to define operational status, pre-flight and in-flight.

Pre-flight operational status is the condition that the weapon system (ground equipment and missile) is capable of responding to a fire mission, or, can be brought to such condition within the time limits specified in the military characteristics.

In-flight operational status is the condition that the missile (and such ground equipment as required to function) operates during flight within the design parameters as specified in the military characteristics.

We can define reliability with respect to the major phases of pre-flight and in-flight operations as follows:

Pre-Flight Operations:

Post-movement reliability is the probability that the system (the ground equipment in travelling condition and the complete missile still in containers) will retain pre-firing operational status after.

1. A ground movement with organic vehicles over battlefield roads and cross-country routes of _____ miles (approximately equal to 1/4 the maximum range of the system).

2. An airlift of _____ miles in phase _____ of an airborne operation.

3. A helicopter lift of _____ miles.

Check-out reliability is the probability that the weapon system will retain pre-firing operational status during the period when the ground equipment is emplaced and checked out in firing position and a missile is checked out and assembled on the launcher.

Countdown reliability is the probability that the weapon system will retain pre-firing operational status during the time period

(as specified in the military characteristics) from initiation of a fire mission at the battery to missile lift-off (with no intervening period of standby).

Readiness reliability is the probability that the weapon system will retain pre-firing operational status during the standby period specified in the military characteristics, and will also meet the firing time requirement when the standby is lifted.

In-Flight Operations:

Arming region reliability is the probebility that the missile will provide an arming signal to the warhead when the missile delivers the warhead to a region in space within the maximum arming limits specified in the military characteristics.

Burst region reliability is the probability that the missile and/or warhead section will deliver an armed warhead to a region in space at which the warhead may effect the required coverage of the target.

Warhead reliability is the probability that the warhead will function and will provide adequate yield or munition lethality for effecting the required damage level to the target.

Our interest in the performance of a system extends beyond the single fire mission. We are interested, of course, in the continued operation of the system on the battlefield; thus, operational reliability definitions are extended to the area of durability with the following definitions:

Ground equipment durability reliability is the probability that the ground equipment will retain pre-firing operational status when it is moved a distance of _____ miles _____times each day for a _____-day period.

Missile durability reliability is the probability that the complete missile will retain pre-firing operational status when it is put through a repetitive cycle, a total of _____ times in a _____-day period:

1. Movement for a distance of _____ miles.
2. Checkout.
3. Assembly.
4. Disassembly.

There is one additional definition which does not fit into any of the categories discussed above, but which reflects one of the requirements normally specified for missile weapons systems. This is:

Rate of fire reliability is the probability that the system can engage successive targets and fire missiles at the cyclic rate prescribed in the military characteristics.

And, finally, there is the general category of natural environmental conditions as applied to the functioning of the system. (It has been assumed in all of the previous definitions that the system is operating in a temperate climate, approximately at sea level, in rolling, cultivated terrain, and with low wind conditions.) Reliability under other conditions are defined as follows:

Environmental reliability is the probability that the system will retain pre-flight and in-flight operational status under specified climatic and other environmental conditions specified in the military characteristics for:

1. Temperature, humidity, precipitation, visibility, fungus, insects, sea spray, and dust in:

   a. Cold-dry or cold-wet zones.

   b. Hot-dry or hot-wet zones.

2. Terrain:

   a. Rolling, wooded.

   b. Desert.

   c. Heavy mud, muskeg, or tundra.

   d. Mountainous with little vegetation.

   e. Mountainous, wooded.

3. Barometric pressure equivalent to extremes of altitude as specified in the military characteristics.

4. Winds, gusts and steady, up to maximum specified in military characteristics.

The reliability factors as defined above should provide the artilleryman with the data he needs to plan and execute his operations. If it is desired to evaluate the missile weapon system as a whole, weighting factors should be applied to each of the reliability figures that have been obtained. These factors should reflect the relative importance of each element of reliability. This is a difficult thing to do, but we have looked at our overall requirements and have assigned such

weighting factors. Admittedly, these are arbitrary and they may change for a particular system or with changes in tactical concepts. The weighting factors are:

	Weighting Factors
a. Pre-flight operations:	
(1) Post-movement reliability	
(a) Ground movement	12
(b) Airlift	8
(c) Helicopter lift	4
(2) Checkout reliability	8
(3) Countdown reliability	12
(4) Readiness reliability	8
b. In-flight operations	
(1) Arming region reliability	8
(2) Burst region reliability	32
(3) Warhead reliability	32
c. Durability reliability	
(1) Ground equipment	12
(2) Missile	12
d. Rate of fire reliability	3
e. Environmental reliability	
(1) Temperature, humidity, precipitation, visibility, fungus, insects, sea spray, and dust in:	
(a) Cold-dry or cold-wet zones	2
(b) Hot-dry or hot-wet zones	1

		Weighting Factors
(2)	Terrain	
	(a) Rolling, wooded	1
	(b) Desert	2
	(c) Heavy mud, muskeg, or tundra	3
	(d) Mountainous, with little vegetation	1
	(e) Mountainous, wooded	1
(3)	Barometric pressure equivalent to extremes of altitude in military characteristics	1
(4)	Winds, gusts, and steady, up to maximum specified in military characteristics	1

The next portion of this discussion is devoted to a method of determining the overall reliability of a missile weapon system using the reliability and weighting factors which we have just defined.

PART II
THE DEFINITION AND EVALUATION OF AN INDEX OF RELIABILITY FOR MISSILE SYSTEMS

Any number of specific contributing factors may be used. Several have already been defined in Part I of this paper. For example, countdown reliability is defined as the probability that the weapon system will retain pre-firing operational status during the time period (as specified in the military characteristics) from initiation of a fire mission at the battery to missile lift-off (with no intervening period of standby).

The specific factors referred to above having been defined, the next step is to depict the reliability of each. It is important to note that each aspect of system reliability is defined as the probability of achieving some standard (tactically significant factor) which has already been stipulated. These specifications are usually written, explicitly or implicitly, in the military characteristics.

A convenient method of depicting these probability numbers is simply to plot them as heights of a probability bar graph. The probability of achieving a given specified factor is the height of the approximate portion (bar) of the graph.

The width (base) of each bar of this graph is proportional to the relative importance of the appropriate tactical factors. Thus, the width of each bar represents a priority.

The probability dimension of this graphical plot has a maximum length of 1 unit. Hence, the maximum height of any particular portion (bar) of this graph is 1. If h_i represents the height of the i-th bar, and b_i the base, then the area of the rectangle representing the relative importance and reliability of the i-th factor is

$$A_i = b_i h_i \tag{1}$$

where A_i represents th area of the rectangle. Each such area is called the reliability index for the particular factor (standard) under consideration. It will be noted that the maximum area of A_i is b_i.

A broken line through the mid-points of the tops of these rectangles represents the reliability profile of the weapon missile system under consideration. Figure 2 is a schematic representation of this.

As many tactical factors as desired can be included in the procedure outlined above. Let the length of the graphical depiction be L. Then the width (probability dimension) has already been defined as 1 unit. Hence, a perfect weapon missile system would be represented by

$$L \times 1 = L \text{ square units.} \tag{2}$$

The entire procedure is illustrated by Figure 1. The Index of Reliability I_r is defined as follows:

$$I_r = \frac{\Sigma A_i}{L} \tag{3}$$

It will be observed that the perfect weapon system, as noted above, would be represented by L square units. Hence, the maximum value of I_r is 1. Therefore,

$$0 \leq I_r \leq 1. \tag{4}$$

It should be emphasized that the evaluation outlined above depends on the tactically significant factors specified in military characteristics and their relative importance when compared with each other. This matter of relative importance must of necessity be the subject of considerable study; for no two tacticians would rate the several factors the same. It is not the purpose of this paper to recommend specific weighting factors.

When there is no general agreement pertaining to relative importance of tactical entities, the evaluation of I_r can proceed on the basis of the assumption that all factors are of equal importance. Such a procedure should be used purely in the absence of any better information. In this case, all bases b_i are equal.

A QUANTITATIVE CONCEPT OF RELIABILITY

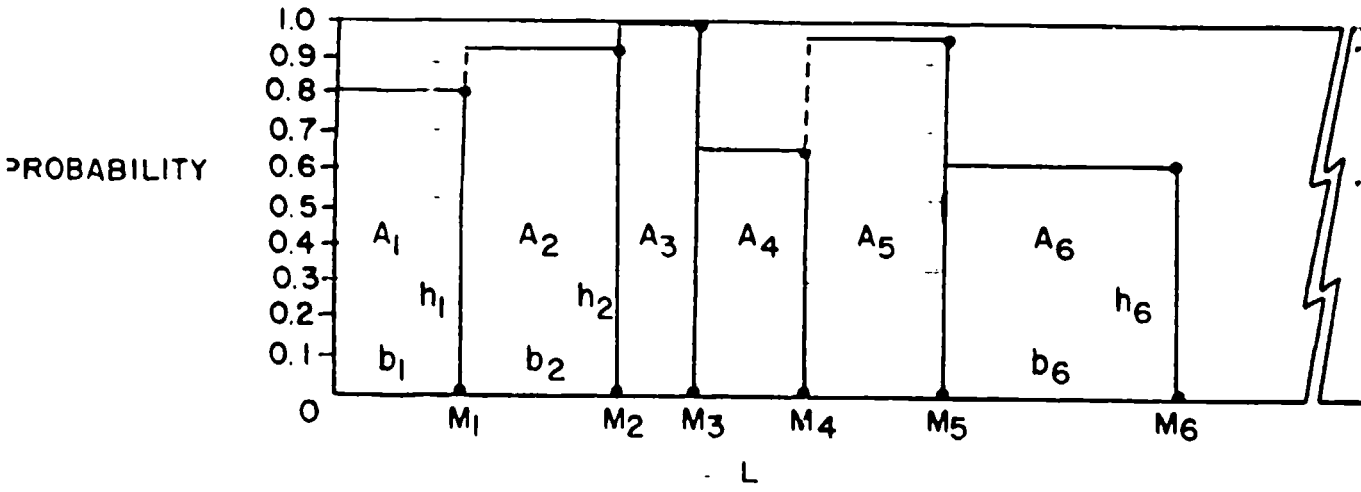


FIG. 1

I_r = Index of Reliability

h_i = Height of the i-th reliability rectangle

b_i = Base of the i-th reliability rectangle

A_i = Area of the i-th reliability rectangle

L = Length of the base of the entire reliability evaluation sheet, from 0 to the last point M.

M_i = The i-th division of L, representing a specified tactically significant factor.

r(x) = Mathematical function describing the reliability-profile curve.

x = Interval measured along L from the point L = 0.

$$I_r = \frac{\sum A_i}{L} = \frac{\int_0^L r(x)\,dx}{L}$$

$$L = \sum_i b_i$$

$$b_i = M_i - M_{i-1}$$

RELIABILITY PROFILE CURVE

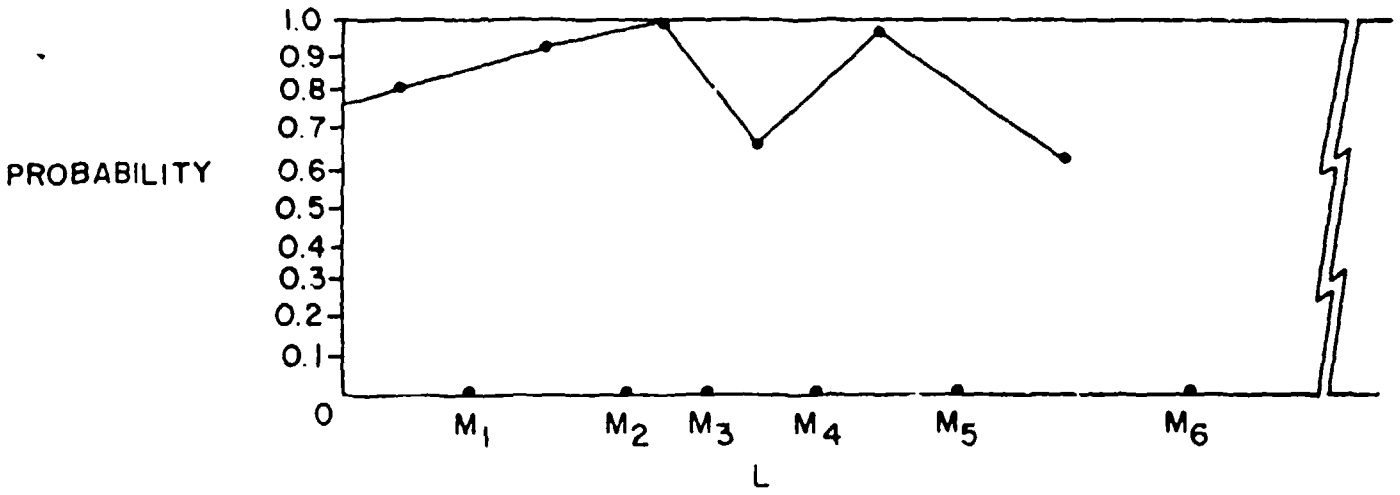


FIG. 2

$$I_r = \frac{\int_0^L r(x)dx}{L}$$

See Figure 1 for explanation of notation.

Dots on the broken line represent mid-points of tops of reliability rectangles.

In equation (3) above, the quantity ΣA_i is merely the total of all reliability rectangles. It can also be regarded as approximately the area under the reliability-profile curve. Let A_r represent the area of this curve. Then, generally,

$$A_r = \sum_i A_i = \int_0^L r(x)\ dx. \tag{5}$$

It is readily seen that the maximum value of A_r is L. Hence,

$$0 \leq A_r \leq L. \tag{6}$$

The concepts and procedures outlined herein represent an approach to the problem of overall evaluation of missile systems reliability. There is a need for standardization with respect to the following:

(1) The number and nature of tactically significant entities to be considered.

(2) The relative importance of these tactical factors.

There will ordinarily be a minimum height for any particular h_i. Below this minimum, the value of A_r will assume the value 0 by definition. The Reliability Index is one measure of reliability. It is not a direct, compound probability of accomplishing a tactical mission, but is a measure related to such a probability. Each M_i is a compound probability, and is calculated by the tactical troops from data collected during field operations and firings. It is a product of subsidiary probabilities. An alternative procedure to that outlined above would be to multiply the probabilities M_i. Let I_m denote this product. Then,

$$I_m = \prod M_i. \tag{7}$$

Hence, a useful concept is one which encompasses both I_r and I_m. This measure is called I_r', and is defined as follows:

$$I_r' = \frac{I_r + I_m}{2} \tag{8}$$

Since the maximum of I_r or I_m is 1, the maximum value of I_r' is also 1. By definition, the value of I_r' is 0 when either I_r or I_m becomes 0.

"LET'S DEFINE OUR COMPONENT RELIABILITY GOALS"

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This paper is intended as a study of the basic nature of the reliability problem concerning the "building blocks" for missiles and space vehicles. The intent is to approach the problem of basic goal definition from the standpoint of our broad national interests and to examine the road-blocks in the way of achieving the goal. Although the problems are equally serious and difficult in the mechanical and the electro-mechanical areas, this discussion is intended primarily for the various managements which comprise the electronics industry of our nation for reasons which will become evident as we read on.

It has been a matter of great concern to the author since the end of World War II that the quality of the component parts which must form the heart of ever-increasingly complex electronic instrumentation is completely inadequate even for present-day requirements. It is encouraging that some leaders in the industry are now becoming aware of the gravity of the situation as evidenced by statements published in the March 1959 issue of "Signal Magazine."[1]

The designer of complex systems today is in much the same situation as an architect would find himself if he were commissioned to design a skyscraper to outdo the Empire State Building, and then discovered that his best building material was adobe blocks.

Why is the vital role of basic parts not evident to us? As Paul Darnell said in the "Signal,"[2] "It should be self-evident." Is it because a resistor tube, capacitor, valve, relay or tubing joint is not a glamorous thing to a designer? This should not be of concern to creative designers who can visualize the completed device. I am reminded of two bricklayers I encountered one spring evening in Philadelphia as I was taking my customary evening walk. These men were working overtime in a large new church. The first workman was doing a sloppy job, spilling mortar over himself and the ground. Just for fun I asked him what he was doing and he grunted, "Laying bricks, stupid." Thus suitably rebuffed I walked on a quarter of a block where the second man was working, and was impressed by the contrast. This lad, a tall, lanky, happy-looking colored lad, was doing an extremely neat

1. Page 6, Signal (Journal of the Armed Forces Communications & Electronics Association).
2. Op. cit. p. 6

job. I repeated my question, and this boy straightened up from his work, looked up into the sky and said, "Suh, I'se building a beautiful cathedral."

Or is it that we, as scientists and engineers, have become enamoured of the mere achieving of performance, and feel that we have achieved the final goal if we prove the feasibility of an idea and have made something that works, even if it is yet far from satisfactory for the required application?

Or have we as a nation been so busy becoming prosperous during the past 14 years that we have accepted lack of progress in our basic building block quality as a normal thing?

I do know one thing to be true, and that is that we have written and spoken enough millions of words in the past ten years on the unreliability of component parts. It's high time we sit down and define what our goal must be, and then go about the job of achieving that goal. I have no quarrel with most of what I've heard or read, but I feel that our thinking has become stereotyped, and sterile, and we either do not mean what we say, or have failed to put our convictions into action. This paper was conceived one sleepless night on an airplane, when I tried to put myself to sleep by reading the previously mentioned issue of "Signal." This particularly well done issue was dedicated to "components" and I read it from cover to cover. I shall hereafter refer to this magazine as "the book." In his article in that "book," Dr. Homer J. Stewart[3] said, in speaking of the NASA program. "The guidance and communication equipment must be tailored to suit the special needs of space missions." What did he mean by this, especially the "special needs" part? Let us examine a specific example of such "special need." Preliminary studies indicate that a satellite electronic system, to be economical and generally suitable, should have a 95% certainty of three years' mean-time-between failure. If the system contains 10,000 component parts, and I know it will if we build it with present techniques, such parts must have a failure rate for each part of approximately 2×10^{-10} or 0.0002 failure per million hours. This is a mean-time-between-failure for each part of about 508,000,000 hours, and this is 58,000 years! Fantastic, isn't it? Impossible too, we might say, and sit down and examine why we want to do such a thing, after all. Obviously, many people are in the frame of mind to thus sit down on the problem, judging from the extreme difficulty of applying resources to the basic problem during the past few years.

I am sure that you will all agree that space has suddenly become our new frontier, one that provides a challenge to all nations, more so than at any other period in history. The only comparable period was the opening up of the new world for exploration and conquest

3. Op.cit.p. 29

following Christopher Columbus. Now, as in that time, the prestige and power of nations will be determined to a large extent by successes in this new frontier. The fact that we falter and temporize is a serious indictment of our long range foresight and planning ability. We must not allow profits and the enjoyment of the good life to blind us to the impact of the future or dull our zeal to achieve this so-called impossible capability. The fact that we concentrate on small-step gains is indicative of our small thinking. I am fully aware that great gains are being made to solve our present day-to-day reliability problems. Many companies are doing this right now. However, I feel that our major resources must be applied to research on the molecular structure of the materials used to perform electronic functions to make possible the solution of the "impossible" reliability problem. I say, "Let's make the foot soldier carry a heavier load of communications gear for a few more months or even years, while we attack the research problems whose solution will provide adequate space vehicle components."

I read somewhere else in "the book" in an article on the great benefits that accrue from miniaturization that "in addition to these size, weight and efficiency factors, it is important to realize that micro-module construction will improve the reliability of Space Age electronic systems." Here we have it again - the relegation of reliability to a by-product status. This is significant because it represents our thinking, that short-term performance and product design are the things we are striving for, and that "isn't it nice if we also can happen to improve reliability at the same time?" Further along in the article the same author writes, "- - - - This must continue at an accelerated pace, for our nation's military techniques depend on our ability to stay ahead in electronics." He did not say what or who we must stay ahead of. I insist again that as far as electronics in the Space Age is concerned, we are not ahead of but seriously behind present requirements. The usefulness of orbiting and space vehicles will be seriously degraded far beyond the point of no-return if we can not make orders-of-magnitude improvement in reliability of complex communications and guidance systems. I hope everyone in this meeting will agree that this kind of improvement cannot be obtained by small by-product improvements in the present component programs. If you do so agree, we are ready to define what our goal must be in component reliability.

THE GOAL: To place reliability at the top rung of the priority ladder in applying resources to our basic and applied research programs and then to direct these resources toward achieving step-function breakthrough in the use of the molecular structure of matter as it relates to long-life performance of the various electronic functions in completely new ways.

The establishment of a goal is no better than the proverbial New Year's resolution unless we immediately turn our attention to the road-blocks in the way of its achievement. Let's now look at some of these:

1. IS THE ELECTRONICS INDUSTRY CONCERNED WITH THE SPACE AGE?

If you agreed with what I said earlier regarding space as the new world frontier, the answer can only be: YES! Since this will be the first involvement of this fast-growing giant with a frontier in which the nation's future position in the world will be determined, this is indeed a momentous conclusion. The revolution in propulsive power development for flight has caught the electronics industry up in its whirlwind, and the two must now be considered as co-equal partners in this technological frontier, even though there may be reluctance on the part of some elements. History shows that pioneering in a new frontier is rarely popular with the masses of people involved therewith. The first recorded pioneering was accomplished by the Israelites under Moses. When life became complicated, they reacted thus, "What have you done to us, in bringing us out of Egypt? Is this not what we said to you in Egypt, 'Let us alone and let us serve the Egyptians'?" The second one of note was the western frontier development out of which grew the United States of America. Here several nations were in competition, but success went to our new nation because we possessed the men of wisdom and foresight, and the technological courage to accomplish their goals. Here again there were many who looked back with longing to the good old days left behind, or grumbled fiercely that the whole thing was not worth the effort, and turned back. The men who had the courage to risk capital and effort grew eminently successful (and rich) and with them rose the fortunes of the nation. I believe the same thing applies in our new frontier in regard to our components reliability situation.

2. SPACE NOT TO BE USED BY THE MILITARY?

The opening sentence of the National Aeronautics and Space Act states, and I quote, "- - - - it is the policy of the United States that activities in space should be devoted to peaceful purposes for the benefit of all mankind." None of us disagrees in principle with this admirable policy. However, I believe it is extremely difficult to distinguish between military and non-military. In fact, I believe that it is a mistake to insist on a differentiation when we are in a "frontier situation" under conditions of "inactive" conflict. Brig. Gen. Homer A. Boushey covered this difficult problem in admirable fashion in an address to the American Rocket Society entitled, "Air Force Uses of Space"4 last 17 November. It is a refreshing

4. Dept of Defense Office of Public Affairs News Release No. 1320-59

and challenging discussion of philosophy regarding "military" and "peaceful" operations. In the technical sense, it is generally true that research and development of military systems requires a much higher degree of excellence and quality in basic components than is commercially available, and that people engaged in this kind of technical work tend to consider in much greater detail the ferocity of the environment in which equipment must operate than do those who are engaged in "scientific applications" work. These considerations are directly applicable to the problem of reliability. We must face up to the fact that unreliability of basic components, right now, is the greatest deterrent to extension of techniques into the space frontier. Here we cannot draw very much on history, because of the revolutionary nature of our approach to this frontier, except to note that success in past-frontiers was due in large measure to the willingness of key men to accept bold new ideas and techniques wherever they arose, with no argument as to whether or not there were military considerations to worry about in a "peaceful" era.

3. THE PHILOSOPHICAL ATTITUDE - "WHY BOTHER?"

This attitude has no place among those who would probe the frontiers. The best example of this attitude was cited by General O'Connell in "the book"[5] in a story about the great naturalist, Thoreau. Thoreau had a friend who was involved with the linking of Maine with Texas by new telegraph lines and who expressed his pride in this accomplishment to Thoreau. Thoreau completely deflated his friend when he thoughtfully said, "What in heaven's name can the people in Maine have to say to Texans?" This philosophy is very prevalent in our country today. There are those who say, "Why in heaven's name do you want a satellite relay that can operate for three years?" and they express themselves by withholding funds for achieving the basic development which would make this possible. These are the same type of people who said eleven years ago, "Why in heaven's name do you want inertial reference equipment, and complex computers in packages small enough for a flight vehicle?" Getting around these obstacles is a formidable management problem.

4. THE SOLUTION IS "MAKE IT SIMPLE"

We do not need to spend much time with this road-block, but we do still hear it. This is the age-old yearning to return to the simple problems of the "good old days." This is the expression of those caught up in "frontiering" against their will or inclination. Our present frontier presents technical problems which are not simple, and it is folly to waste time in hoping that the solution can be a simple one.

5. Signal (Journal of the Armed Forces Communications & Electronics Association) p. 34

5. RELATIONS OF MATERIALS TO COMPONENTS NOT UNDERSTOOD

This statement, of course, applies in general, but I am most concerned with this relationship in electronic components because I see no general awareness of the need to understand the molecular structure of the materials used for such components. On the other hand, I know that there exists, at least within the Air Force, a potent program of materials research to speed the availability of reliability in other types of components. Published statements have indicated some of the problems that exist in this regard, chief of which is the matter of who should pay for such basic work. Some spokesmen for the components industry have said that government must pay for the basic research and development program. This indicates that it is felt that the requirement is only a military or defense problem, which is true in a narrow sense. However, in the broad sense, if the electronics industry is to assume its role as copartner with the propulsion industry in the space frontier, then the problem becomes one of identification with the future strength of our nation, and hence, a problem of solution for the common good. I feel that our economic history proves that the financial rewards to those who have taken up such challenges in the past have always been substantial. These rewards have been so substantial in many cases in the past that they have been cause for alarm on the part of our government. Obviously this discussion is most pertinent to the large companies who are leaders in the industry, because only they possess the resources necessary to adequately attack such an expensive and difficult endeavor.

6. PRODUCTS VS QUALITY

I have previously alluded briefly to the tendency we have, as a nation, to concentrate most of our effort on new applications made possible by a major research breakthrough and live with any quality which happens to evolve. Mr. P. E. Haggerty, writing in the March issue of "Signal"[6] said, "The transistor is important, not just because of its own amazing properties and what they mean to electronics, but because it was the big breakthrough the industry needed to make it focus on a new frontier. This new frontier is the very structure of matter itself. - - - - The Maser and the parametric amplifier already have resulted, and it is safe to predict these are just the beginning. As our insight into the solid state deepens, we will be able to construct true solid state circuits performing complete electronic functions and obsoleting our concepts of components such as the transistor, diode, resistor, capacitor, or inductance as we hold them today. Solid state circuits promise size

Op.cit.p6.

reductions of 1000 to 1 from present printed circuit concepts, large reductions from present concepts of miniature module circuits, and almost immeasurable improvement in reliability - - - -." It is highly gratifying to hear this from leaders in the industry. There is no more precious commodity in our nation today than analytical thinking on the part of management, coupled with foresight and planning ability based on a technical foundation of know-how as to what is important. I also have complete faith in the ability of our scientific community to achieve tremendous things if given the resources and the encouragement which they need. I feel that in the past a preponderance of emphasis has been placed on making "things." That these "things" are commercially successful is not a final answer. I believe we have reached a point of decision on this. I don't think that there is much doubt that unreliability has been the main stumbling block in sales of color television receivers. Is this the order of complexity that can be tolerated with the present level of components, even commercially?

Drastic steps must be taken by both government and industry to achieve the reliability goal we have set. A start has been made by the Department of Defense through its Ad Hoc Study Group on Parts Specifications Management for Reliability. Many of you have heard a description of this effort. The work of this Ad Hoc Group uncovered many problems which government must solve, particularly in regard to specification control of basic parts quality and to procurement and operational practices. One especially acute problem in regard to procurement practices lies in the resupply of components for field replacement. Many forces have been at work to make competitive pricing the only basis of selection of resupply sources. This, of course, precludes any hope of maintaining a high quality level of these parts - in fact forces a situation in which absolutely inadequate parts are purchased for replacement of field failures. Solutions to these wrong practices must be found to make present equipment useable. This is but one example of the many things which must be corrected simultaneously with immediate action to achieve the goal described herein.

In conclusion, both Industry and Government must:

1. Have the courage to admit that our present component reliability situation is indeed serious.

2. Have the zeal to achieve step-function advances by liberal support and by encouragement of esoteric ideas.

3. Develop a sense of proportion which will avoid the expenditures of billions for system development and next to nothing toward achieving the component reliability which will make the systems worthwhile.

It is significant that the achievement of building components of quality which made the Empire State Building possible was attained by learning the molecular structure of concretes and steels and developing the required strength and durability by careful control of that molecular structure. Our goal is clear: We must achieve this kind of durability and reliability in missile and space vehicle components.

A UNIQUE AP ROACH TO RELIABILITY DESIGN REVIEWS

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Introduction

The broad objective of our design review effort is to create early project awareness and final system compliance with quantitative military requirements. The primary challenge in this area has become the translation of this general objective into specific task activities. In other words, it has become necessary to clearly define the responsibilities of cognizant individuals in the program. As a result of experience acquired on several projects, it became apparent that an integrated, comprehensive manual was required as the basic vehicle for implementing this activity.

Early Project Experiences

The initial manual which was developed attempted to provide the requisite components for a successful design review program. The organizational relationships among engineering personnel were defined in great detail.

Throughout the first phases of the project an attempt was made by reliability engineers to review designs entirely segregated from development personnel. This type of operation proved unsuccessful due to the lack of background information which the development engineer possessed, but which was not obvious on the detailed drawings under study. It became obvious that a well-integrated plan of close liaison among cognizant personnel was necessary. As a result, the conference approach for design review was chosen.

Initially, conference meetings were time consuming and burdensome. It was found that due to the lack of communication prior to the conference, discussions centered about a technical understanding of the circuit or package involved rather than a comprehensive design review. As a result, one major deficiency consistently prevailed; the development engineer did not have a clear concept of the areas in which the committee could contribute to his design. He was confused as to the real purpose of the meeting. His attitude could be summarized by two questions, "What can this group contribute that I have not already considered?" "If they really have the ability to inject reliability into designs, why can't it be expressed in specific terms and made available to me as a design guide earlier in the project?" The answers to these questions have become the basis of our latest approach to design reviews.

Current Design Review Procedures

The present design review activity, in connection with one of our major projects, incorporates what we consider to be a unique approach. In order to successfully implement the effort, we have developed a new, comprehensive manual. This document, in addition to listing organizational requirements, provides detailed design checklists for use by development engineers throughout the entire development cycle, from initial specifications to ultimate system evaluation. In other words, we have attempted to itemize in a logical manner all the necessary ingredients for developing a reliable design. The integration of the design review effort with over-all development has been attempted by time-phasing reviews with established program milestones.

Item 1 of the Appendix illustrates the general areas for which reviews are scheduled. Notice the variance in the scope of meetings versus time. As can be seen, design reviews should be started early in the program on a broad general level. When development approaches the hardware phase, detailed meetings of reduced scope are required. Finally, as system integration takes place, the area of interest again broadens. There is one common pitfall associated with the above scope variations. The scope of the meeting must not exceed its intended purpose. In other words, we should not attempt to resolve all the shortcomings of the project in one all-encompassing discussion. In addition, only the required personnel must be brought into each conference. For example, a high level project engineer might not be necessary in a discussion of a particular card hold-down. However, his services are mandatory in a meeting which establishes and interprets specification requirements. It should be the responsibility of an appointed design review coordinator or meeting chairman to insure that cognizant personnel are informed and prepared prior to each meeting.

At this point, let us briefly discuss the various sections and checklists which have been devised for the development cycle. In this manner, we can further illustrate the nature of the items that we feel are necessary for a comprehensive design review.

Logic Reviews - Electrical

The electrical logic review is performed prior to the preliminary layout of circuitry. During this meeting, pertinent checklist questions are discussed briefly. Specific personnel are called upon to provide the basic answers. However, all attendees, having developed a familiarity with the checklist, are aware of the general nature of the conference material scheduled for review.

The intent of this conference is to review required system effectiveness and investigate possible specification problem areas. Such things as the feasibility of logical system functions and reliability requirements come under close scrutiny.

If unresolved problem areas remain at the conclusion of the meeting, action items are assigned to attendees and a follow-up conference is scheduled. Some of the checklist questions for this meeting are included in Appendix Item 2.

Logic Reviews - Physical Concept

The physical concept logic review is performed after the electrical review but prior to preliminary layouts. The intent of this meeting is to review physical design proposals for size, weight, density of packaging, cooling techniques, and mechanical layout. Prior to the meeting, it is necessary for attendees to familiarize themselves with physical environments, vehicles and available space, and tentative system block diagrams. During the meeting, the group reviews areas such as proposed module sizes, card hold-down techniques, and RFI requirements. Some of the considerations included on the checklist are shown in Appendix Item 3.

Functional Circuit Reviews

The functional circuit review is conducted after the preliminary drawing-board layout but prior to hardware fabrication. The purpose of this meeting is to review, for the first time, actual circuitry with regard to feasibility and reliability. The development engineer, who has used the checklist in developing his design, is prepared to discuss such things as input and output requirements, interface problems, and effects of failures upon functional capabilities. At the completion of this phase, the original logic diagram should emerge complete and substantially verified. Appendix Item 4 contains some selected questions from this checklist.

Part and Module Reviews

Part and module reviews are scheduled after preliminary layouts during the "haywire" breadboard stage. All questions pertaining to module configurations such as hot spots, heat generators, and vibration sensitive parts must be resolved at this time, prior to detailed drawings. The module, defined in this paper as the next lower level of assembly from a line replaceable unit, must be checked with regard to the proper application of parts, coolant

adequacy, and marginal operation versus environmental combinations. During the meeting, the group discusses the engineers' sketches, test reports, reliability predictions, and calculations. Once again all personnel attend the conference with full knowledge of the checklist which will be used to establish conformance with reliable design practices. Item 5 of the Appendix lists selected questions from this list.

Line Replaceable Unit Review

After the module design has been established and preliminary LRU design initiated, the unit reviews are implemented and continued until design is complete. The intents of these meetings are quite similar to those indicated for the part and module reviews. However, the scope of material increases to include larger segments of the hardware. Greater emphasis is placed on packaging, environment, cost, ease of maintenance, and fabrication. This particular phase of development becomes the last major hardware effort. Outstanding problems concerning physical design should be resolved at this point. Item 6 of the Appendix lists some questions from the LRU review checklist.

System Worth Reviews

As soon as completed line replaceable unit designs are available, the final logical marriage reviews are implemented. It is the purpose of these meetings to assure system capability, effectiveness, and over-all worth. Final specifications, block diagrams, and system test results are reviewed for adequacy. The checklist questions of Appendix Item 7 are included to further illustrate this area.

Design Review Pitfalls

As mentioned previously, the greatest pitfall in design reviews has been the over-ambitious objectives of the meetings. Both economic and engineering limitations have necessitated compromise and redirection. We cannot expect the design to be fully discussed at these conferences. The prime purpose of a formal design review meeting must be to insure that an adequate effort has been made by the designer. This is evidenced by the calculations and reports required by the checklists. In addition, where particular problem areas develop, the design review group must insure follow-up and resolution. It would hardly be feasible to expect a group to review in detail the great number of considerations involved in development. For this reason, our manual, composed of some 420 checklist questions, was designed to be self-contained. In addition, -

an appendix, containing approximately 100 detailed design procedures (see Appendix Item 8),was included to provide the engineer with the knowledge and experience of experts without making their constant presence mandatory.

Once a manual of this type is developed, proper introduction into the project becomes a major challenge. The natural reaction of most design engineers receiving this type of formidable document is to file it for future reference. The necessity for indoctrination, wherever necessary, becomes of paramount importance at this point. Once development engineers become aware of the usefulness of the manual, implementation becomes self-sustaining. However, the traditional inertia against adopting new thoughts and working habits has to be overcome.

Existing Problem Areas

In an objective analysis of the four months since the introduction of our new manual, several problem areas become apparent. Additional clarification has been found to be necessary in establishing exactly when a formal meeting should be called. Each design has an optimum period for review, depending on such things as complexity, functional requirements, and caliber of cognizant development engineers. Proper scheduling will result in maximum economies and technical contributions. On the other hand, incorrect scheduling will cause a general degradation of the entire design review effort.

Another area which has warranted careful scrutiny has been the manual itself. At present, the checklists are presented in a manner which closely follows the development cycle. However, the need for cross-referencing related items of various checklists has become apparent. Undoubtedly, some checklist questions can be rephrased, expanded, combined, eliminated. We are now in the process of re-evaluating the items. In addition, it is felt that a subject index will add considerably to the usefulness of the document.

The need for constant improvement in a critical activity such as design review cannot be overemphasized. Seemingly minor modifications may provide the extra impetus required to develop the valuable contribution possible from this endeavor.

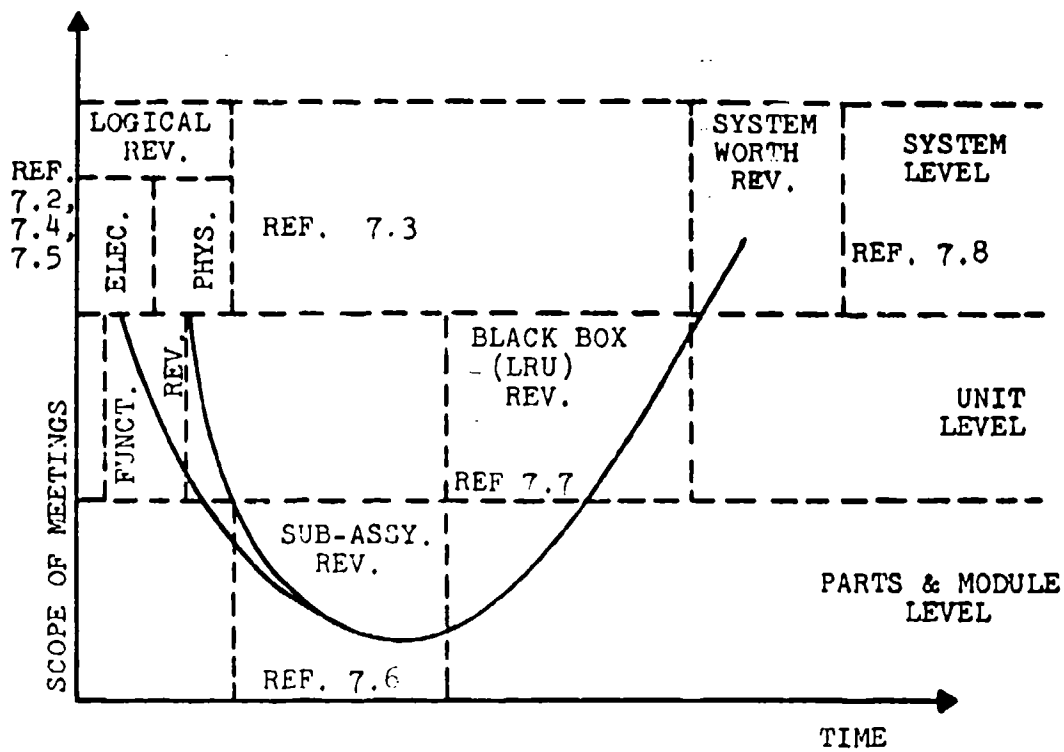
Summary and Conclusions

In order to insure adequate design reviews, we have developed a comprehensive manual which contains detailed checklists and design methods. The primary effort has been to encourage the development engineer to effectively review his design as it progresses. At various milestones in the development program, formal meetings are held to review the adequacy of his methods, not necessarily the design itself.

Design review conferences have grown less time consuming, with analytical computations rather than intuitive feelings forming the basis for discussions. The necessary ingredients for reliable designs have been more clearly defined, removing some of the previously experienced ambiguities. However, further areas of improvement for policies, procedures, checklists, and design methods are now being planned for the increasingly complex systems and severe development schedules anticipated in the near future.

APPENDIX

Item 1. 1 - Design Review Phasing Diagram



Item 2 - Logic Review - Electrical

a. Have the restrictions imposed upon performance of equipment by limitation of vehicles carrying the equipment been fully evaluated? Calculations will be discussed at the design review meeting, i.e.,

1. RFI due to functional parts of vehicles

2. Flutter and vibration natural frequencies and responses of the vehicles at equipment mounting points in each axis of excitation.

b. Have a philosophy and a system of interconnecting grounds been established to avoid undesired interference effects? Has a report been generated defining this philosophy and setting up the ground rules for interconnecting grounds? (See Appendix Item 1 of Design Review Manual.)

c. If a requirement of a specification is not consistent with the existing state of the art, are all risk areas being identified and personnel being assigned to keep track of progress?

d. Has a report been prepared using Value Engineering techniques to determine the relative actual value of each function specified to balance the cost of each function specified in money, weight, schedule, volume, reliability, primary power, cooling air, and maintainability. (See Appendix Item 6, Design Review Manual.)

e. (Reference Check List Item No. 52, 8.1 System Logic Review, Design Review Manual). Has a report been prepared which:

1. Lists and defines all functions?

2. Assigns weighting factor to each function?

3. Establishes reliability of each individual function?

4. Determines over-all reliability from formula? (Reference Appendix Item 10 of Design Review Manual).

Item 3 - Logic Review - Physical Concept

a. Has a study been made with formal analytical computations to determine the relative merits and tradeoffs of alternate module structural concepts?

b. Where vibration schedule inputs in vibration exceed plus or minus 5 g at any forcing frequency, has an effort been made to determine the true actual dynamic environment at takeoff by tests or analysis?

c. Has a report been generated defining:

1. Categories of units?

2. Types and mounts of cooling available for each unit?

3. Ambient surrounding each unit:

Temperature and altitude?
Thermal shock?
Pressure variation?
Pressure variation with time?

4. Cooling air:

Temperature versus altitude?
Maximum change of temperature with time?
Change in pressure across unit and tolerances?
Change in pressure versus altitude for all governing flight conditions?
Contaminant content?

d. Have computations been performed determining heat transfer effectiveness of typical units and modules, as per Appendix Item 21 of the Design Review Manual or Item 8A of this paper?

e. Will air-cooled units withstand 3 psi differential pressure with plus 0.50 margin of safety versus permanent deformation of dust cover or structural members, utilizing large deflection membrane theory of hoop stress plus bending stresses as per reference R. J. Roark, Second Edition, "Formulas for Stress and Strain"?

Item 4 - Functional Circuit Review

a. Have all input and output signal characteristics been fully coordinated with those of associated blocks? (See Appendix Item 36 of Design Review Manual or Item 8B of this paper.) Is a summary of such signal requirements available?

b. Typical Circuit Check Lists

Video Circuit

1. Is the function economically achieved?
2. Is the design correct so that the circuit will do what is desired?
3. Will it function correctly over the range of environment and component tolerances?
4. Are capacitors within voltage ratings?
5. Are resistors within power ratings?
6. Are relay contacts within current and voltage ratings?
7. Are diodes within forward-current and back-voltage ratings?
8. Are transistors within current and voltage ratings and properly bias-stabilized?
9. Are amplifier inputs and outputs sufficiently isolated (physical spacing, common leads, power supply returns, etc.) to prevent parasitic oscillations?
10. Are stray capacitances low enough to avoid undesired time delays?

c. Typical Flip-Flop Circuit Check List

1. Is it stable?
2. Does it respond to desired flipping signal?
3. Does it abstain from responding to undesired noise spikes, power supply transients, etc.?
4. Is its output properly (correct voltage and impedance) coupled to its load?
5. Are its parts all within their ratings?

6. Are appropriate re-set signals connected to it?

7. Is speed of response proper (neither too fast nor too slow) for desired functions?

d. Have pulse widths, circuit delays, and pulse shape deterioration been examined, as per Appendix Item 43 of the Design Review Manual or Item 8c of this paper, to establish that signals are properly synchronized?

Item 5 - Part and Module Reviews

a. Is natural frequency of module structure (as defined in Appendix Item 49 of the Design Review Manual or Item 8d of this paper) greater than 100 cps?

b. By moment distribution, are cross-sectional module bending stress margins of safety greater than plus 0.50, as defined in Appendix Item 51 of the Design Review Manual?

c. Is there sufficient coolant to reduce the temperature of sensitive members to their safe operating temperature with a reasonable margin of safety, as defined in Appendix Items 21 and 22 of the Design Review Manual?

d. Is data available defining derating program to improve estimated component reliability numbers due to temperature, electrical stress, vibration, environmental stress, aging, humidity, etc.? This data will be presented at the design review meeting. The presentation should set up general ground rules.

e. Are transistors or subminiature tubes available with

1. Frequency characteristics, as per specification?

2. Noise figure in first transistor or tube, as per requirement?

3. Requisite stability characteristics with aging and temperature?

4. Sensitivity, as per specification?

f. How does module perform when

1. B plus is varied to plus or minus 10 per cent?

2. Filament voltage (if any) is varied plus or minus 10 per cent?

3. B minus (if any) is varied plus or minus 10 per cent? (Reference Appendix Item 69, Design Review Manual)

Item 6 - Line Replaceable Unit Review

a. Has a report been generated summarizing all unit hotspots, all heat generators in unit, and all critical heat-sensitive parts? Is the report adequately quantitative so as to include location of critical parts, time-rate generation of heat, degradation of performance with temperature and time, etc.?

b. Has analysis been made to solve for heat transfer coefficient (integrated for entire unit), as per Appendix Item 77, Design Review Manual?

c. Has a test and analysis report been generated attempting to define the true dynamic environment direction for various suitable aircraft with respect to:

1. Location of equipment in airplane?

2. ~~Axis of excitation?~~

3. Cumulative cycles at each frequency?

4. Bandwidth frequency spectrum?

5. Acceleration input?

d. Will air-cooled unit withstand 3 psi differential pressure without

1. Excessive leakage of coolant through gaskets, etc.?

2. Development of gaps which may permit RFI leakage?

3. Permanent deformation of dust cover through membrane diaphragm action?

Item 7 - System Worth Review

a. Have all input and output signal characteristics, as defined in Appendix Item 80, Design Review Manual, been fully coordinated with those of associated units? Summary of such signal requirements, as per Appendix, will be furnished at design review meeting.

b. Is system output high enough to guarantee producing desired effect? Is noise level of system output low enough not to produce a false alarm or other undesired effect? Reference Appendix Item 80, Design Review Manual.

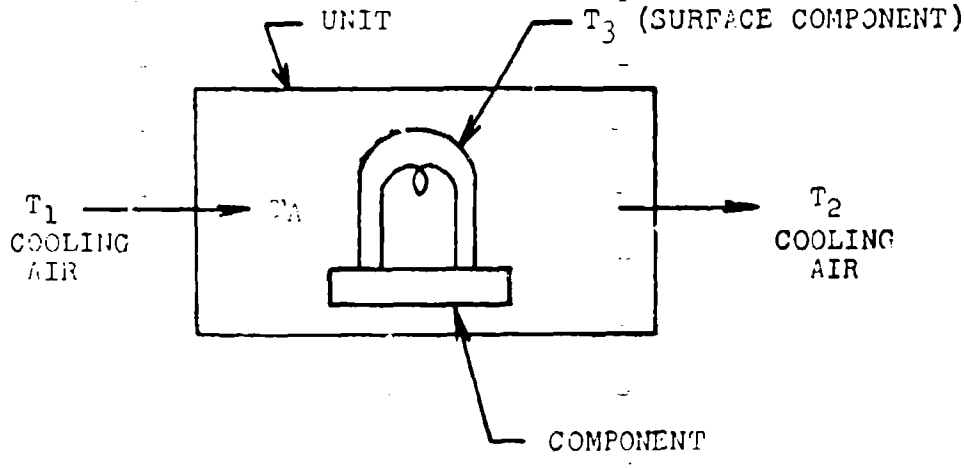
c. Have all the power leads been determined to be located at the maximum distance from the signal leads that the physical configuration of the packaging will allow?

d. Has the packaging technique provided for flexibility in design which will enable the system to grow in complexity or be reduced, at the request of the customer, without affecting the units that would not be changed?

Item 8 - Design Methods

A. Effectiveness of heat transfer = $\frac{T_2 - T_1}{T_3 - T_1}$ - - -

Where T_2 = Temperature cooling air out (°F).
T_1 = Temperature cooling air in (°F).
T_3 = Temperature surface of component (°F).



Heat Transfer:

Step 1

In test, monitor surface temperatures of critical components.

Operate modules and units.

Completely insulate module or unit to minimize conductive and radiation heat losses.

Unit generates own heat.

Step 2

Supply cooling air until maximum temperature of critical air is obtained.

Step 3

Monitor T_1, T_2, T_3.

Step 4

Compute effectiveness = $\frac{T_2-T_1}{T_3-T_1}$

B. Input and Output Signal Characteristics

1. Impedance
2. Amplitude (voltage, current)
3. Pulse Duration
4. Background noise level*
5. Circuit delays and pulse shape deterioration

1. Impedance

Impedance of interconnections should be low to minimize capacitive pickup from one lead to another.

a. Circuit impedance should be as low as possible to minimize capacitive pickup of interference, degradation of pulse shapes, undesired feedback. Where possible, impedances should be held to between 1000 and 10,000 ohms, maximum.

b. Stray capacitances should be minimized by locating components to keep critical leads short. Try where possible to hold leads to 1 inch, maximum length.

2. Amplitude

a. Is circuit design capable of handling existing amplitudes without overloading, instability, and waste of power? e.g., Amplifier (transistor)

$$B^{+} \simeq 1.5\ (G)\ V_{i}$$

where B = Collector supply voltage
G = Voltage gain of circuit
V_i = Input voltage

*Is the output background noise level tolerable to the input to which it is connected?

b. Is output signal of one circuit reliably sufficient to perform desired function as input to another circuit?

c. Is circuit uneconomical in using excessive amplitude of signals connecting one box to another?

3. Pulse Duration

Pulse duration which is trying to trigger a flip-flop or produce other action should be long enough to produce desired result with adequate margin of safety (e.g., +1.50), taking into account all tolerances affecting desired result -- resistors, effect of stray capacitance, tolerance on transistor parameters, temperature effects, etc.

4. Noise

Compute noise level of input signal, e.g.,

Thermal noise voltage at input

$$N = C_1 \times G_r$$

where N = Noise at input to circuit
C_1 = Noise figure of receiver
G_r = Gain of receiver

Capacitive pickup noise voltage

$$N = V_1 \left(\frac{Z}{Z \quad Z_c}\right)$$

where N = Undesired induced noise voltage
V_1 = Voltage level of nearby interfering circuit
Z_c = Impedance of undesired capacitive coupling
Z = Impedance to ground of circuit under investigation

Inductive pickup noise voltage

N = Inductive pickup noise voltage
I_1 = Current in nearby wire
M = Mutual inductance between wire carrying undesired signal and wire under investigation.
Z_i = Input impedance of circuit to which signal is being fed.
Z_o = Output impedance of circuit from which signal is being fed.

$$N = M(I_1) \frac{Z_i}{Z_i \quad Z_o}$$

Interference noise produced by common power supply and ground return impedances between module under consideration and interfering modules:

Let N_{actual} = Interfering voltage actual
Z_i = Common impedance
I_1 = Undesired current
K = Derivative of circuit output voltage with respect to induced undesired voltage

$$N_{actual} = KI_1Z_c$$

$$N_{actual} < \frac{2}{3} E_t$$

Where E_t = Threshold signal that will operate flip-flop or produce other undesired effects of tolerances and environment

Step #1 - Determine noise

Step #2 - Determine square root of sum of squares of noise voltages.

Step #3 - Compare result of Step #2 with amplitude of signal appearing at that point in the circuit under investigation.

Step #4 - Determine margin of safety versus false alarms and other undesirable effects exceeding tolerable limits.

5. Circuit Delays and Pulse Shape Deterioration

It is recommended that individual circuit delays not exceed 5 per cent of the mean pulse width employed in the computer.

Delays are additive: rise time contributions combine approximately as the cube root of the sum of the cubes.

$$T_r = \sqrt[3]{T_{r_1}^3 \quad T_{r_2}^3 \text{ - - - - - - - - } T_{r_i}^3}$$

T_{R_1} = Rise time of output of first of a chain of circuits when input has zero rise time.

T_R = Rise time of output of chain of circuits.

T_{R_i} = Rise time of input.

It is recommended that test measurements of the following be made on oscilloscope input and output signals of adjacent major circuits:

1. Pulse Shape: Rise and fall time of signal.
2. Pulse Width: Time between half amplitude points.
3. Circuit Delay: Time between half amplitude at input and half amplitude at output. Then, it is necessary to compare the output signal of the drive circuit with the desired input to the driven circuit.

C. A pulse must occur during a gate signal. Does gate precede and succeed beginning and end of pulse by at least 25 per cent of pulse width? Have circuit delay tolerances been analyzed similar to pulse amplitude analysis as per question No. 6, Check List 8.1 of Design Review Manual?

Synchronizing (information retiming)

The inherent time-delay properties of most computer components, and the unequal path length of logic circuitry that various information must pass through, cause different delays in arrival of two signals to a logic point. Therefore, measures must be taken to assure synchronization of various operations of the computer.

The use of a highly stable crystal-controlled clock pulse generator which also serves as a time reference may help to accomplish synchronization of the pulses.

D. It is requisite to determine the natural frequency of each significant type module. The deflections and flexibilities of the modules are functions of the natural frequencies, which, in turn, are functions of the distributions of masses and inertias of the modules.

$$y = a \sin w_n t$$

where y = Amplitude of module (inch).

a = Maximum single amplitude (inch).

w_n = Natural frequency (radians/second).

t = Time (second).

$$\ddot{y} = (-y)w_n^2$$

Determine module natural frequency.

Step 1 - Determine all dimensions of the module. What are the boundary conditions, simply supported or fixed? Locate all masses in the module. Set up reasonable mathematical models and load paths.

Step 2 - Compute the moment of inertia of a typical cross-section of the module about a principal axis of the cross-section.

Step 3 - At first load path, consider the module as a box beam and compute the static deflections at every mass point due to 1 ρ leads. Include both flexual and shear deflections.

Step 4 - Compute first approximation of the natural frequency of the module by the formula shown in Appendix, Physical Design Review, Design Review Manual.

RELIABILITY EDUCATION*

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ABSTRACT

This paper covers the fundamentals of Reliability Education. It contrasts the desires and contributions of Industry with the educational developments and offerings of the Universities. The need for Human Engineering is pointed out and also for simpler and improved evaluation techniques for Reliability. When should action be taken with respect to components or the system as a whole due to lack of control with respect to its reliability? Supplementary educational material is presented indicating different methods for establishing statistically sound control limits based on desired Confidence Levels. An educational and training program for management, engineering, purchasing, production and other associated groups is outlined.

Emphasis on the team approach used in Operations Research and in many current contract negotiations is given, together with consideration of the contributions that are being made by committees and groups working in logistics, maintenance, specifications, testing and research. Economic standards of quality are discussed and in addition the methods to be used to educate individuals in this field so that close liaison may be maintained between standards, specifications, design, value engineering, fabrication and reliability in all its phases. Finally the educational precepts and methods for scientific and reliability education are noted and methods of implementing these are proposed.

1. The Reliability Problem

The need for reliability in its different aspects has been apparent for centuries. Protection was needed in early times against nature and the wild beasts. Homes were built in caves and elsewhere and protective weapons were made. Clubs and spears were produced that were deemed inherently reliable. Later bows and arrows were developed that would function without too many failures in hunting food or in battles with enemies of all kinds. Men and allies were selected as team mates or workers because of their inherent integrity. They also were considered reliable if they proved to be effective allies. Events

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are expected to occur according to some fairly well defined pattern. Some deviations are expected. If one unit or event is widely different, sometimes termed the maverick of the group, the future performance of other units in the group is questioned. What steps can be taken to reduce the probability of the occurrence of the unusual? Also, what information is required to determine how wide a band of unreliability exists? Can individuals be trained to differentiate between cause systems that produce satisfactory events or products and those cause systems that contain unfortunate tendencies towards the production of erratic events and performances? Being able to control the environment in which we live is extremely important. Being masters of the situations that arise rather than being controlled by the current events or by irresponsible individuals requires knowledge and training. Reliability means stability, dependability and adequate controls. Thus education that develops an appreciation of how to attain this valuable feature, namely reliability, will contribute greatly to the national welfare.

The generalizations above point out the necessity for appreciating what the reliability problem is and what steps may be taken to achieve the reliability desired. Events, products, actions are dependent upon many causes. One group deals with another group. If those dealings are mutually beneficial, these relations are continued. If practices are sharp, products bought are unsatisfactory, schedules are delayed unduly, and the liaison results in adverse reactions, then relations are severed. Ignorance may be the cause. Lines of communication have broken down, no agreements have been reached that are so simple that possible differences in reactions may not occur - thus lack of confidence and a feeling of uncertainty exists. Products made or shipped tend to be of such poor quality that they would ordinarily be returned except that they are needed to meet schedules. The result is an unreliable assembly or system. The meaning of reliability, dependability, service, longevity is not clear. Hence, some educational program is required to develop a better knowledge of reliability and its meaning, and also to introduce effective measures to secure a reliable product.

The reliability problem is as old as civilization. Now it is being stressed since allowable variations are being narrowed. Parts and performance must be satisfactory. In each field custom has developed a standard of some kind which is considered economic. If achieved then the notion of reliability in that area has certain definite connotations. If not achieved the causes of failure must be determined. Weighting these causes, taking proper steps to reduce the failures or potential failures to a minimum - all are functions that must be understood. Training is needed. What type of education is best suited for this task? Consideration will be given to both desirable and possible undesirable elements in Reliability Education as it exists today. This lays the groundwork for a strong rudimentary training program in Reliability.

2. Elements in Reliability Education

Quality Control as applied in industry was started by Dr. Walter A. Shewhart of the Bell Telephone Laboratories in 1924 and was extended into commercial practices by Messrs. Harold F. Dodge, George D. Edwards, Donald A. Quarles, Dr. Paul M. Olmstead and many others including the author in the Bell System and in a few other industries. It was taken over into Military operations about 1941 and in the Aircraft and Missile Industries was part of many contracts which included MIL-Q-5923 (original, A, B & C issues) as mandatory. It is now replaced by MIL-Q-9858 issued by the Department of Defense. Many in Research and Development work do not feel that MIL-Q-9858 covers R & D work as well as Phase A of MIL-Q-5923C. The Quality Control specification did not result in the Reliability, Dependability and Longevity including ability to perform after 5 years shelf life, that was desired. Maintainability also was not deemed to be covered as well as it should be. Reports were issued covering certain areas indicating replacement costs were often as high as 10 times the original costs. Action was warranted. Reliability was selected as the factor that must be stressed.

Some concerns already had decided that Quality Control was not sufficient. However, many did not really know what Quality Control should do, what its functions actually were. Many renamed their Inspection Departments Quality Control and wrote a manual. Some included Test in Inspection, renamed Quality Control, but few had any Quality Control functions in Engineering, or Research and Development. Others needed to use smaller samples so took their clue from Research and Development customs and used small samples or no samples for intermediate tests. Others acquainted with more recent techniques added "Statistical Quality Control" mentioned in MIL-Q-5923. Section 4 of the Military Specifications was titled "Quality Assurance" so Quality Assurance departments were organized. Their functions differed considerably from those covered by the Quality Assurance Department of the Bell Telephone Laboratories.

Next came a series of Reliability specifications covering different areas. Some were preceded by the "AGREE" (Advisory Group on Reliability of Electronic Equipment) Report covering Reliability requirements. A series of Military Specifications and Exhibits covering Reliability, Maintainability and allied areas were and are being issued. Some are now incorporated into Missile and Electronic Equipment contracts. Many conferences and symposia on Reliability have been held, this being one of a series.

The above background indicates roughly the historical background of Reliability. What elements should be included in a Reliability Educational program? Which are most critical? These should be tabulated and analysed so that training effort may be applied most efficiently.

The following elements should be considered:

1. Definitions and description of Reliability.
2. Mathematical Models for Reliability Evaluations.
3. Reliability of Materials - tests, checks and controls.
4. Reliability of Components - tests and measurements, longevity.
5. Mean Time Before Failure (MTBF) - meaning and use.
6. Minimum Time Before Failure (mtbf) - distribution theories for minimum and maximum values.
7. Confidence Limits - Degree of Belief.
8. Mission Times - Nature of Missions: Three possible categories::
   (1) Instant Response - Immediate reaction and performance.
   (2) Short Time performance - dependable response.
   (3) Long Time performance - requirements for space operations.
9. Variables and Attributes data - Evaluation methods.
10. Analysis of Variance - Experimental Models - Securing Reliability data by planned experiments.
11. Reliability in Design and Engineering.
12. Reliability in Pilot Runs.
13. Reliability in Production.
14. Reliability in Purchased Parts.
15. Reliability Tests and Environmental Tests.
16. Bench Tests and Flight Tests - Reliability evaluations.
17. Malfunction Reports - Use and Benefits.
18. Field Reports and Unsatisfactory Reports (UR's).
19. Standards - Economic Levels; Choice of Parts; Suppliers; Sources.
20. In Military Contracts - Handling of Nonstandard Parts.
21. Bills of Materials - Lists of Standard and Nonstandard Parts.
22. Accelerated Tests - Life, Longevity and Shelf Life.
23. Data Processing for Reliability.
24. Reliability and its Satellites - Quality Control, Quality Assurance, Inspection, Test, Testing Equipment, Calibration, Primary and Secondary Standards, Standards of Performance.
25. Applications of Designs of Experiments and Operations Research.
26. Present Reliability Organizations.
27. Changes in Design and Specifications - Part played by Engineering, Reliability and Design Review Boards.
28. Need for unbiased reports on Reliability - Independent versus non-independent organizations.
29. Project System of Reliability - faults and merits.
30. Centralized System of Reliability - faults and merits.
31. Independent Laboratory System for Reliability Evaluations - Benefits and losses.

32. Ideal Quality Engineering Organization.
33. Manuals and Instruction Books in Reliability.
34. Committees and Conferences for Reliability.
35. Training for Reliability.

Elements in Logistics and Operations Research may be added as they contribute heavily in many areas. The detailed elements above can be covered by extensive training programs. Human engineering is written in but its effect is difficult to evaluate. Training in obtaining data before and after human engineering elements or other parts have been added is required. For example, some have reported that on certain vacuum tubes, removing the old JAN shields improves the Reliability 10 to 20% roughly, but adding the new MIL shields increases MTBF values from 1,000 hours to 6,000 hours. Costs are increased for the initial installation but overall costs are decreased when maintenance costs are included.

3. Industry Looks at Reliability - Contract Requirements

Industry seeks a profit. Our economic system is geared to extensive growth patterns with population expanding, number and varieties of products being continually augmented, national wealth increasing, defensive and offensive military needs continually changing in line with scientific improvements. Looking over contracts for military products including missiles, why should there be any reliability paragraphs added? The products to be delivered are supposed to function and perform the tasks noted in the contracts. If all features of these contracts were met, there would apparently be no need for reliability requirements.

If the designer has made the best possible economic unit within the present state of the art, the tolerances allowed are reasonable, and the best possible reliable and quality parts are called out in the bill of materials and have been secured from the most reliable vendors in the field, a reliable and quality product should be obtained and require practically no checking. A satisfactory product is assured since, with all parts at minimum or maximum values in an unfavorable direction one way and at maximum and minimum values in an unfavorable direction the opposite way, all such assembled units have been found by tests to operate satisfactorily. In addition, other tests show they have no current failures and after 25 to 75 months of shelf life still operate if placed in service. Also, no failures in operations occur for 25 to 100 months for all units accepted. With such a history then no inspections and tests other than routine inspections on the line may be required during fabrication. Such may be the case for an automatic production line wherein, if necessary, automatic measurements may be made at certain stages of the assembly and all nonconforming parts are rejected by the machine automatically. This is the ideal setup for continuous production and may be very satisfactory for the majority of simple component parts such as

capacitors, resistors, diodes and the like. Some commercial resistors have been made for years by such machines. Some shoes also are practically made automatically by machines obtained by rental from a general corporation specializing in automatic machinery. Such is true for the production of bottles. One production line even made cheap alarm clocks automatically. For electronic equipment some parts such as potentiometers, diodes and even some modules may be made by unit construction methods. When automatic assembly and fabrication are used, units are produced so rapidly that automatic inspection devices must be installed at strategic points. Samples of checked parts must be made to provide assurance that the automatic testing devices maintain their accuracy and that they are calibrated properly and at appropriate intervals against primary standards. Also their precision must be good, i.e. successive variations in repeat readings must be maintained small with allowable maximum variation permitted less than 10% of total tolerance band width with 1% preferred.

With the above facts noted, Industry accepts these reliability requirements and adds the Reliability Tests as necessary costly tests that it believes might be eliminated if the customer would only be satisfied with the assurance that performance and flight tests will eliminate the weaker elements. There exists one group in industry, still operating in spite of improvements in available techniques, that use trial and error methods. Their contention is that performance is the key check for a satisfactory product, hence, make a series of different types of units, operate them, then select the one that operates best. Analyses of test results for various characteristics and environments show that such units work. Ship these to customers but assume no responsibility for future operations. If failures occur, rework and, if necessary, redesign. The argument is that the changes in the art are so rapid for electronic equipment that units become obsolescent more rapidly than they even approach half-life and few ever reach the point where shelf life is an important factor. In some areas this contention is valid but nevertheless some assurance must be provided showing the product is satisfactory.

The Educational Program for Reliability must be geared to consider these adverse reactions. Typical of these antagonistic feelings against outside inspections and tests are the following. Each instrument payload for scientific investigations in space is different from the next payload. Each engineer and designer makes his portion of the whole as reliable as possible within the area of his knowledge of operations. The scientist or engineer working on the design confers with his colleagues and has a one unit assembly different from any other unit and one that probably may never be made again. He firmly believes that there is no need for additional tests, reliability evaluations, consideration of components, tabulation of expected performance for parts, hence, additional costs incurred by reliability are unnecessary. Reliability, Quality Control and similar

techniques only apply to mass production of parts and even then only in a limited way. Their efforts impede the schedule. Design reviews, even by recognized experts brought in as consultants, are a waste of time and money. Such may save thousands of dollars by recommending early changes in designs that will never work or will operate inefficiently. Costly rework will be reduced and unit costs may be reduced through Value Engineering so that the company making the part is in a strong competitive position when contrasted with similar products made by competitors.

The demands of Industry are for simple techniques to evaluate the reliability of parts and assemblies in mass production. The models, preprototypes and breadboard designs made in Research and Development undergo such critical examinations by the design engineers and technicians when being built that auxiliary reliability checks are considered a farce in many cases. A good Reliability Engineer will realize that this point of view is valid in a great many cases. Making tests with little meaning and no possible constructive reactions may satisfy your customer that reliability action is taking place when such tests add nothing. There exists a need for constructive training in this area.

Reliability organizations provide basic services to design engineers. Interchange of data-covering all parts and module assemblies should be established in a central standard agency on a non-profit basis. Establishing such a central source for pertinent design information on parts and components of all kinds provides the basic elements for a good design. Limitations on certain parts must be recognized and the design must reflect these limitations by strengthening other supporting elements. The Reliability Education program should cover this service and provide training so that maximum use may be made of such data.

Industry appears to like Panel discussions. Many training programs include several sessions for a panel discussion of selected topics. If handled properly by a good moderator it is very educational. With a poor moderator many panel discussions waste the time of those in attendance. Formal training with scheduled classes is preferred for in-plant or out-of-plant training when the demand for such training is extremely urgent. Generally, Industry expects the Universities to provide formalized training in Reliability and kindred fields and particularly in the mathematics and statistics required for reliability engineers. Contract stipulations sometimes require Industry to write procedures, instructions, training programs, make moving picture films, and perform other tasks required to implement a large complex system. These are often considered as merely instructions whereas a great many of these tasks result in fully oriented training programs. Industry absorbs a minimum of these tasks and desires that the Universities assume the responsibility of covering the remaining areas for Reliability Education.

4. University Courses and Contributions

The Universities are continually revising their curricula. More courses on more subjects are being added. In the Reliability field the university contributions to the program consist of regular courses in Engineering Statistics, Mathematical Statistics, Quality Control, Operations Research, Point Sets, Industrial Engineering, Management Courses, and special courses, such as Logistics, Analysis of Variance and Decision Functions given by the Economics, Mathematics, Engineering, Physics or even Business Administration Departments. Many evening courses are given through extension although some universities give accredited night courses in special areas such as guided missile design, propulsion, instrumentation and industrial processes, using as lecturers industrial experts, many of whom only give one course each year or each semester. Two day, one week, two week or several weeks of special conferences are provided. For the shorter periods special groups meet together for two days to two or three weeks and work co-operatively in one or two fields. Some universities even cover Reliability in somewhat similar concentrated Conferences or Training Programs.

The Military have arranged with some universities to provide complete college programs in these areas, such as reliability and maintainability, that are usually missed otherwise. Some special conferences are arranged through special trust funds such as a recent conference on Logistics at Columbus, Ohio. Recently in Los Angeles a combination University and Industry Panel covered in two days techniques for specification writing. Quality Control is covered by a large number of Universities in special two-week all-day courses arranged at times where Industry may be able to send their men there for full-time training or for essentially a refresher course. Men from Industry are on the advisory boards of the Universities and assist them in establishing short courses that will be most beneficial to the local industries.

Technical societies are holding regular periodic evening meetings, conferences, conventions and panel discussions. The various university professors that are conversant with statistics, some phases of reliability, industrial engineering processes, formal and applied mathematics and various kindred fields of engineering and administration contribute heavily to these conferences, etc. Training courses have been sponsored by many technical societies. University professors conduct many of these courses. They also act as consultants on many projects. Unfortunately, in many areas, those elements that contribute to quality and reliability are not even mentioned. Such elements are taken for granted. It is assumed that if parts are made right, and designs are right, then these parts must be reliable.

Reliability Education programs should be arranged at periodic intervals in the universities where the professors meet so that there

will be more consciousness of the need to stress reliability in all its phases. This approach might increase the effectiveness of the universities in this field. Reliability, being taken for granted, is not achieved because there is no formal effort to present its needs in the various university programs. Where quality-consciousness exists, reliable products result.

5. Reliability Controls

In Reliability training, emphasis generally is placed upon the techniques and not the fundamentals. Consequently, when one specific part or component fails more than once it is desired to know whether such a part failure is significant or not. It is necessary to first develop control charts for Reliability values that have meaning and to establish expected levels, expected variances, expected standard deviations and to choose selected Confidence Levels. This selection is not as easy as it looks since there are a large number of variables involved. Many of these are not known as completely as is desired. Consider a Reliability value of 0.99. Using the theory developed by the Task 3 Group for the AGREE report involving Mean-Time-Between-Failures (MTBF) where from equation (2) of page 177 of the AGREE Report, $P_0 = e^{-t/\bar{T}}$ is used to determine R the reliability value. The value of P_0, the probability of no failures, is taken as the numerical measure of Reliability R. For a reliability value of 0.99, $e^{-t/\bar{T}} = e^{-.010}$ Actually, $P_0 = 0.9900498$ for $t/\bar{T} = .010$. In this relation t is the period of time that operation is required, sometimes considered the time required to complete a mission, while $\bar{T}$ is the Mean-Time-Between-Failures and per equation (3), p.176 of the AGREE report is $\bar{T}=t_1/F$, where t_1 is the total operating time for each equipment under investigation and F is the total number of failures. This may be rewritten as $1/\bar{T}=F/t_1$, the failure rate for the inspection items under test.

Since this paper is primarily a consideration of Reliability Education and not a complete technical development of control limits, a discussion of possible limits for the case above will illustrate the nature of the material that must be developed and presented to reliability engineers. These engineers, in turn, must understand these principles sufficiently well to be able to explain these limits to management, research and design engineers, and also to production.

Assume that t_1 is maintained constant, then $1/\bar{T}$ varies with F only. F now is the number of defects and for R=0.99, t=10 and $\bar{T}$=1000 for $t/\bar{T}=0.010$ hence $F=.001t_1$ and must be integral for an observed value, i.e. 1,2,3, etc., but may be treated theoretically, equal to non-integral values. For t_1=1000 hrs., F=1. Treating F as a Poisson distribution then the standard deviation of F, $\sigma_F = \sqrt{F}$, hence, $\sigma_F = \sqrt{1} = 1$ Then for control limits including three times the standard deviation about the expected value $F' = F \pm 3\sigma_F = F \pm 3\sqrt{F}$

and for F=1, the limits are -2 to 4. Since negative failures have no meaning, a spread of 0 to 4 includes from 89% to 99.73% of the distribution, possibly from 89% to 99.865% since the distribution is not symmetric, but skew. When F=9, then $F^* = F \pm 3\sqrt{F} = 9 \pm 3(3) = 0$ to 18 and an equal spread about F=9 occurs. For F=9, then $\bar{t}_i$ = 9,000 hours.

What might occur when t_i = 1,000, F=1 and consideration is given to an F value at the upper three sigma (3σ) Control Limit, where F* is 4. Then $1/\bar{T} = 4/1000 = 1/250 = .004$. For t=10, then $R=e^{-10/250} = e^{-10(.004)}$ and for $R = e^{-0.04}$, R per Poisson Tables is reduced to 0.96, actually 0.9607894 per table. The seven figures given by the table should not be used as the data are usually not good for more than one or at most two significant figures.

What happens when t_i = 9,000 hours and F=9 for a value at the upper control limit, i.e. F*=18. $1/\bar{T}^* = 18/9,000 = .002$. For t=10, then $R=e^{-10(.002)} = e^{-0.02} = 0.98$. Thus, for t_i = 1,000 a value of F at the 3σ upper control limit reduces R from 0.99 to 0.96. However, if t_i = 100, then F = 0.10 and $F^* = F + 3\sqrt{F} = 0.10 + 3\sqrt{.10} = 0.10 + 3(.31623) = 0.10 + 0.9487 = 1.0487$. For this value $1/\bar{T}^*$ is $1.05/100 = .0105$ and $R = e^{-10(.0105)} = e^{-.105}$ and R = 0.90. Small samples provide less reliability. Shorter periods of operation do likewise. All these values were computed for t = 10 hours. The table below tabulates these upper 3σ values of F for t values of 1, 10, 100 and 1,000 hours, respectively for a few selected values of F. The probability values of .89 and .9973 noted for 3σ limits about the expected or mean value are obtained from two assumptions. The .89 comes from Tchebycheff's Inequality which reads as follows: "The probability that a variable X should deviate from its mean by more than k times its standard deviation is equal to or less than $1/k^2$." When k=3 then $1/k^2 = 1/9$ and 8/9 = .8888 or .89 to two significant figures. The .9973 is the probability value read from normal law area tables for $\bar{X} \pm 3\sigma_X$. It should be noted that no restrictions on the shape or nature of the distribution are applicable when using Tchebycheff's Inequality. For this case the Camp-Meidel extension may apply. It reads: "If the distribution of X is unimodal, the probability that X should deviate from its mean by more than k times its standard deviation is equal to or less than $1/2.25k^2$." For k=3, then $1/2.25k^2 = 1/20.25$ or equals 0.0494 so that this Confidence Band may be considered as being 0.95 for all practical purposes.

TABLE 1: POSSIBLE VARIATIONS IN RELIABILITY VALUES

CONFIDENCE LEVEL = 0.95 (Approximately)
Upper Control Limit $F^* = F + 3\sigma_F$ Level Determined for Selected Values of F, t and t_i

for $R = P_0 = e^{-t/\bar{T}} = e^{-0.010} = 0.99$

where $1/\bar{T} = F/t_i$ and $1/\bar{T}^* = F^*/t_i$.

	t = 1 1/T̄ = 0.01, T̄ = 100 Hrs.				t = 10 1/T̄ = 0.001, T̄ = 1,000 Hrs.			
t_i =	10	100	900	1,600	10	100	1,000	9,000
F =	0.1	1	9	16	0.01	0.1	1	9
F^* =	1.05	4	18	28	0.31	1.05	4	18
$1/\bar{T}^*$ =	.105	.04	.02	.0175	.031	.0105	.004	.002
$t/\bar{T}^*$ =	.105	.04	.02	.0175	.31	.105	.04	.02
R =	.9003	.9608	.9802	.9827	.7338	.9003	.9608	.9802

	t = 100 1/T̄ = 0.0001, T̄ = 10,000 Hrs.					t = 1,000 1/T̄=0.00001, T̄=100,000 Hrs.		
t_i =	10	100	1,000	10,000	90,000	10	1,000	100,000
F =	0.001	0.01	0.1	1	9	0.0001	0.01	1
F^* =	.0959	.31	1.05	4	18	.0301	.31	4
$1/\bar{T}^*$ =	.00959	.0031	.00105	.0004	.0002	.00301	.00031	.00004
$t/\bar{T}^*$ =	.959	.31	.105	.04	.02	3.01	.31	.04
R =	.3837	.7338	.9003	.9608	.9802	.0493	.7338	.9608

The table above illustrates the point that in a true Reliability Training Program it is necessary to consider all phases of Reliability evaluations since the usual cases given in articles and texts are the simpler cases given to illustrate the principles. In practice, the cases are more complicated so that good estimates of actual reliability attained are obtained by taking into consideration all factors. It is no wonder that little credence is given to reliability figures as now given since their error is necessarily very large. In many cases reliability values are just guesses since practically no data are available in the field covered. In other cases however, there is little excuse for the large errors found in the estimates. Mean values must be supplemented by possible ranges within which the actual values may fluctuate. These may be found by evaluating reliability controls that reflect both control and also lack of control. Possible worst cases when considered carefully might hold up the firing of a missile.

However, if the indication of potential trouble results in the location of several possible causes of potential malfunctions before the firing and results in a success rather than a failure, such reliability evaluations have more than justified their compilations and evaluations.

6. Education for Reliability

It is necessary to cover all the different areas wherein it is possible to have any degradation in the quality, reliability and operation of the product or article under consideration. The article might be a complete missile or only a screw, rivet or washer. If a lock washer is not in its proper place and is ineffective, parts may not work due to vibration, hence, it is imperative that attention be paid to all minute details. Hence, one of the first elements in an educational program for reliability is to show those individuals responsible for making an article the importance of maintaining specification requirements at every stage of development and production and particularly for those elements that are critical and also for those inaccessible parts difficult to replace or repair. The first educational objective for reliability is the development of quality-consciousness.

There arises another area where reliability education is required. Many companies are not certain concerning the exact demands in a contract or purchase order concerning its reliability requirements. Intrinsically managements strive for the best quality available for the price or budget money allotted. Sales and Schedules, the two S's, come first with profit possibly having even a higher priority. Design, engineering, quality, reliability, longevity, satisfactory performance after storage for long periods of time such as after five (5) years of shelf life, and many other features are secondary and are often taken for granted. The educational program should place these in their proper perspective.

Since many specifications for the military devote 50 to 80% of their pages to reliability requirements, it is necessary to meet these stipulations. Unfortunately, hardware, electronic parts, modules and units may be assembled without too much difficulty and the resultant assembly will usually work after a fashion. If parts used came from controlled universes that satisfy the specified engineering requirements, including minimum and maximum values for a large number of the parts, the resultant products may be extremely satisfactory. What must be emphasized is that this is not always true. Quality engineering requires constant vigilance. Since it is too costly to perform 100% inspections and tests time and again, train technicians and engineers in sampling techniques so that adequate check or audit inspections may be made at strategic stations. Also train these individuals in such a way that they can select the strategic stages. This additional protection is needed in Research and Development contracts particularly at the time

parts are being assembled, bench tests are being run, environmental tests are being conducted or waived, so that sufficient information is available to insure a reliable design and a quality product. What is needed is an appreciation of integrity, dependability, reliability, ruggedness, ability to stand shock and abuse, and what each individual can do to ensure that the overall quality and performance desired will be achieved. The second objective in reliability education is to train individuals to differentiate between minor and critical details and use their efforts most effectively in the areas of greatest importance. Tersely this may be stated as placing first things first to obtain maximum reliability.

A third objective must be stressed. Training must be given in modern methods and techniques for reliability evaluation. There must be developed an appreciation of the limitations of certain parts of the theory to date and the necessity of doing research in reliability theory and allied areas such as operations research, mathematical statistics and also basic physics. Reliability engineers working in electronics must realize that much of their data is subject to change and re-evaluation, being based on relatively small samples. Environments are changing and the demands of service, particularly the military, are much more exacting. Errors of measurement that formerly could be ignored must now be considered. Hence, the third objective is advanced technical training in reliability methodology.

7. Economic Factors - Standards, Value Engineering, Interchange of Data and Reliability

In Reliability Education, use must be made of all past available material, methods and techniques. The truly effective Reliability Engineer must not only know the product being considered better than those in charge of the product but also must be acquainted with the most recent engineering advances in all fields. Hence, his design evaluations will be accepted as being authentic, valuable and a contribution to the project. He must be acquainted with critical tests so that he can take charge of the most modern test facilities and conduct tests that are meaningful. Since it is impossible to obtain all these qualities in one man, then a director plus experts in the areas under consideration will make up a valuable reliability team. The approach is similar to that used in Operations Research based on the handling of problems by properly chosen teams.

Standards must be established that are economic. They must be in line with market demands and prices. It is necessary to work with Value Engineering groups in properly evaluating the selection of proper designs and component parts. Evaluating complaints on similar equipments, establishing the level of customer demands, setting up procedures and tests for evaluating component parts - all are a part of the proper training in Reliability. Establishing excellent laboratories for obtaining controlled data is a must since there must be

established more economical means for evaluating component parts obtained from varied sources. Specifications and procedures as well as designs are written around "hardware". This means that the characteristics of this "hardware" commonly used for military products must be evaluated, tabulated, and be available to all contractors.

Attempts have been made to secure some central agency to maintain such files. With proper publicity and broader training programs in reliability an appreciation of these needs will eventually be so apparent that steps will be taken to achieve this goal. A start has been made through interchange of data on very similar projects involving missiles at this time. Training engineers to carry out this task in such form as to be most effective will forward the reliability program and allow more time for new evaluations, new researches and also release funds for audit inspections and tests as well as better design evaluations. With much more basic data available to the designers and the engineers, their designs should improve in many areas and in particular in the field of Reliability.

Since this Section is devoted to the Economic Factors with respect to Reliability, it is necessary to reconsider the problem as a whole and see what steps were taken in the early stages of Quality Engineering to achieve Reliability. Reliability Education must consider not only new knowledge but past history with respect to the basic factors of Reliability, kindred or allied areas of activity, and what Reliability was achieved in the past by these other methods and techniques used prior to the cry and contracts for Reliability.

In 1926 the Bell System had Committees on Inspection and Rating of the Quality of Manufactured Products operating and holding regular meetings about every two or three months. The Rating Committee was concerned w th Reference or Standard Quality Levels, Control Charts for maintaining control at these levels, and methods for taking into consideration the complexity of the equipment and systems, but also the seriousness of the requirements. Economic Standards of Quality were established as Standard Demerits per Unit values. These levels were based on Manufacturing performance, but were modified to take account of costs, malfunctions, field reports, and actual complaints received from the Telephone Companies using the Equipments and Apparatus.

Many will not agree that such a Rating System is related to the evaluation of Reliability. The results were tied in with other results and one series of charts was developed that presented Troubles per Trouble Unit. Many of the charts were established so that with the current Check Inspection or Audit Inspection samples being used, the number in such samples was such that with the current standards of Demerits-Per-Unit values and the Standard Constant C_s used to determine the control limits, based on sound Statistical Theory, the occurrence of a single Critical defect with a Major classification would throw the

D_u (Demerits-Per-Unit) Value outside control limits, where a minimum monthly sample size was given. Defects or Nonconformances really Critical, are generally always inspected 100%. Major A's and B's with Demerit weights respectively for each item of 100 and 50 Demerits were established so that effective standards and controls over in-process and final products may be achieved. Minor C's and D's had assigned to them respectively demerit values of 10 and 1.

This Rating System was tried out on Jet Engines by General Electric and appears to have been found very satisfactory. It has been applied to Repair operations in the field by the Air Force. The Bell System uses it in all their various divisions and activities, including their 29 Supply Depots scattered over the nation. Missile and Aircraft Manufacturers have been against this system as they were afraid that it would be too complicated. Very few companies tried the right approach in setting up Demerit Lists for the characteristics and inspection items applicable. These can readily be grouped. Setting up individual values for each characteristic would be too costly. As a compromise, using the group method it is possible to establish sample sizes, criteria, courses of action, methods of presentation, etc., to such an extent that all items used in quality and reliability evaluation are covered by sample results. Rating Charts may judiciously be used as a Reliability Index if arranged in Index Form. The mathematical relations are given in the next paragraph.

The most general case occurs when each characteristic or inspection item is considered separately so that the demerits per-unit value, is obtained from the relation:

$$D_u = \sum w_i d_i / n_i \ , \qquad (1)$$

where D_u = Demerits - per-unit,

w_i = Demerit value assigned to inspection item i,

d_i = Observed number of defects for the ith inspection item in a sample of n_i units,

n_i = Sample size for the ith inspection item, and

Inspection Item = Any characteristic, property or requirement for which inspection (including test) is required.

Now, it is easier to have the same sample size for a group of items where a four-fold classification of defects for other than critical items is used, i.e. for major and minor defects, and a sample of size n_A is used for all Class A defects or inspection items, n_B for Class B defects or inspection items, n_C for Class C defects or inspection items and n_D is the sample size for inspecting the Class D defects or inspection items. This reduces equation (1) to

$$D_u = w_A d_A / n_A + w_B d_B / n_B + w_C d_C / n_C + w_D d_D / n_D \ . \qquad (2)$$

The standard or expected value of D_u is written as D_{u_s} and is derived either from past history or from an analysis of customer demands and desires. Then the following standards are established for each of the four groups:

$$p_{A_s} = \sum d_A/n_A,\ p_{B_s} = \sum d_B/n_B,\ p_{C_s} = \sum d_C/n_C,\ p_{D_s} = \sum d_D/n_D, \quad (3)$$

where $\sum n_A$, $\sum n_B$, $\sum n_C$, & $\sum n_D$ are the sums of samples taken during a representative period of production or development. Usually $n = n_A = n_B = n_C = n_D$ for ease of administration.

Control Charts for these D_u values may be determined from the general relation for D_{u_s}:

$$D_{u_s} = w_A p_{A_s} + w_B p_{B_s} + w_C p_{C_s} + w_D p_{D_s} . \quad (4)$$

From the theory of errors by taking successive partial derivatives the standard deviation for relation (4) is

$$\sigma_{D_u} = \sqrt{(w_A^2 p_{A_s} + w_B^2 p_{B_s} + w_C^2 p_{C_s} + w_D^2 p_{D_s})/n} = \sqrt{c_s/n} . \quad (5)$$

Thus the Standard Constant C_s takes the place of p in determining standard deviation and control limit values. The relation for C_s is

$$C_s = w_A^2 p_A + w_B^2 p_B + w_C^2 p_C + w_D^2 p_D = \sum w_i^2 p_i,\ (i=A,B,C,D), \quad (6)$$

where these p values are expected values. Control Limits may be written as

$$D_{u_s} \pm t\ \sigma_{D_u} = D_{u_s} \pm t\sqrt{C_s/n}, \quad (7)$$

where $t = 3$ for staff purposes and $t = 2$ for production purposes. The Confidence Levels are from 0.89 to 0.9973 for $t = 3$ and from 0.75 to .9545 for $t = 2$. Other forms are written as follows:

Demerits: $D_s \pm t\ \sigma_{D_s} = D_s \pm t\sqrt{C_s n}$, (8)

where $D_s = n\ D_{u_s}$ = expected demerits in sample of size n.

Index: $I = D_u/D_{u_s}$, (9)

$$I_s \pm t\ \sigma_I = 1 \pm t\sqrt{C_s/n}\ /D_{u_s} . \quad (10)$$

It must be noted in our Reliability Educational Training program that the reliability desired is perfection, 100% satisfactory performance. This means no defects, no demerits, no failures, no malfunctions and perfect performance. This cannot be realized as we have

slight deviations and also wearout. Hence, the controls for Reliability must be similar to those above for the index where we set a reliability goal as an R_s and then determine how closely we approach this goal. Thus $I_R = R/R_s$ and

$$I_R = R/R_s \quad , \tag{11}$$

and $$\sigma_{I_R} = \sigma_R/R_s \quad , \tag{12}$$

with control limits of

$$I_{R_s} = 1, \; I_{R_s} \pm t\,\sigma_{I_R} = 1 \pm t\,\sigma_R/R_s \quad . \tag{13}$$

The rating system used for many years is practically equivalent to these measures of reliability. Use may be made of a lot of past data and training material when developing a comprehensive training program for Reliability.

8. Reliability Training Programs - Modern Techniques

Summarizing the above thoughts on Reliability Education, it must be noted that the most important element is to know when constructive action must be taken. A historical treatment of reliability can be made when the last unit of any type has been destroyed or has worn out. Then the true reliability of the units in that group may be observed. Modern demands are for accurate estimates of reliabilities that will be obtained. How to make valid Reliability forecasts is one phase of Reliability that must be covered.

When working in Reliability and Quality Engineering what action must be taken to guide designs into channels where available data indicate the optimum reliability may be obtained. Operations Research deals with the optimization problems of management. Hence, Reliability Education requires a knowledge of Operations Research techniques.

Systems are being developed from new components. Many new articles and parts are being considered in these system designs. Two objectives must be considered here in an educational program. One is a knowledge of System Engineering and liaison work. The second is knowledge of component part reliability values. The first is a philosophy evaluating the whole from its parts and needs to consider management philosophies and also statistical checks such as those embodied in the Analysis of Variance. The second requires laboratory test results with checks for significant differences between different parts and their characteristics. Management Science and Advanced Statistical Techniques, even possibly Decision Functions, need to be covered in a complete Reliability Educational Program.

Reliability evaluations, point sets, theory of numbers and related techniques need to be covered to some extent. Basic statistical techniques are used to establish the various probabilities that need consideration such as existence probabilities and the like. A part of these methodologies include distribution theories, Monte Carlo methods, use of Poisson exponentials, binomials, Normal law theory, Lexis, Poisson and Bernoulli sampling and their respective errors. Not all apply but those parts that do may prove to be very profitable indicating where reliability may be obtained at minimum costs.

Thus, Reliability Education must concern itself with:

1. Valid forecasts of Reliability - techniques and errors.
2. Optimizing designs - techniques of Operations Research.
3. Component part reliability values - tests for significance.
4. Systems engineering - management science.
5. Distribution and probability theory.
6. Design reviews - value engineering.
7. Reliability block diagrams - flow charts.
8. Nonstandard parts - establishment of economic standards of quality for standard and nonstandard parts.
9. Laboratory tests and evaluations.
10. Life tests, reliability tests, longevity, storage life.

Many others could be noted. These will cover the rudiments of Reliability.

9. References

1. AGREE Report, "Reliability of Military Electronic Equipment" Report by Advisory Group on Reliability of Electronic Equipment, Office of Assistant Secretary of Defense, 4 June 1957. 377 pages. Supt. of Documents, U.S. Government Printing Office, Washington 25, D.C.

2. AMCP 74-1 "Quality Control Reliability Evaluation Procedures for Pilot-Production and Production as Recommended by Task Group No. 3 of AGREE", 31 March 1959, pp. 1-16.

3. AFBM Exhibit 58-10, "Reliability Program for Ballistic Missile and Space Systems", 1 June 1959, pp. 1-20.

4. Duncan, Acheson J., "Quality Control and Industrial Statistics" 1952. Richard D. Irwin, Inc., Chicago, Ill., 663 pages. (p.69 in particular).

5. MIL-R-26667A(USAF), "Reliability and Longevity Requirements, Electronic Equipment, General Specification for," 2 June 1959. (MIL-R-26667B has been released but is in very short supply and differs little from the A issue according to reliability engineers who have seen both issues.)

6. Molina, E.C., "Poisson's Exponential Binomial Limit" "Table I-Individual Terms, Table II-Cumulated Terms", 1949, D. Van Nostrand Co., Inc., Table I 45 pages, Table II 47 pages.

7. IRE Transactions on Reliability and Quality Control. Most of these papers should be checked in a Reliability Educational Program. A few typical examples are noted below:

   7.1 Peterson, N.M., "Application of a Method of Inspection Testing to Assurance Reliability", IRE Transactions on Reliability and Quality Control, PGRQC-15, December, 1958, pp. 19-26.

   7.2 den Broeder, G.G., Jr., and Kane, W. E., "A Reliability Analysis of Recoverable Missiles," IRE Transactions on Reliability and Quality Control, PGRQC-16, June, 1959, pp. 34-40.

   7.3 Heyne, J.B. and Brotman, L., "The Employment of Failure Rate Data in Logistic Planning," IRE Transactions on Reliability and Quality Control, PGRQC-16, June, 1959, pp. 41-52.

8. IRE Symposium Procedures for the past 6 years should be part of a Reliability Education Bibliography.

DEVELOPMENT OF A RELIABILITY COURSE SPECIFICALLY FOR DESIGN ENGINEERS

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SUMMARY

Most reliability training courses have been directed to reliability engineers, manufacturing personnel and management. Such courses are broad in scope and cover all phases of a reliability program. Improving intrinsic reliability, however, is the design engineers' problem, and a need exists for a reliability course specifically aimed at helping him to improve his competence.

This paper describes the development of such a course for use in the Defense Electronics Division of the General Electric Company.

INTRODUCTION

For several years, those operations of the General Electric Company which serve the Department of Defense have had in place organizational functions devoted exclusively to reliability improvement.

These reliability groups have been working toward their objectives by such means as apportionment, evaluation and selection of component parts, tolerance analysis of circuit design, mechanical and electrical design reviews, manufacturing quality control, environmental testing and field reliability measurement, analysis and feedback.

From these activities considerable experience has been gained in the techniques for improving reliability as a result of participation in all phases of system flow or evolution, from the specification through design, manufacture, shipment, and installation, to field use.

This system flow, however, spans a considerable period of time, up to several years on complicated systems, and means that the functioning of a reliability group is spread out in time as well as being spread over all the established functions such as engineering, manufacturing, field operations, etc.

These two factors, time span and functional span, are significant reasons for the difficulties encountered in establishing the authority of a reliability group in any organizational structure.

In the areas of defining and specifying reliability programs, significant progress has been made by governmental agencies, an example being AFBM Exhibit 58-10; entitled, "Reliability Program for Ballistic Missile and Space Systems". However, when a reliability program is to be implemented, it is still necessary to determine a clear concept of those specific activities of the organization to which the reliability group can make effective contributions.

A review of the responsibilities and authorities of all functions in the total system flow of an organization reveals that each function, with the exception of design engineering, has a responsibility for reliability which is limited by the engineering drawings and other documentation. In other words, these other functions cannot produce, install or operate a system that is any better than the design.

This may be considered to be just another way of saying that reliability is inherent in design, but it does serve to emphasize that there are basic, fundamental limitations to the improvement in reliability that can be expected or achieved in functions other than engineering.

There is good logic in this situation, in that the system and equipment are first created in detail when the engineering function has completed the design. Then, with drawings and other engineering documentation passed to the manufacturing and succeeding functions, there exist the detailed criteria against which the output of each function can be measured, as by Quality Control, Inspection and Test. These functions cannot be required or expected to provide output that is any better than their input, which has been spelled out by the engineering function.

Evaluation of an engineering function is difficult to measure because its inputs are in the form of general and functional requirements. On the other hand, output cannot be measured until something is created --the detailed design. In the creative process, engineering must originate the detailed design and build breadboard and prototype models by which the function can be measured. Even then, final measure cannot be made until the system flow has progressed to the operational phase. Consequently, Reliability improvement and the development of techniques to achieve it must be concentrated at the early design stage.

These are reasons why reliability groups are generally in the engineering function, and why the strongest reliability efforts should be devoted to the early design phase. There, we have the earliest possible opportunity in the time flow of a system to improve its inherent reliability, and can operate most effectively to fulfill realistic engineering responsibilities.

Reliability groups perform many line and staff services in the engineering function. An additional service is to improve the competence of the engineers themselves. This is accomplished by individual counseling, design reviews, publications, and more recently in our own Defense Electronics Division, by an engineering course specifically prepared for design engineers.

Development of the Engineering Course, "Reliability by Design"

The introduction emphasized the amount of consideration that was given in the development of the course to the extraction of specific work activities from the philosophical concept that "reliability is everybody's business." These are the areas in which reliability groups can accomplish the most good.

The development of the course started with the preparation of an outline by a task force. Since it had been decided that the student body should consist principally of design engineers, it was necessary to focus attention on those subjects which would be of use to them, and to resist the tendency to include those which are generally included in an overall reliability program.

Then, recognizing that "Reliability" may be considered "Performance as a function of time" it was decided that the objective of the course must be to augment the design engineer's knowledge of how to achieve specified performance with expanded knowledge of how time and environment affect materials, parts and circuit functions.

Also, it was decided that we would not spend too much early course time on the mathematics of probabilities, which might mislead the engineer into believing that reliability is statistics rather than engineering.

Instead, the outline was developed with a concentration on the basic engineering technologies, which are the ultimate source of design for higher reliability, and the mathematics was introduced as needed.

Outline of the Course

The course sessions were held weekly for two class groups, and lasted about 2-1/2 hours each. One group met in the morning, and the other in the afternoon, on Mondays. Several reliability engineers from General Electric plants in other cities also attended for the purpose of applying the material to reliability courses at their locations.

The outline of the course as it was conducted this past Fall term of 16 sessions is as follows:

Session	Subject
1	Introduction
2	Probability Concepts
3	Reliability Design Principles
4	Mechanical Design
5	Heat Transfer
6	Nuclear Radiation
7	Reaction Kinetics
8	Dielectric Behavior
9	Predicting Reliability
10, 11, and 12	Mathematics of Reliability
13	Reliability Measurements
14	Design of Reliability Tests
15 and 16	Design Case Histories

With the exception of the case history sessions, the course was written and conducted by eight consulting engineers of the General Engineering Laboratory, which is a service operation for the entire General Electric Company. The case history sessions were presented by engineering personnel of the Defense Electronics Division.

The homework consisted principally of reading the lecture notes, a total of about 450 pages, which were distributed prior to the class sessions.

At this point a summary of each of the sessions may be of interest.

Session 1 Introduction

Two managers of reliability groups, Messrs. C. M. Armour and B. D. Hatch, who have developed and directed reliability activities in the Defense Electronics Division for a number of years, described the history, problems, accomplishments and challenges of this relatively new field of engineering.

Mr. E. G. Bianco, coordinator of the course development in the General Engineering Laboratory and also a lecturer, presented the outline and objectives of the course.

Session 2 Probability Concepts

This session was a fundamental exposition of probability as it applies to the basic reliability tenets. It was intended to serve as a precursor to such concepts as prediction, analysis and redundancy. Much of the material covered here was expanded and illustrated in subsequent lectures. The format followed that of a basic course in probability, including

Definition of Probability

Probability Rules Given:

- Mutual Exclusion

- Independence

- Conditional Probability

Bernoulli Trials and the Binomial Model

- A Basic Method for Acceptance Testing

Poisson Behavior and the Exponential Law

Session 3 Reliability Design Principles

A detailed program plan was presented for the design engineer, covering the product flow from specification to field data feedback. Some of the principal steps included were:

Requirements

Preliminary Design

Parts Selection

Estimation of Reliability

Design Centering

Tolerance Analysis

Drift Effects and Aging

Design Reviews

Test Planning

Quality Control Requirements

Testing and Analysis

Field Operation Analysis

Design Improvement

Session 4 Mechanical Design

The mechanisms of failure in mechanical design and the means for testing and designing to avoid them were the subjects of this session. Emphasis was on the analysis of the probability of failure, and accelerated life tests and evaluation methods.

Some of the subject headings were:

The Design Problem

- Types of Failure
- Manufacturing Tolerances
- Quality Control
- Design Philosophy
  - Fail Safe
  - Redundancy
  - "One-horse-shay"

Environment

- Loads
- Temperature
- Corrosion

Stress Analysis

Material Behavior

Laboratory Tests in Designing for Fatigue

Test Analysis Techniques

Session 5 Heat Transfer

This session was concerned with the techniques of designing for control of temperature, in order to avoid reliability degradation and failure. This involves heat generation, dissipation, and temperature rise, and specific subjects included:

Failure Rate as a Function of Temperature

Sources of Heat

Modes of Heat Transfer

- Convection, Free and Forced
- Radiation
- Conduction
- Evaporation and Boiling

Temperature Rise

Temperature Distributions

Arrangement of Parts and Enclosures

Heat Sinks

Measurements

Session 6 Nuclear Radiation

The several kinds of radiation from nuclear materials and explosions, and their effects on electronic equipment, both instantaneous and cumulative were presented. Some of the subject headings were:

Types of Radiation

Interaction with Matter

Effects on Materials

- Organic

- Inorganic

Effects on Electronic Components

Designing for Radiation Service

Radiation Testing

Effects on Circuit Operation of High Dose Rates

- Recovery Rates

Session 7 Reaction Kinetics

This session dealt with the fundamental causes of failures in terms of the reactions between materials which alter their molecular and atomic structures. The subject headings included:

What Materials May Interact

Effects of Temperature and Concentration

Reaction Speed

Effects of Catalys's

Reactions in Enclosed Modules

Irradiation Effects on Reaction

Corrosion as a Reaction

Effects of Reaction on Mechanical Failure

Session 8 Dielectric Behavior

The mechanisms and causes of degradation and failure in dielectric materials, and what can be done to evaluate them in designing for reliability were the objectives of this session. Specifically considered were:

Mechanism of Gaseous Breakdown

Corona

Mechanism of Breakdown in Liquids and Solids

The Effects of Voids in Dielectrics

Differences Between a-c and d-c Test Procedures

Insulation Testing for Moisture, Polarizable Contamination, etc.

Session 9 Predicting Reliability

In this session there was described the generally accepted techniques for predicting the reliability of equipment with the exponential or constant failure rate process assumed. A thorough critique of these techniques was presented. In addition, the effects of other failure rate processes were reviewed. Subject headings included:

The Exponential Case, Assumptions and Limitations

Analytical Procedures

Reported Failure Rate Data

Random or Chance Failures

Secondary Failures

Early-Life Failures

Wear-Out Failures

Degradation Failures

Non-Exponential Failure Distributions

Derating of Parts

Sessions 10, 11, and 12 Mathematics of Reliability

In these sessions a mathematical treatment of failure processes was developed. Principle failure mechanisms were illustrated and derived from stochastic models. Particular emphasis was given to methods of estimation and evaluation of life behavior parameters from test data. The subjects covered were:

Derivation of the Poisson Process

Generalization of Poisson Behavior to Weibull, Gumbel, Gamma and "Pareto" models

Estimation Theory

Conditional Failure Density and Failure Rate Structures

Techniques for Analysis of Failure Data

- Tests for Appropriateness of Model
- Methods of Estimation for a Particular Model
- Significance Tests

Confidence Statements

Sessions 13 and 14 Reliability Measurements and Tests

These sessions extended the earlier developed theory and technique into the realm of acceptance and estimation life testing. Careful distinctions were noted between the two types of test approaches. Detailed attention was given to aspects of the accelerated test rationale in which both compressed-time testing and increased-severity testing were explained. Further emphasis was given to new techniques in this field e.g. Life "barometer" studies; life-stress relationships via response surfaces, etc. The principal subject headings included:

Definition of Product Life

Life Testing Theory

Determining Estimation Test Requirements

- How many samples, how long, how many failures?

Determining Acceptance Test Requirements

- How many samples, how long, how many failures?

Life Test Designs

- Replacement
- Non-replacement
- Sequential
- Time-truncation
- Sample-truncation

Test Environments and the Stress-life Model

Advanced-stress testing

Compressed-time testing

Survey of K-dimensioned "Stress-space" via Orthogonal Designs

Life Indices and Barometric Testing

Some aspects of Controlled Field Testing

Sessions 15 and 16 Design Case Histories

In these sessions, experienced engineers described the problems and procedures of designing specific equipments for high reliability. The case histories chosen were from among those for which operating experience has been obtained for evaluation of the designs.

Results of the First Run of the Course

The reaction of the engineers taking the course has been generally good. However, a criticism has been that using ten lecturers, each expert in his own field, has resulted in some lack of unity or integration of the material presented. Also, there was not sufficient "cook-book" information to satisfy some of the engineers.

The Spring term sessions of the course this year will endeavor to alleviate these conditions by having a single instructor conduct most of the sessions, and integrate more "cook-book" procedures in the flow of the course. However, those sessions which are particularly oriented to single technological areas will again be presented by specialists.

The basic lecture notes as they now exist (about 450 pages) will be used as reference material and will be supplemented to reflect the changes and additions to the course.

Other departments of General Electric in other cities are also presenting reliability courses. These are being developed for the particular needs of those departments, many of which are in the industrial and commercial fields, and will utilize portions of the subject course as they are applicable.

INCREASING RELIABILITY THROUGH

OPERATOR AND INSPECTOR TRAINING AND CERTIFICATION

Robert F. Koenig, Manager, Materials and Processes Engineering
General Electric Company
Missile and Space Vehicle Department

Substantial amounts of money, and even more important - time, are being saved in our re-entry and space vehicle development programs by an extensive program of training and certifying operators and inspectors. Reliability is also being increased thru reduction of operator variability and improved process inspection.

The training and certification of operators and inspectors is not new. For instance, weldors (1) and penetrant inspectors (2) require certification to work on military equipment (even though such a requirement is contrary to the generally-accepted practice of specifying results instead of methods for achieving them). One factor which undoubtedly led to the weldor certification requirement was the wide variation observed in the interpretation and application of standard welding procedures by individual operators. A second factor was the difficulty in some cases of determining weld quality on completed airframes and structures.

What is different about the training and certifying of operators and inspectors is the extent and depth of the program at G.E.'s Missile and Space Vehicle Department. The delays and cost of rework observed as our reentry vehicle program entered initial production stages were great enough to justify investigation and corrective action. Inspection reports and failure analyses showed that many rejections and failures were directly attributable to operator technique, inspector knowledge, or both. Consideration of this situation led to the conclusion that one of the characteristics of today's R. & D. business - the absence of sufficient repetitive production for the development of high degrees of proficiency - was a significant factor. Even though the same basic process may be used in a series of models, there was usually enough difference from model to model to require variations in technique. One way around this was to give the operators and inspectors some understanding of what they were doing and the reasons for the steps in standard processes so that they would be better able to cope with a variety of applications of the same basic processes.

(1) MIL-T-5021, Test, Aircraft Welding Operators' Certification
(2) MIL-STD-410, Certification of Penetrant Inspection Personnel

A second factor in the decision to provide a training and certification program was the rapidity with which new and relatively unevaluated processes were introduced into the production cycle. Metal-to-metal and metal-to-plastic joints are being bonded routinely today when only a few years ago this was considered an experimental achievement. In many cases the process was every bit as critical and just as subject to variations as a result of operator performance as welding. Why should any less care be exercised in selecting personnel to bond critical assemblies together than we would use in selecting weldors? The same is true for solderers - in missile systems, soldered joints can be just as critical as weldments.

These considerations led to the decision to adopt training and certification program for the following processes:

Manufacturing Processes	Testing Procedures
Alodining	Inspecting Arc Welding
Bonding	Hardness Testing
Foaming	Magnetic Particle Testing
Heat Treating	Penetrant Testing
Lay-Up Laminating	Tensile Testing
Passivating	Ultrasonic Testing
Potting	Interpreting Radiographs
Soldering	
Spot Welding	
Spray Painting	
Torch Brazing	

New courses are added as new processes are introduced in the shops.

With each course, the same general procedure is followed. The candidates for qualification attend a period of one or more hours of class room instruction in the basic theory behind each step in the operation procedure. Abbreviated texts covering the subject matter presented are given to each operator. Following that, they are taken into the laboratory where they observe experienced, capable technicians carrying out the operation. They also have the opportunity to practice themselves during this period. The third and final phase of the program is the written and practical test of the operator. Certification cards are issued to those who pass the written test and successfully fabricate the test samples. Make-up lectures, demonstrations, and tests are provided for those who miss sessions for valid reasons. Also, retesting is provided after some additional instruction for those who fail the first time. Reassignment is recommended for applicants who repeatedly fail the same test. Outlines of typical programs are presented in Appendixes I and II.

After less than a year of operation, the operator and inspector training and certification program has resulted in improved workmanship and fewer

rejections. We have not run controlled experiments to obtain reliability data, but there is no doubt from the other evidence that potential failures from processing deficiencies are being eliminated, and that we may eventually reach a manufacturing process failure rate approaching zero.

APPENDIX I

SPRAY PAINTING

A. Lecture (2 hours)

1. Principles of Spraying - reason; types of spray.
2. Equipment and Facilities - guns; systems.
3. Preparation of Coating Materials - thinners; primers; storage, etc.
4. Procedure and Operation - preparation of surfaces; technique; touch-up; care of equipment.
5. Inspection of Coatings - continuity, thickness; adhesion.

B. Qualification Requirements (2 hours)

1. Written Questions on Lecture
2. Practical Exercise - spraying of three (3) panels.

C. Requalification (2 hours)

1. Annual Practical Exercise - spraying of three (3) panels.

APPENDIX II

INSPECTION OF MANUAL ARC WELDING

A. Lecture (1½ hours)

1. Requirements of Welding Inspector

2. Duties of Welding Inspector:
   Interpretation of drawings and specifications; verification of procedure; selection of test samples; interpretation of test results.

3. Weldment Defects

4. Testing of Welds and Welded Joints:
   Chemical; metallographic; mechanical; visual; magnetic particle; penetrant; radiographic; ultrasonic.

B. Demonstration and Application (1 hour)

C. Qualification Requirements (1 hour)

1. Written Examination on Lecture

2. Macroscopic Examination of Weldment

3. Identification of Five Defects in Weldment

D. Requalification (1 hour)

1. Annual Practical Exercise - Macroscopic examination of weldment; identification of three defects in weldment.

HUMAN FACTORS AND MISSILE SYSTEM UNRELIABILITY[1]

Charles Bates, Jr., Aerospace Medical Laboratory
Wright Air Development Division

John E. Short, Directorate of Systems Management
Wright Air Development Division

Albert Shapero, Stanford Research Institute
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INTRODUCTION:

Anyone associated with the test of missile systems has experienced cleaning rags left in LOX lines, inaccurately read meters, and switches inappropriately activated. Unfortunately, these "malfunctions" always seem to occur at especially critical times in the test program and usually go undetected until the investigation of the test failure. When these human errors are exposed by investigation, there is usually very little constructive action taken to prevent their reoccurrence. Generally this kind of system malfunction is categorized as "human error" or "random failure" and dismissed with the assumption that as long as you have people in a system, such things will occur.

Because of the lack of concrete evidence on the magnitude of human error in Air Force missile test programs, the Aerospace Medical Laboratory, WADD, in cooperation with the Directorate of Systems Management, WADD, instituted a research program to attempt to establish the scope of this problem, and if possible, to propose some practical solutions. It is the result of this research effort that we wish to discuss here.[2]

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1. The research reported here was performed under Contract AF 33(616)-5688 with the Stanford Research Institute, Menlo Park, California, and is more fully reported in WADD TR 60-36.

2. The authors wish to express their appreciation to Brig. Gen. Don Flickinger for his encouragement during the initiation of this research effort.

RESEARCH PROGRAM:

The urgency of this problem dictated that several limitations be placed on the research effort from the outset. First it was determined not to collect or generate any new raw data. It was believed that more than enough data existed in the form of range records, malfunction reports, countdown recordings, and unscheduled hold reports to provide reliable evidence for the scope of the problem being investigated. Secondly, due to time limitations, it was believed necessary to limit our sample of missile systems whose test programs would be investigated, and to consider only Air Force missile systems.

During our preliminary contacts with Air Force agencies and contractors to make arrangements for obtaining the necessary test data, extensive interviews were obtained with as many contractor and military groups concerned with the development of missile systems as were believed to possess experience with human error in test programs. These interviews and all subsequent data were obtained from personnel connected with the following missile systems and contractors:

Missile System	Contractor
Atlas	Convair, San Diego
Bomarc	Boeing Airplane Co.
Goose	Fairchild Airplane Co.
Hound Dog	North American Aviation, Inc.
Mace	Martin Co.
Matador	Martin Co.
Titan	Martin Co.
Nose Cone System for Atlas and Thor	General Electric
Snark	Northrop Corp.

Our sample of systems therefore included four strategic surface-to-surface missiles, two tactical surface-to-surface systems, one surface-to-air, and one air-to-surface missile system. One major missile subsystem was also included. As was pointed out previously, because of time limitations, only Air Force missile systems were included in this study.[1]

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1. The authors wish to express their appreciation to the many Air Force and contractor personnel who, through their cooperation, greatly facilitated the completion of this project. In many instances, entire case histories of missile launch activities were made available for analysis.

As an initial step in this research effort, a review was conducted of weapon system documentation in an attempt to determine if any formal attempt was being made to cope with the human-initiated malfunction. The reports reviewed included those dealing with program management, test planning, testing, malfunction reporting, reliability, and human engineering. From the review, it was found that:

1. Present malfunction reporting systems are inadequate in identifying human-initiated error or for providing analyzable data pertinent to human-initiated malfunctions that could be used in originating appropriate corrective action or for cross-comparing human-initiated malfunction among different missile systems. Though the portion of the equipment failure reports and unscheduled missile holds reviewed that displayed strong evidence of human error was large, these malfunctions were not reported in adequate form.

2. Little, if any, formal or systematic human engineering testing is being conducted. Of the nine programs reviewed, only one indicated any evidence of attempting a human engineering performance test program. This one approach, which was only a plan at time of review, was briefly described as a program for observing blockhouse operations in order to determine their adequacy, efficiency, and safety. No further detail was available at the time of review.

Since no evidence was found of past or currently active human factors engineering performance testing, the subsequent review of the data was primarily devoted to a determination of the frequency of human-initiated malfunction and an analysis of the current practices employed in reporting these data.

FREQUENCY OF HUMAN-INITIATED MALFUNCTION:

An effort was made to ascertain the relative frequency of human-initiated malfunction from available malfunction reports from seven of the nine missile systems listed above. In addition to these data, estimates of human-initiated failures were obtained from human engineering personnel who had independently conducted such analyses. Since the philosophies and methods of identifying and collecting malfunction data vary considerably among contractors, and even between divisions of the same contractor, and since the types of missile, the periods covered by the data, the number of missiles represented, and the extent of system development were different for each missile system examined, the data collected on any one missile system are not comparable with that collected on any other system. The results for any single system have been obtained by using the data available on that system in its own terms. Because of the limitations imposed by the data, the results here reported must be considered, therefore, to represent an attempt to determine conservatively the relative importance of human-initiated malfunction in missile system test programs.

Each of the malfunction reports collected was analyzed and the malfunction was classified as either human-initiated or equipment-initiated. An equipment failure or an unscheduled hold was considered to be human-initiated if the human component could be clearly identified as the causative agent in the immediate train of events leading to the system malfunction. Equipment failures that could be ascribed to such causes as misassembly, mishandling, or misadjustment by the operator were identified as human-initiated. Failures that ultimately might be ascribed to such causes as poor design were not so identified.

The specific procedure followed in identifying human-initiated failures varied according to the manner in which the original failure data were recorded. In most instances, the failure report system employed extensive failure codes which permitted gross sorting by code. In systems lacking some coding scheme, individual failures were reviewed individually with cognizant personnel from the missile contractor organization. Where failure codes were employed, the following steps were taken:

1. The reports were sorted to separate from the total those equipment failures that were clearly not human-initiated. Examples of failures thus classified were those coded as "microphonic", "fungus effect", "hysteresis", "loss of residual magnetism", etc.

2. The remaining reports were sorted to separate those equipment failures that were clearly human-initiated. Examples of failures thus classified were those coded as "human error", "reversed leads", "wrong part installed", "torque incorrect", etc.

3. The remaining reports were examined in further detail before they were classified. For instance, where the failure was coded as "broken wire", it was not classified as human-initiated unless there was supporting evidence indicating, for example, that it was broken by being placed under too much tension during a maintenance operation performed by an individual.

The data collected consisted of 3,829 equipment failure reports and 419 unscheduled hold reports. The largest number of failure or hold reports for any one missile was 1,391; the smallest number, 130. Of the 3,829 failure reports analyzed, 29 percent were classified as human-initiated failure, and of the 419 hold records, 20 percent were classified as human-initiated. For individual missile systems, human-initiated error ranged between 20 and 53%, as follows:

Missile[1]	% Total Failure Reports Examined
A	23
B	20
C	26
D	42
E	26
F	53
G	52
J[2]	36
K[2]	36

Because of the limitations of the available data, no precise assessment can be made of the relative frequency of missile system malfunctions attributable to human initiation. The data are sufficient, however, to warrant the conclusion that a large portion (1/5 to 1/2) of all missile system malfunctions, perhaps the largest single identifiable portion, is human-initiated. This conclusion is further supported by the following:

1. There is a good possibility that many of the equipment failures reviewed in the reports that were classified as not human-initiated were human-initiated. For example, a failure coded only as "overloaded" may have been initiated by an operator connecting 28 volt equipment to a 110 volt source. In the absence of additional information, this failure would not have been classified as human-initiated.

2. There is evidence to support the conclusion that many human-initiated malfunctions are not reported in order to avoid any implication of fault on the part of reporting personnel. During the course of this study, interviews with contractor test personnel revealed that at least one disastrous launch or flight failure in each of the programs under review was human-initiated. This fact was seldom reflected in malfunction reports or flight failure reports. For example, in one R&D program, several successful launches had been experienced using the same crew and equipment until one occasion when a technician connected a plug into the wrong one of two adjacent, identical receptacles. This error resulted in a scrubbed launch and a damaged missile. An examination of the reports concerning this major failure revealed no indication of this sequence of events. Furthermore, interviews with reliability and design personnel indicated that even informal knowledge of this occurrence had not been made available to them.

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1. Identity of the systems has been intentionally obscured.

2. Company estimates based on independent studies.

CURRENT PRACTICES IN REPORTING HUMAN-INITIATED MALFUNCTIONS:

As noted above, most malfunction reporting schemes employed some method of coding malfunctions. Several of the systems reviewed employed some explicit code term for human-initiated failure. The results of this study indicate that perhaps the use of such code terms as "human error" tend to diminish the number and honesty of failure reports.

Even in cases where the procedures or equipment were inadequately designed, thereby forcing the operator to initiate the causal chain leading to a failure, it is highly probable that the operator does not choose the term "human error" because of its implications of guilt. The avoidance of this term is borne out by the results of the analysis of the failure data employing "human error" as a code term. Both of these systems rely on the operator to report failure data. The results were as follows:

Missile System	# Malfunctions Reported	Malfunctions Coded as Human Error	Malfunctions Analyzed as Human-Initiated in this Project
A	1,391	3	322
B	977	0	193

Little evidence was found in the various malfunction report forms, instructions, and procedures of any attempt to alert the reporter or analyst to a consideration of the possible effect of the human component in the immediate causal chain leading to failure. In systems where the term "human error" was used, it appears that the existence of the term itself was considered sufficient. As for mechanism to assure corrective action, only one of the reviewed systems included a statement to the effect that failures initiated by humans should be referred to human engineering personnel.

Without exception, the failure reporting systems reviewed were designed to identify and report on specific equipment components. In some cases, the malfunction report had to be accompanied by the failed part. Since human-initiated malfunctions cannot in present reporting systems be adequately described in terms of a discrete, identifiable entity such as the equipment component, only the narrative statements on the reporting forms can be used for their identification. The use of narrative data in malfunction reports was found to be unsatisfactory for this purpose in many respects. It was pointed out many times by missile contractor personnel being interviewed that it was difficult to procure such data from operating personnel. In addition, the physical space that is provided for the narrative statement on most failure forms is so limited as to discourage a full description of the events preceding the failure.

One additional serious disadvantage of equipment malfunction forms for the reporting of human-initiated malfunction data is their failure to report malfunctions that do not result in equipment failure. Such procedural malfunctions are as capable of failing a mission as hardware failure and are as indicative of system unreliability and required redesign of the system or its equipment as are purely hardware malfunctions.

PROPOSED SOLUTION:

The investigators in this project were impressed with the positive contribution made to reliability by the human component when effectively utilized. In the majority of the human errors that could be isolated and analyzed, human-initiated failure was attributable to the improper use of the human as a component in the system or the violation of the most elementary principles of human engineering in the design of the system hardware. Such items as mistaking red power-on lights for malfunction indications, switching through missile power to shutdown, and four operators attempting to communicate simultaneously on the same hot line are examples of the human errors discovered. Based on such evidence, the authors firmly believe that intensive human engineering of both the system and its hardware is necessarily the basis of any solution to the human error problem. In essence, this would amount to directing the same amount of human engineering attention to our missile test programs as we devote to the design of our operational systems. In the majority of the systems surveyed, the contrast between missile flight test equipment and the functionally same equipment designed for operational use is dramatic. Alert management on several of the systems surveyed have recognized this problem and have instituted the policy of designing equipment to operational configuration as nearly as possible from the beginning of system design and utilizing this equipment in the missile flight test program. Such an approach has many advantages, not the least of which is the ability to "flight test" more than the air vehicle alone.

Coupled with the increased participation of human engineering personnel in the design of test systems, we propose that the human engineer participate in system design in a fashion more in keeping with other engineering disciplines. In essence, the design of a system or its components is an iterative process that includes such elements as system analysis, design of the hardware, performance prediction, test of the design, and either design acceptance or modification based on test results. The profession of human engineering has traditionally participated in system analysis and hardware design, but, as the evidence from this study indicates, little effort has been devoted to human engineering testing. For such a human engineering test program to be practical, it is necessary to consider the selection of entities appropriate to the human component which can provide the basis for design, performance prediction, test, data collection, and system modifications as they concern the system human components. These entities

must be capable of being referred to existing or potential models that describe the dynamic relationships of the human component within a weapon system. To be considered appropriate, these entities must meet the following criteria:

1. They must be readily and consistently definable, observable, and measurable by those concerned with the system test.

2. They must be referable to existing models of the human components of a weapon system.

3. They must be subject to design and modification.

From the viewpoint that man participates in a weapon system through the operations he performs, it appears appropriate to use the operation as the entity that is the human engineering equivalent of the hardware designer's "black box". An operation could be defined as any process that translates a system, or a portion of a system, from State A to State B. With the human operation concept, the human engineering test program as proposed here would consist of the following steps.

1. Identification and selection of critical human operations.

2. Specification of pertinent parameters of these operations.

3. Prediction of the values of these parameters.

4. Confirmation through test of predicted values.

5. Acceptance or redesign.

Although the human operation is proposed as the human engineering black box, only "critical operations" in a system would be subjected to test. These critical operations are defined as those human operations which, if not performed in accordance with estimated design values, would have severe effects on system operation or cost. For example, any operation which, if improperly performed, might cause a hold in a countdown, can be considered a critical operation. A second type of critical operation would be one which, if improperly performed, would lead to increased costs, as for instance, an improperly performed checkout routine which would lead to the rejection of a "good" missile. An operation may be defined as critical if it falls into one or more of the following categories or combinations of the 3 categories:

1. Time-Valued Operations - operations which, if malperformed, may cause time delays in the operating or support cycles of the weapon system.

2. Accuracy-Valued Operations - operations which, if

malperformed, may, for example, cause the missile to miss the target or the warhead to detonate improperly.

3. Cost-Valued Operations - operations which, if performed improperly, may increase the cost of the operation.

Once the critical operations have been identified, the human engineering test program would be conducted much as other engineering test programs. The iterative processes of parameter prediction, design, test, evaluation of test results, and acceptance or rejection of the design would be performed on the critical operations selected for test. With such a program, only one major difficulty remains, that of collecting usable human-initiated malfunction or failure data. Such data is necessary for the test and evaluation of both critical and non-critical operations as well as serving as an important check on the identification of the critical operations to be tested. It is proposed here that a relatively simple modification be accomplished on the present malfunction reporting forms. Once the test mission is analyzed into its human operations, it would only be necessary to make it possible for the operator to identify on the failure report form in which operation a failure occurred to make the data useful for human engineering analysis. The identification of the operation would make it possible to reference the failure event to those models of the system that do describe the dynamic interactions of the failed item with the human component. With a model such as task analysis, it would be possible to reconstruct the man-machine relationships that are involved to determine the demands made upon the operator and to identify the important environmental conditions. This process would be analogous to referring a failed component to the appropriate circuit diagram.

This relatively simple extension of present reporting systems would inevitably lead to improvement in understanding exactly in which areas and in which ways the human contributes to failure, holds, and other malfunctions and how human operation can be modified to help achieve desired missile checkout, launch, and flight performance. Conceivably the data then received could also be used in the analysis of the human contribution to missile system reliability. At the very least they would supplement and possibly replace much of the data gathering techniques presently being employed that have not proven to be adequate. Techniques such as interview and observation could still be utilized but they would no longer be the primary data gathering methods.

SUMMARY:

The data in the present study indicate conclusively that the contribution of human-initiated malfunctions to system unreliability is of a significant magnitude. It appears that even a partial solution to this problem could contribute substantially to the attainment of the high reliability necessary for our forthcoming missile and space

systems. The program outlined above of human engineering performance testing of critical system operations and improved collection of malfunction data is believed to be the most fruitful first approach to this problem. What is most needed at this time is a systematic trial of this testing concept to insure its practicality and to develop sound rules for its application. Plans are now being formulated within the WADD weapon system development complex to subject the above proposed program to a test during the research and development phase of a weapon system. It is anticipated that such a trial will result in an approach to the system reliability problem that would merit serious consideration for general application.

PERSONNEL LOGISTICS AS A FACTOR IN ACHIEVING WEAPON SYSTEM RELIABILITY

D. Meister
Convair-Astronautics

Engineers have been concerned about the reliability of their equipments for a long time, even long before this concern was channeled into what today is called reliability. Originally this concern was for the performance without failure of individual machines or groups of machines. Recently, however, the concept of the "system"and the need for "system reliability" has become dominant.

This "system" now encompasses not only groups of machines performing a unified operational function but also the personnel who operate and maintain these machines. The system functions not only deal with the ultimate tactical operation- in guided missiles, the launch- but also with all of its associated supportive operations: checkout, preventive maintenance, logistics, planning, etc., all of which involve varied personnel functions occurring hours or even days prior to the launch, and, in the case of a deterrent weapon system, even if never launched.

To talk about system reliability, then, means that one must not only be concerned with the evaluation of equipment efficiency, but also with the efficiency of the men who operate and maintain that equipment.

For this reason Convair reliability engineers have for some years been concerned about the effect of "human factors" on reliability and rightly so. Our experience at Convair-Astronautics suggests that when an equipment system, or any part of it, makes the transition from laboratory testing to testing by field personnel; or after factory testing, is handed over to military personnel for operational use, a considerable drop in reliability (system performance) occurs. If we could measure these things in a sophisticated fashion, we would probably be able to confirm this quantitatively.

Various explanations are given for this loss of system reliability. When reliability drops after we transfer the system to military control, we say that military personnel are not initially as adequately trained as our civilian technicians; hence the former encounter greater difficulties. But something similar occurs when our own field test personnel receive equipment for testing. Convair-Astronautics Operational Reports, which are sent into the plant by our field sites when operational problems arise, describe many instances in which system performance is inept. Why? What are the factors that result in reduction of reliability after equipment is put into the hands of any new group of using personnel?

The first factor is the one engineers are most familiar with. This is a design weakness which prototype and preproduction testing have not revealed, but which the presumably more stressful operational environment (whether test site or operational site) reveals for the first time. The operation of multiple subsystems together for the first time may introduce an incompatibility resulting in failure. This is very likely to be the case where systems are designed and tested as individual packages by different associate contractors. The result of a design deficiency is usually a functional failure of the equipment; that is, the equipment simply fails to operate at all, or operates in so erratic a fashion that it rapidly ceases to function. Such a design deficiency in almost all cases winds up as an equipment failure report, generated by using test personnel, in the hands of the reliability engineer.

The second factor is one which engineers are beginning to recognize more and more: inadequate design of machines for human operation and maintenance. By this is meant such things as improper layout of control panels, inaccessibility of components for maintenance, failure to provide sufficient controls- all those factors that make the operation and maintenance of a piece of equipment by a man difficult, tedious or highly subject to error. This type of inadequacy is not usually recognized at the prototype and preproduction testing stage, because machines at this stage are not operated or maintained in anything comparable to operational conditions, using set procedures performed in a required time period. Operation and maintenance at the prototype test stage resembles troubleshooting more than operational use. There is then little opportunity to discover inadequate design for human use unless specific studies of man-machine operation that simulate operational conditions are made at this time by a team of design, test and reliability human engineers.

The result of poor human engineering design is not generally functional failure of the equipment, although it may produce an error that does lead to such a failure. In most cases the equipment can be operated and maintained, but with difficulty. This difficulty is manifested in increased time to perform required procedures on the equipment; and increased down time when adjustment and maintenance must be performed. Since the usual loss is time, this is almost never reported as a defect against the equipment. Estimates of lost time can be, however, extremely useful in estimating system reliability. At Convair-Astronautics our Operational Report requires that an estimate of the time lost from accomplishing a testing task be reported.

The third factor is one that has received little or no attention to date, but which can seriously reduce system reliability even though equipment has been designed correctly for functional use and for use by personnel. This third factor

involves a class of human factors problems which may be called "personnel logistics". Personnel logistics (or PL, for short) deals with supportive aids for the man in the system just as equipment logistics deals with support for the machine. Table 1 indicates what PL encompasses:

Table 1

Personnel Logistics Means that
1. Written and Unwritten Procedures and Job Information;
2. Tools, Test Equipment and Spares;
3. Required Transportation;
4. Training and Training Aids;
5. Physical Work Environment

Are Optimal and Available When Needed.

To be entirely correct and additional PL factor should be added, morale- This covers such items as opportunity, recognition, organization and leadership. But most systems (and the organizations that develop systems) either ignore this factor or consider it as one which they will deal with in their own way.

How does inadequate PL affect a system's reliability? All systems- particularly guided missile weapon systems- have in addition to their stated functions (or as part of these functions) a designed or specified reaction time. For example, if a potential enemy allows us only 30 minutes before our missile bases will be destroyed, something less than 30 minutes becomes the system's required reaction time. Greater delay then involves the risk of destruction of our bases before our weapons have been launched. This is of course a failure at the system level and amounts to zero reliability. Even when reaction time cannot be specified, it is understood that every effort will be made to reduce it to a minimum. The reason why reaction time is so important to us in this country is that our weapon systems are essentially deterrent instruments. Our missiles react in defense, they do not act in offense; hence our primary reaction time is determined by our estimate of what the potential enemy allows us. Anything that increases the system reaction time beyond that specified reduces our system's reliability because it reduces the length of time we have to utilize the weapon. Poor system reliability can then be defined at least partially in terms of slower reaction time. Inadequate PL- such as the lack of proper procedures- can slow down a system's response to the point that its reliability is gravely impaired. How?

Let us assume that we are in the midst of an operational Atlas countdown and a malfunction has occurred which, after it has been diagnosed, requires a replacement component. How will the

various PL factors affect the speed with which that component is replaced?

1. Inadequate procedures or procedures that were not clearly written, might cause the Launch Control Officer to attempt to secure a replacement component from the wrong source. There would be an indefinite amount of delay until he had contacted the Maintenance Officer and made known his needs.

2. Inability to acquire transportation will delay delivery of needed replacement components. If the spare is in the maintenance area, the length of time needed to transport it to the launch pad becomes vital, and must be added to the system's reaction time. In addition, if the needed transportation vehicle is not immediately available and must be sought for, the reaction time is increased.

3. If the spare part is not available, or if it requires a special tool to install it, and the tool is not immediately available, additional time is lost.

4. If our missile maintenance mechanic has not been properly checked out in the installation of the component; or has not practiced the installation a sufficient number of times, then his reactions may be slow and add to the system reaction time.

5. If his work environment is such that it is difficult for the mechanic to get into position to install the component, so that he takes precious time setting himself up for his task, it will take him longer to install the component.

6. And finally, if the mechanic's attitude is such that he is uninterested, bored, or resentful, we can be sure that the installation will take measurably longer. The amount of time lost by the operation of individual PL inadequacies may be slight; but added up, the total becomes respectable. For example, in our studies of malfunction countdowns we have had to add automatically 10-15 minutes to all malfunction correction times just to get the maintenance man from the blockhouse to the launch pad proper.

In the countdown malfunction situation I have just described in which PL was important, no error was made by the maintenance personnel involved. Human error could have occurred under these circumstances, but it did not, yet system reliability was reduced. The important point to remember is that even though no human error occurred and no equipment malfunctioned, system reliability was reduced because system reaction time was increased.

It may appear that these PL factors are merely obvious, garden variety types with which as engineers we need not be vitally concerned. However, I would like to advance the thesis that these factors are responsible for at least as much system unreliability as the equipment failures with which we are vitally concerned.

Is PL really important in field operations?

A survey was made approximately a year ago in which Convair field personnel (technicians, engineers and mechanics) at our three field test bases were asked to indicate what their major operating problems were at the time.(1) A substantial part of the problems reported were of the PL type.

The following are some verbatim quotes, merely to indicate the flavor of the responses:

1. Calibration curves not available for installed transducer;
2. Need table of resistance values for maintenance;
3. Operating procedure inadequate;
4. Instruction manual inadequate,
5. Schematics and drawings obsolete;
6. Procedure inadequate or misunderstood;
7. Inaccessible for maintenance;
8. Availability inadequate.

The relative emphasis on procedures is not fortuitous. The inadequacy and unavailability of procedures (construed in the larger sense of manual, schematics, instruction material of all types) is by far the outstanding PL problem we face.

PL problems occur at all stages of field operations- captive tests, flight tests, military operations, and they probably extend beyond weapon systems into such entities as large industrial organizations. They also affect the reliability engineer directly through the collection of reliability information. Like most Reliability organizations, we at Convair-Astronautics have had reason to believe that our equipment failure information reported from the field is incomplete and to some degree erroneous. A written questionnaire and personal interview survey was made of our field personnel who report these failures to determine if they had any problems that might be responsible for these deficiencies. (2) We found that reporting personnel were experiencing grave difficulties for three reasons:

1. Their instructions for filling out failure forms could be improved in clarity and content (PL factor 1- procedures)
2. Some of the information they needed to complete the forms correctly was either unavailable or available only with much difficulty; (PL factor 1 - job information)
3. From a motivational standpoint, these reporting personnel

did not know the uses to which their information was being put. (PL factor x - morale). This tended to make them careless and indifferent. Once these problems were established as valid, they were remedied to some extent, with consequent improvement in the information reported.

Such personnel logistics problems are not solved through the more adequate design of equipment, because they have very little to do with equipment design. Rather these problems are administrative and organizational in nature; and must be solved by management in the planning stages of system development.

There is, fortunately, nothing especially complicated about the task of anticipating and forestalling PL problems. In the early planning for field test and ultimate operation of a system, the various jobs that make up the missile operation at an R & D and/or operational site must be determined. The individual jobs must then be analyzed in terms of what they will require of the various PL factors. For example, take the job of transporting an Atlas from its squadron maintenance area to the launch site. Obviously, this job requires a missile handling trailer; it needs special procedures for installing the missile on its trailer; and it may require some special training of the driver. As long as we have a description of each job, we can analize it in a similar fashion. The task of predetermining PL requirements can be summed up in the form of a matrix checklist, in which the various jobs that describe the system operation are listed running horizontally across the checklist; and the special PL factors run vertically down the checklist. A sample checklist might look (very roughly)like this:

Table 2

	Job 1	Job 2	Job 3	Job 4	Job 5
Procedures		X		X	
Special tools			X		
Spares	X	X			
Transportation		X			
Special Training	X				X
Work Environment				X	

Each of the PL factors and each of the jobs may be broken down into as molecular detail as is found useful. For example, if descriptions of the various special tools that may be required are available, they can be listed by name as sub-categories under the heading of special tools. If job 1 is composed of a number of individual tasks, one may wish to break out each task as a subcategory under job 1. This depends on the amount of information available and the usefulness of subcategorising this information for our purposes.

To refer to table 2, if emphasis on procedures is required in job 2 and job 4, but not in 1, 3 and 5 (because, let us say the latter are common tasks with a great deal of skill transfer from other types of work), then checkmarks are placed in the appropriate categories. The checklist simply reminds the planner that special care must be taken to provide detailed procedures for jobs 2 and 4. The same analysis is performed for the other factors. The essential part of this entire process is the analysis of the job; and the asking of the particular question, what special PL requirements does the job have?

If human factors affect system reliability, there should be some quantifiable measure of the effect of these factors. At the present time we have no method of measuring this effect- which I have arbitrarily called by a short hand term, "human reliability", although there are significant differences between equipment reliability and human performance characteristics.

Present trends suggest that in the future reliability indices will be used more and more as evaluative criteria in weapon system contract specifications. It is therefore highly desirable that we derive some measure of the effect of the human factor on system reliability, since an equipment reliability index by itself provides only half the necessary story to the weapon system buyer. It is necessary to supplement or integrate it with a measure of the human reliability one can or has achieved.

There is an important additional reason for developing an index of human reliability which can be included in contract specifications. This is the pragmatic reason that if such a measure is included in contract specifications, management will pay much more attention to solving these human factors problems.

Reliability engineers can define equipment reliability in terms of equipment failure (mean time between failures). Their reliability data are generally translated into predicted failure rates.

In thinking about human performance we tend to think of human error as comparable to equipment failure. An error is a failure of the human organism to perform as needed. This definition has not, however, proven very useful to us in our study of human reliability for two reasons:

1. After the initial period of learning a task is over, errors are relatively infrequent;
2. People are reluctant to discuss their own or other's errors and therefore report them rather infrequently.

At Convair-Astronautics we have tried various methods of securing indices of human performance. The Failure and Consumption Data form used- BMDO-50- had at one time a code for equipment failure resulting from human error but the number of failures reported as due to human error was a very small percentage of all equipment failures reported. In an independent estimate based on an examination of 5000 equipment failure reports received we estimated that approximately 20% of equipment failures were caused by various human factors. (3). The maximum percentage (see Figure 1) of human errors reported over an 18 month interval was 6% of the total received.

"Percentage of Human Error Reports Received"

(See Page 1 - 172 for Figure 1)

Figure 1

Another form used at Convair-Astronautics is the Operational Report (OR) which was referred to previously. Among the categories of problems requiring an OR is a human factors problem. This form too has shown comparatively few human errors or human problems reported, even though we are reasonably certain that many of them are being overlooked.

The reason for such inadequate human error reporting is that almost all reporting systems are focused on equipment failure; and the reporter thinks of the form in terms of equipment failure only. It is obvious that we need some system of gathering human performance data which is distinct from systems directed primarily at reporting equipment breakdown or failure.

It is suggested that human performance measurement be centered around the concept of system reaction time. This reaction time is defined in terms of the time required to perform each of the jobs required by the system. Our definition of human reliability is then the extent to which actual performance deviates from theoretically optimum performance. The deviation can be expressed mathematically, and one can presumably determine the probability that any given task performance will deviate a given amount from the optimum. This is in contrast to the definition of equipment reliability which is a proba-

bility estimate of equipment performing without failure over a specified time.

In system reaction time we do not deal directly with human errors. There are several reasons for this:

1. Any human error resulting in an equipment failure is automatically included in the reliability index based on equipment failure when that failure is reported;
2. Any human error that does <u>not</u> result in equipment failure serves merely to increase the system reaction time and accomplishment of the system mission; such human errors will therefore be included automatically under this concept;
3. The number of human errors reported and the difficulty of securing a representative sample makes it difficult to assess human reliability in strictly human error terms. How would this reaction time measure be utilized?

1. First, as part of a job analysis made to determine particular PL requirements, determine how long a particular job should take to accomplish. It would take entirely too long in this paper to go into a complete dissertation on job or task analysis, as it is also called. Techniques for performing job analysis do exist and are being applied daily by human factors specialists.

   A job analysis can be performed at any time, even prior to the job being performed in the field. A job analysis in an R & D situation presents some difficulties, since the job is in process of being developed; but as more information is gathered, the analysis can be refined. Certainly the analysis should be available no later than the start of field testing, if one is attempting to assess field human performance; and certainly by the time the system is turned over to the military, if one is to assess operational human reliability.

2. The estimated time for completion of a job or task should be the absolute minimum time required to perform the job without error. This estimate should be based on an analysis of the factors involved in the job plus one's experience with similar jobs.

3. During field operations determine the actual time taken by reasonably skilled personnel to perform each job. It is essential that personnel be trained to perform the particular job whose time one is measuring, and that the procedure being performed is accurate. Time measurements should be made by direct observation and timing of personnel performing the job under standard operational conditions. Special arrangements should be made to insure that irrelevancies do not interfere with and distort the

performance of the task. If at all possible, performing personnel should not know they are being observed; however, this may in actual operations be impossible to prevent.

4. Obviously, a single time measurement on a single individual or group has minimal statistical validity. It is suggested that, if at all possible, two measurements should be taken on each of 5equally skilled individuals or groups normally performing the job. Circumstances may, however, force one to use a smaller sample.

5. Compare the estimated minimal (or criterion) time with each actual performance time. The latter should in each case be larger than for former or at best equal to the former. If actual time is less than criterion time, the original job analysis was performed incorrectly and must be repeated.

6. The relationship between the criterion time and the actual time, expressed as a decimal ratio $\left(\frac{\text{C time}}{\text{A time}}\right)$, gives one a tentative measure of human performance for a single task. It will be necessary to develop C/A ratios for each individual or group in a sample and then average each ratio with other to secure a mean ratio for the particular task being studied. The Standard Deviation (SD) of these mtio might also be secured.

7. The mean C/A time ratio and its SD for a particular job serves as a description of that job's human performance reliability. Where A time is identical with C time this ratio is optimal (1.00). The greater the discrepancy between C and A times the lower is this performance or reliability indiex. Where the C/A index is low, it indicates that human performance is inadequate. An investigation can then be made of the situation to remedy the problem.

In some tasks a significant part of the system reaction time depends on the fixed equipment running time. For example, the Atlas launch control system, once activated, has a fixed, invariant running time, regardles of any accompanying operator activity. In tasks of this type it should be possible to subtract the fixed equipment reaction time from overall performance time and examine only that part of the performance affected by the operator. (4)

Since the system is built up of units of different size- individuals and groups- it is necessary to decide upon the size of the unit we will deal with. Logically, the size of the unit should depend on the number of people programmed to perform the job. Where a task requires 4 men, we take the time required to perform the task, rather than the times for the individual contributions of the four men. Any system

contains N number of individual jobs or tasks. Assuming that we have determined a mean C/A index measurement for each job in the system, there is still the necessity for combining these measurements in order to secure a total, unitary value of human performance for the system. It might of course be possible to simply average C/A indices, but how accurately we average these values will depend on our knowledge of the basic interrelationships among the various jobs we have timed and the weights to be assigned to each job. It is to be expected that our measurements of human reliability, while they will bear some as yet unspecified relationship to equipment reliability indices, will be measurably lower than these latter. Moreover, precisely how much human performance measurements could be combined meaningfully with equipment measures is something that only additional research can determine. The methods suggested are only preliminary and require investigation to determine if they can be useful. The primary reason for suggesting them is to provoke some interest in the general problem of measuring human performance within the reliability context. Such a measure of human performance could be of great value to the reliability engineer, since it would plug a significant hole in his estimates or measurements of system reliability.

Summary

The major points that have been made are:

1. Increasing attention should be paid to various personnel logistics factors because they significantly affect system reliability;

2. They reduce system reliability by increasing the system's reaction time;

3. These personnel logistics factors can be anticipated and optimized by analyzing the various jobs to be performed and then asking which of these factors are involved in the job.

4. A proposed measure of human reliability has been suggested. The measure involves a comparison of criterion (minimum) time to correctly perform a task and the actual time required. This ratio expressed in decimal form can be considered a measure of human reliability.

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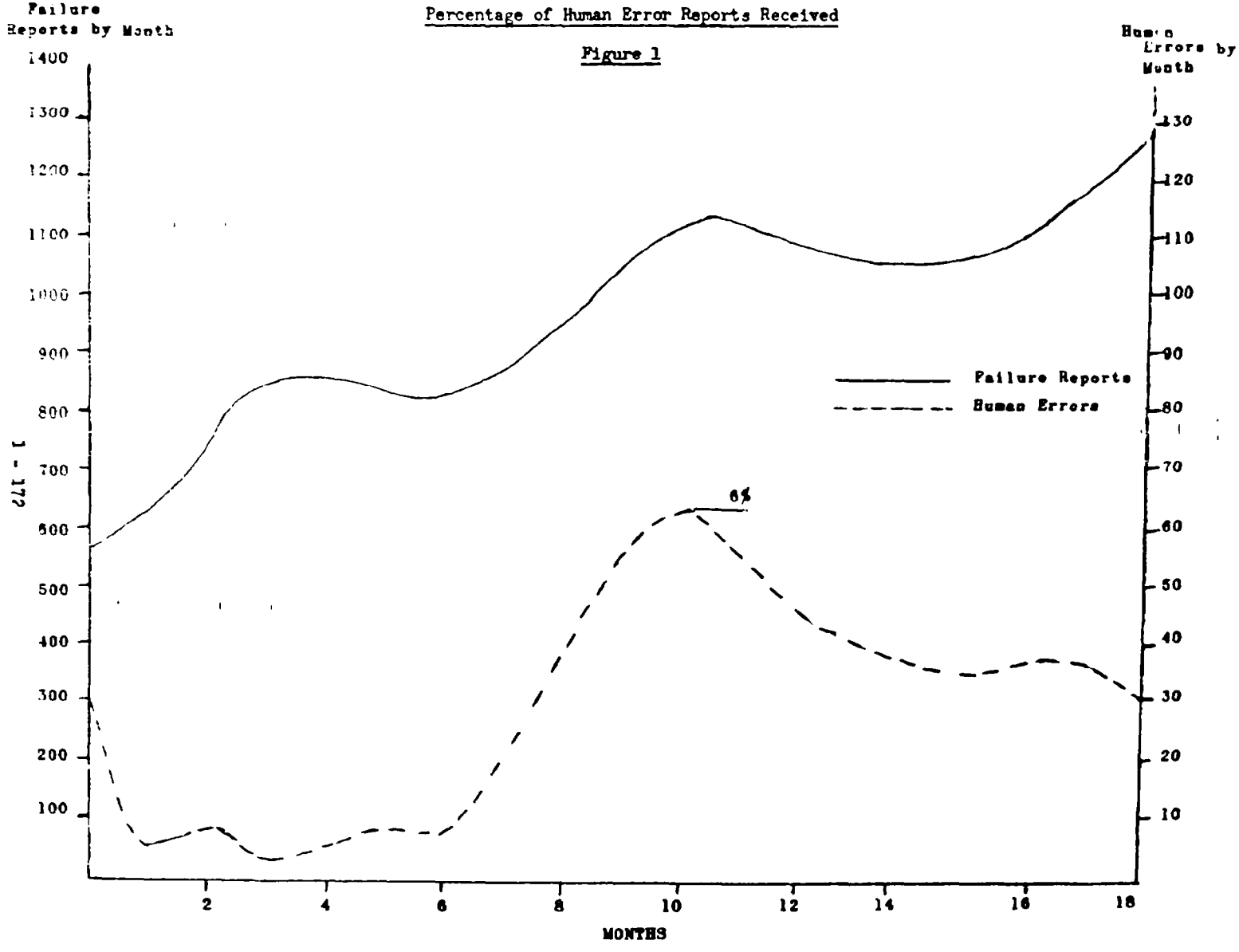
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Percentage of Human Error Reports Received

Figure 1



THE "HIDDEN DISSUADERS" OF MISSILE SYSTEM RELIABILITY

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The total operational reliability of a complex system can be no better than the reliability of its most unreliable subsystem. This is, simply, another way of saying that a chain is as strong as its weakest link, and is consequently a rather obvious comment. For some time now, human factors specialists and others have been looking at complex systems in a fashion which includes the operating personnel of such systems as an intrinsic system component. In addition, it has become apparent in many situations that this personnel subsystem typically exhibits a greater amount of performance variability than does the hardware itself. If we can assume that this is so, it follows that the human subsystem exerts one of the most important influences on total system reliability.

Missile systems today are truly complex systems. This total system complexity will probably not become more simple in the future, even though the hardware itself will be more rugged and reliable. There are many analogies to this in the developmental histories of other complex systems, such as aircraft and electronic equipment. In these situations, there have been undeniable improvements in component hardware, certainly in terms of operating efficiency if not always with respect to operating reliability. System complexity, however, has increased to a large extent because of an ever increasing subtlety in patterns of component interaction and feedback functions. This complexity has also brought about many crucial problems in the selecting, training, and assigning of personnel to operate and particularly to maintain such systems. These personnel problems are certainly not solved today and undoubtedly will not be completely solved in the foreseeable future. However, there is at least agreement that they do constitute problems, and many aspects of the problems are amenable to direct and well-established research techniques. It would consequently be appropriate here to consider directly such factors as the selecting, training, and assigning of people as these apply to the functioning of the total missile system, and as they affect the operational reliability of the total system. However, there are some sources and causes of this personnel subsystem variability which unfortunately are not so clearly recognized as problems, are not well documented, and certainly are not easily investigated by usual techniques. We have chosen to emphasize these causes of unreliability, and have labeled them "the hidden dissuaders", because they are in a sense the opposite of the hidden persuaders currently popular in the advertising business.

The sources of the hidden dissuaders are the attitudes, motivations, and other emotionally based functions which all humans inevitably possess, and which are continually being reflected in external behavior. Because

they are emotional in nature, the hidden dissuaders do not always follow the rules of logic and common sense. It might also be added that they will seldom be eliminated or even reduced in degree by a better human engineering job on a control console. With these considerations in mind, we may now define hidden dissuaders, and proceed with a discussion of how they might affect system reliability through the kinds of behavior they engender in the human subsystem.

The hidden dissuaders are basically inclinations to not perform a function well, not learn a task properly, and not achieve success in a given situation. They are, furthermore, reactions which are not readily available for common sense analysis and direct remedial action because the persons revealing these behaviors are often not aware consciously of such negative motivations in themselves. In addition, supervisors and administrators may be unaware of these negative reactions in their people, because at the observable level of behavior, the people may appear to be trying their utmost to perform satisfactorily. Although this may seem to be a little vague at the moment, let us go further in assessing how these functions, assuming their presence, may have a negative effect upon system reliability. These factors exist in all varieties of activity encountered in life, but we are interested specifically in the operation of missile systems, and in uncovering the kinds of hidden dissuaders which might be peculiar to this particular operation.

The hidden dissuaders likely to occur in missile system operation can generally be categorized on the basis of their reference to the total personnel group or to individuals only. They may also be considered in terms of their occurrence in crew members as opposed to supervisory or administrative personnel.

Group Hidden Dissuaders:

Let us first consider some of the group reactions which might negatively affect operating reliability in a missile system. To begin with, it may be a reasonable conjecture that there exists an almost universal attitude toward missiles which has a negative tinge as a result of many factors. To many Americans, the idea of missiles and rockets, and the rapid development in the last few years of entirely new dimensions in the world, have produced tensions and anxieties which even the arrival of the nuclear age did not engender. In this sense, missiles may be thought of today in about the same way that airplanes once were considered, as rather dangerous toys which in the long run will not succeed, or more precisely should not succeed. This latter qualification is quite important, since there are large numbers of people who have rather strong feelings about the "rightness" of such things as space exploration, virtually unstoppable ballistic weapons, and so forth. There have been public statements by various people to the effect that certain goals being sought and to be sought through the use of rockets

and missiles are in themselves undesirable or at best unimportant. Attitudes are expressed which question the reasons for anyone wanting to find out what is on the moon or the other planets in the solar system, even at times intimating that explorations such as these are somehow un-Christian and immoral. We should not discount the long-range effects of such attitudes, particularly if they prevail in large numbers of our population, and especially in influential people. It is conceivable that the sociological and cultural milieu of the present-day United States has not as yet entered the missile age wholeheartedly. The fact that another major power has demonstrated certain competence which appears to exceed ours in this area has created additional anxiety which many find somewhat uncomfortable. The personnel available for training and assignment for missile system duties are people who have been drawn from this cultural environment, and if a situation occurs in which a particular operating group is composed largely of persons who previously had little interest in or basic emotional acceptance of the world of missiles, negative effects on operating reliability might unintentionally develop.

Another less general kind of group hidden dissuaders may arise from attitudes and thinking patterns which are characteristic in certain military circles. For example, it is rather difficult to categorize a missile, particularly a major missile, in standard military equipment terms. Depending upon branch of service, and type of unit within a service, there are traditional ways of doing things and long-established patterns of thinking about things which in reality are not appropriate for missile systems, but which have nonetheless determined much policy concerning them. The very same missile system can be looked at in an entirely different fashion if one is thinking of it as an Army artillery weapon than if one were considering it an unmanned air and space craft. While this in itself may have no effect upon system operation, there may be an unconscious tendency to apply methods of the past, no matter how effective they once were, to problems of the present. If the methods do not match the problems, solutions produced are something less than ideal.

These generalized group attitudes, feelings, and habits of thinking are precisely the kinds of things which always occur with the introduction and development of new concepts and new inventions. History has taught us over and over that such attitudes frequently do constitute a very effective dissuasion factor in the development and operation of such new endeavors. It must be emphasized that in most cases these group dissuaders are based on genuine convictions, the careful application of so-called common sense, and with a sincere sense of righteous responsibility. Unfortunately, the circumstances dictate that good intentions are insufficient, unless they also happen to be compatible with reality.

Individual Hidden Dissuaders:

All groups are ultimately collections of individuals, of course,

and it is the performance of the individual and his behavior relative to a group endeavor which can be most pertinent in a specific missile system operation. It is possible to produce an unreliable missile system simply by selecting the wrong people to operate that system. Further, even if the right people are selected, the same effect can occur if they are improperly trained and improperly supervised. An almost perfect system from an equipment standpoint can be designed, constructed, and delivered to the operational setting, and subsequently prove to be extremely unreliable and unable to accomplish its mission in an adequate fashion. If, on the other hand, we have selected personnel carefully, trained them competently, and assigned them to operational missile systems judiciously, and if we are futher sure that the equipment is i itself relisble, we may still end up with an unreliable system. It is this latter kind of situation which is most puzzling, since it is so difficult to analyze the causes of unreliability. And it is precisely in this setting that we must look for the hidden dissuaders if the situation is to be rectified.

For many of the specific tasks which crew members in a missile system must perform, we may find that, contrary to general opinion, the difficulties and complexities are really not beyond the learning capability of available personnel. Although in some cases, there is no question but that relatively high level persons are required for effective performance, there are a large number of duties associated with any missile system which in actuality do not demand greater than average ability in most respects. In situations where system reliability is low and personnel performance is poor, we should consider not only the abilities and capacities of the people, but also their motivation. It is readily apparent that a person who does not really want to do a particular job will, in most circumstances, simply go through the motions of doing it because of external pressure. Lack of motivation represents one of the most common sources of poor personnel performance. However, the word dissuaders implies a more active negativism than would be a product of ordinary low motivational level. In the latter, it would be expected that evasion of extra work and slowness of learning would be apparent. The pattern of hidden dissuasion, however, is found more frequently in individuals who have had strong positive motivation, but for one or another reason have become demotivated. In this situation, the element of frustration has been added which in turn breeds chronic resentment, a feeling of futility, and generalized disillusion.

The foregoing discussion points out some of the basic areas in which reliability-destroying hidden dissuaders find their nourishment. The unmotivated and the demotivated will between them succeed in lowering the reliability of any complex system of which they happen to constitute a subsystem. There are certain unmotivating and demotivating factors which may be particularly relevant to missile system operations, and perhaps it would be desirable to discuss a few of these at this time.

In almost all missile system activities, a crew member must follow

a written set of procedures, and it is really not necessary for him to understand the relationships implied in these procedures or for that matter even the effects of performing them. While the proceduralized approach to the operation of complex equipment is a thoroughly established way of doing things in our culture today, it may very well tend to keep some people at an emotional distance from their tasks. During World War II, it was a great joke among soldiers that the Army always does things by the numbers. This procedural approach to simple tasks as well as complex ones was frequently a source of humor, scorn, and even anger among individuals. It is unimportant that such methods are an objectively appropriate way to get a given job done quickly and adequately with a wide variety of personnel. What is important is the fact that such techniques may tend to keep the individual at an emotional distance from the situation, and thus not permit him to form a personal and to him meaningful identification with what he is doing. A further effect of such procedures involves the unintentional implication that persons for whom the procedures are designed are so incompetent and ignorant that they must be led step by step through a given sequence of activities. For those individuals who must be handled in this manner, because they really do not have the capacity for full understanding of the system and its many complex interactions, a demotivating emotional response can be even more extensive because they implicitly realize that they have met their match. Such a realization, one which few of us care to face, inevitably breeds hostility and negativism. This in turn produces a sort of "who cares" type of resistance as a chronic attitude. Unfortunately, none of these things occur on the surface where they can be handled by logical and sensible thinking. They are emotional in nature, and in many cases so unavailable for conscious analysis that little is accomplished by usual personnel handling techniques.

An additional and quite important source of hidden dissuaders in individuals is the motivational pattern which they perceive in the group leadership. This, of course, is an age-old and universal problem, and certainly not one that is peculiar to missile system operation alone. However, as was discussed previously, it is possible that missile systems today are more likely to reveal evidence of unmotivated or demotivated personnel leadership than perhaps some other systems where the aforementioned group factors may not be so extensive. In many operational missile systems, administrative and sometimes even technical leadership is composed of people who have had minimal interest, experience or training in areas related to missiles. Through no fault of their own, these persons are forced to make sudden and extensive personal transitions from their previous career activities to these new duties. Since it often happens that their past experiences have little direct applicability to the missile field, it is no surprise that they may develop feelings of anxiety and lack of confidence. Even where such feelings are well controlled, frustrations and demotivations can occur which are perceived by other members of the group and reacted to by the development of similar responses.

Another source of individual demotivation involves training methods and programs that are inadequate in scope or ineffective in results. We might define training according to its real functional purpose. In this sense, training might be thought of as those methods and techniques which are used to adapt and modify one subsystem, personnel, so that it merges effectively on a functional basis with another subsystem, equipment. This merger then results in a total functioning system which operates smoothly and efficiently. If this system merger turns out to be incomplete or deficient as a result of inadequacies in training, there will be functional conflicts between segments of the personnel and equipment subsystems. These tend to reduce the operational quality of the total system. From an individual's standpoint, this situation can breed lack of confidence, an incomplete knowledge or sense of the various job dimensions, and even ignorance of specific task demands. In many situations involving other types of systems, experience would tend to overcome many of these factors. In missile systems, however, the opportunities for extensive practice in all phases of the operation are somewhat limited. It is seldom feasible from a number of standpoints to provide frequent and extensive dry-run practice with major missile systems, particularly where continuous maintenance of high component reliability is necessary. As a result, it is difficult for operating personnel to achieve a great deal of working experience with many missile systems until they have been associated with such systems for a considerable length of time.

Finally, there are some purely situational factors which contribute to the development of hidden dissuaders. These usually involve personal reactions to large numbers of frustrating circumstances. There is a certain amount of chaos in present day missile system activities, and a rather frantic trial and error approach is often the rule at all levels of the work. It is possible that many persons develop stronger and stronger feelings of frustration as they gain experience simply on the basis of their continuous encounters with large numbers of mistakes and frequent operational failures. The latter may be particularly upsetting to individuals who have little emotional tolerance for the "building up to a big letdown" phenomenon, and to persons who need frequent concrete rewards for their hard work. As with inadequate training, these frustrating experiences can produce a chronic lack of confidence, which in turn leads to the type of negativism which characterizes hidden dissuaders.

So far, we have been discussing hidden dissuaders in terms of missile system administrative and operating personnel. It is conceivable that this situation also exists in other types of people associated with missile systems. Designers, engineers, business persons, and many others are no less susceptible to these same emotional reactions. Consequently, some of the errors seen in design and manufacture may arise from this source. Here also, such factors as lack of confidence, distrust of one's own abilities, and insecurity resulting from frustrations may breed

demotivation. In situations where problems are extremely difficult and success rewards infrequent, this sort of development may be expected.

The Diagnosis of Hidden Dissuaders:

A thorough analysis of any given missile system operation will reveal certain symptoms which suggest the presence of hidden dissuaders in the personnel subsystem as a reliability-reducing element. If a given missile system has proven reliable in some situations and with some operating groups, and unreliable in others, we have a potential symptom. If, over a period of time, this pattern shows itself to be consistent, we can be almost sure that hidden dissuaders are at work in the less successful group.

In situations where reliability problems in a missile system appear to defy all objective and sensible analysis, no matter how thoroughly conducted, some thought should be given to the possibility that these more subtle influences are involved. This particular symptom will often be indicative of the system development stage at which hidden dissuaders are or have been operating. A missile system which has never worked properly, and which has defied all efforts to improve its reliability, may be the victim of hidden dissuaders in research, design, or construction personnel.

The Elimination of Hidden Dissuaders:

If it is found in a given missile system that overall operating reliability is being adversely affected by the kinds of human subsystem factors we have been discussing, there are some methods which can be used to reduce or eliminate such problems. Furthermore, the taking of certain measures may help to prevent the development of hidden dissuaders in future missile systems.

One of the first steps to be taken in achieving these ends is to provide some sound structure in the personnel subsystem. Within the limits of available personnel, selection procedures should be aimed at acquiring a reasonably well balanced operating group. This means that various ability levels, appropriate to the different tasks and duties, should be sought. A system which is overloaded with highly able people may be just as prone to personnel difficulties as one in which general ability is too low. A thorough analysis of tasks and duties involved in the specific missile system should precede personnel selection and assignment.

A second step in attempting to eliminate or prevent hidden dissuaders involves the training methods to be used with personnel selected. When special training equipment is utilized in this endeavor, it is necessary to determine whether the equipment itself and its manner of utilization are producing the desired training results. Keeping in mind

the system merger goal of training, there should be much attention given to ways in which the goal can be achieved with a minimum waste of time and effort.

A very large portion of potential or already existing hidden dissuaders can be eliminated by a basic change in leader attitudes. Careful selection of leaders can take care of some of these problems, but in other cases considerable reeducation may be necessary. The responsibility for this reeducation lies to a large extent with the leader himself. He should make a serious effort to determine whether his own feelings and attitudes are the kinds which are likely to produce hidden dissuaders in himself and others. If they are, he should try to find practical ways of altering them. Such self-analysis unfortunately has limited usefulness, since all persons rationalize their own attitudes and behavior, not dishonestly, but as an unconsciously motivated self-protective device. Whether we like it or not, an objective appraisal from a disinterested source is necessary occasionally, if constructive solutions to these particular problems are to be found.

Finally, greater awareness of the sources of variation in human behavior, other than usual and obvious ones, should become part of the knowledge pool of administrators. In addition, further research is needed in methods of compensating for human variability, which is after all inevitable, rather than attempting to completely eliminate it. Some refined concepts in this area are presently under development. It is intended that improvements considerably beyond those accomplished to date by human engineering and human factors work will be made in the personnel - equipment system interaction. It is not appropriate here to go into details of this development, but an example might suggest its direction. An airline pilot, when asked which is his favorite airplane, replied "Why the old DC-3 of course. The reason I like the ship is because I can make a lot of mistakes when flying it, and it helps compensate for my errors. In a way, you might say that it can actually think a little bit and take over for me when I am wrong. Most of our newer high performance aircraft are much too 'stupid' in this regard, and everything depends upon my performance in a tricky situation." In the near future, we hope to provide methods by which complex systems, such as missile systems, can be greatly increased in efficiency, performance, and reliability by means of a new approach to the personnel - equipment interrelationship.

Summary:

We have been discussing the negative influence of subtle human emotional reactions on missile system reliability. These reactions have been called "hidden dissuaders", since they are seldom clearly revealed by usual methods of personnel handling and investigation. Hidden dissuaders may arise from several sources:

1. Mixed feelings which may exist rather generally in the United States today about missiles and rockets, particularly with regard to their eventual purposes and uses.

2. Differences in viewpoint as to the proper categorization of a missile as a weapon.

3. Non-motivating and demotivating influences, such as frustration, disillusion, frequent failure, over-proceduralization, leader attitudes, and ineffective training.

Hidden dissuaders are probably operating in missile systems which:

1. Over a period of time show some non-equipment-based pattern in their reliability problems.

2. Have never worked well, and seem to defy all attempts to analyze the sources of unreliability.

Suggested methods for reducing or eliminating the hidden dissuaders include:

1. Establishing the system personnel structure carefully and on the basis of factual knowledge of job demands.

2. Providing effective training so that personnel confidence will be improved.

3. Selecting or producing leaders who do not themselves instill demotivation in subordinates.

4. Looking for new approaches to personnel - equipment system interactions. A new development in this area is currently being worked out which may help to solve many specific system problems in the future.

THE DEMONSTRATION OF EQUIPMENT RELIABILITY THROUGH ACCELERATED LIFE TESTING TECHNIQUES

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Since data associated with variable type sampling is readily analyzed by use of known and tried techniques only data concerned with attribute type sampling will be discussed.

Although it is of primary interest to know the "critical stimulus" it is often quite difficult to obtain this in practice; especially if we are dealing with animate samples. Therefore, it behooves us to run parallel experiments, on such items as munitions or strength of materials.

The decision as to whether a lot meets the desired requirement (e.g. small fraction failing) under specified operating conditions will be based upon inferences from a sample. Which method is chosen will depend on whether it gives the maximum reliable information from a minimum of data Let us consider the following types:

A. Tests conducted only at the stimulus called out in the specifications.

B. Tests conducted at some stimulus more stringent than that required in the specifications.

C. Tests conducted at two or three stimuli, all of which may be different from the one required in the specifications.

D. Complete run-down tests - All stimuli, equally spaced, from 100% failing to none failing.

In actual industrial or Government practice, many tests fall into category A. This is due in a large part to the manner in which the specifications are written; such as 105A. However, tests of this kind are generally inefficient, since if small samples are used, a high degree of confidence that the lot has the high quality called for by the specification cannot be attained even if all the items in the small sample pass the test satisfactorily. To attain a high confidence level that the submitted lot actually has the specified quality very large samples are necessary.

The following table will serve to illustrate the probability of accepting material of a given quality based on samples of 20 and 100 where the basis of acceptance is finding no defects in the submitted sample.

TABLE I

Sample Size	Probability (of accepting lots whose percentage defective is as shown in the table)						
	.01	.05	.10	.50	.90	.95	.99
20	21%	14%	11%	3.5%	.5%	.25%	.05%
100	4.5%	2.9%	2.3%	.77%	.1%	.05%	.01%

This table shows that, based on samples of 20 or even 100, it is almost impossible to guarantee the acceptance of lots having a quality level of less than .1% defective. As shown above 90% of lots which have .1% defectives would be accepted on the basis of no failures in a sample of 100. Actually, to ensure the rejection of lots containing more than .1% defective 95% of the time, would require a sample of 3250. To ensure the rejection of such lots 99% of the time would require testing a sample of 5000 and finding no defects. This, of course, leads directly to the question: How can we ensure the rejection of inferior lots and still use a reasonable small sample?

The answer to this question is contained in tests falling into Category B, that is, conduct the test at a stimulus level which will produce a large percentage of failures, say 20% to 50%. This method, however, can be used only if an actual distribution function exists connecting the percentage failing with the applied stimulus. Without the existence of this relationship, data collected at the 50% failure point would be of absolutely no value in attempting to predict any results at a stimulus giving a small percentage failure rate.

In order to determine that stimulus which should give 50% failure it is necessary to perform an initial rundown test on samples drawn from a standard lot. A standard lot may be one that has given satisfactory performance and meets the specification requirements.

Making one assumption, namely; 'critical' stimuli are normally distributed with the standard deviation for all lots being equal; then increased severity tests conducted at a single stimulus, giving 50% failures, (in reference lot) are sensitive indicator of significant differences among lots at the specification stimulus even with relatively small samples.

In order to get some idea of the efficiency of an increased severity test, let us consider the following example:

1. Let's call acceptable any lot having .1% failures in a standard lot.

2. Let's call unacceptable any lot having 1% (or more) failures at same stimulus as above.

3. Let's call marginal those lots which fall in between .1% and 1% failures.

4. The producers risk, or the risk of rejecting a lot having .1% failures, shall be .05.

5. The consumers risk, or the risk of accepting a lot having 1% failures, shall be .01.

Based on the above, it can be shown that even under the best possible sampling methods an average sample size of 600 will be needed in order to reach a decision concerning the acceptability of the lot.

However, suppose we translate the problem involving the discrimination between lots which give .1% and 1% failures respectively at the stimulus giving .1% failure in the standard lot, into one involving a comparison carried out at a stimulus giving 50% failures in the standard lot, then what sample sizes are required in order to arrive at a decision with the risks stated above?

Making the assumption stated previously, namely; "critical" stimuli are normally distributed with the same standard deviation (σ), then the critical stimulus giving 50% failures in a lot having .1% failures at the specification stimulus is 3.09σ away from that stimulus. However, application of the stimulus giving 50% failure in a lot having .1% failures in the standard lot results in 78% failures in the second lot.

Figure 1 shows this graphically, where Curve I is Distribution of critical stimuli in the standard lot having .1% failures at specification stimulus and Curve II is the Distribution of critical stimuli in lot having 1% failures at the specification stimulus. What has been done then is to convert a comparison between lots having 1% and .1% failures at the specification stimulus into one between lots having 50% and 78% failures respectively at the "increased severity" level. As a result of this transformation we shall now require to take on the average a sample of only 32 (or less) in order to reach a decision of acceptability. Thus, the required sample size has been reduced from 600 to 32 by the method of increased severity. We wish to point out, however, that the large saving in sample size results from assuming a constant and known standard deviation for the critical stimuli and that these stimuli are normally distributed.

In actual practice, the value of the stimulus giving 50% failures is not constant and neither is their standard deviation. Because of this, tests of increased severity conducted at only one stimulus can give misleading and erroneous results. For example, if the standard deviation of critical stimuli associated with an explosive mixture is large, than the explosive mixture is undesirable; since there is a chance that it may either fail to explode at the stimulus designated in the specification or that it may explode prematurely.

Because of this fact, tests of type C were evolved; that is increased severity tests at two or more stimuli. When two stimuli are used it is customary to choose them at about the 20% and 80% failure points. Actually, the best estimates are achieved with the 6% and 94% failure points. However, trying to achieve these percentages could result in 0% and 100% values being obtained thereby nullifying the method. Let us designate as the true fraction failing at stimulus x_i, then the π_i can be represented as integrals of a normal distribution from x_i, to ∞.

$$(1)\quad \pi_i = \int_{x_i}^{\infty} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-(x-\mu)^2/2\sigma^2}\, dx$$

Therefore, what has to be determined are the estimates of the true mean, μ and true standard deviation, σ. These estimates are determined experimentally and labeled $\bar{x}$ and s respectively. The following are the parameters to be evaluated:

p_i = observed fraction failing at x_i

π_i = true fraction failing at x_i

$\bar{x}$ = sample estimate of true mean critical stimulus

μ = true mean critical stimulus

s = sample estimate of true standard deviation

σ = true standard deviation

On the assumption of a normal distribution, and by treating the experimentally determined P_1 and P_2 as the true π_1 and π_2 and associating with each π_i a t_i, where $t_i = y_i - \frac{5}{2}$ and where values of $t_i \sim \sigma$ are to be found in any standard tables of normal areas, the following simultaneous linear equations are obtained:

$$(2)\quad t_1 = \frac{x_1 - \bar{x}}{s}$$

$$t_2 = \frac{x_2 - \bar{x}}{s}$$ which may be solved

for $\bar{x}$ and s as follows:

$$(3)\quad \bar{x} = x_1 - \frac{d t_1}{t_2 - t_1}$$

$$(4)\quad s = -\frac{d}{t_2 - t_1}$$ where $d = x_2 - x_1$

This is known as the "probit" method of estimating the parameters of the normal distribution. By carrying out the test at two stimuli, the two lots are compared as to their means and their standard deviation or given symbolically.

$$(5)\quad \mu + K\sigma$$

If we use three stimuli, the third stimulus P_3 will serve as a check on the validity of the assumption of normality. However, if we use more than two stimuli for sensitivity tests, then the equations $\bar{x}$ and s shown above will no longer hold, instead, $\bar{x}$ and s will have to be determined by means of least squares.

It is therefore, a logical extension of the two and three stimuli test to the complete run-down test, for this test the stimuli used range from the stimulus for which none of the objects are affected to the stimulus for which all of the objects tested as affected.

A simple visual manner of summarizing the various methods discussed above is by means of operation characteristic curves, abbreviated OCC. By means of these curves a complete picture of an inspection plan or an experimental design is obtained.

Let us consider the example discussed previously, that is if in a sample of 20, if no defects occur, we accept, otherwise reject. The same plan can be used with a sample size of 100. The OC curves for these are shown in Figure 2. These are tests run at the specification stimulus. Let us, in addition plot the OC curve for an increased severity test on the same graph. Inspection of the curves shows that the only difference between curves I and II are that curve B is steeper and shifted to the left of curve I. The meanings attached to these differences are as follows:

1. The shift to the left shows that the chance of accepting material is less which is to be expected, since the probability of finding no defects in 100 samples is less than in 20 samples.

2. The steepness indicates that the risk of accepting bad lots or rejecting good ones are decreased.

Curve III, tested at the stimulus where 50% fail shows a marked improvement without sample size.

There are numerous cases in manufacturing processes where it is extremely important to have no defectives. However, since this is impossible to achieve with any sampling plan it resolves itself into a problem of assuming a very small risk of accepting

material with .001% defective or more. This type of condition occurs in the manufacture of ballistic weapons where costly items may fail completely because the primer or detonator did not function properly.

Let us assume for illustrative purposes that we wish, say 50% assurance that a lot contains no more than 3 defective in 10 million. With an increased severity test, either a 2 stimuli or complete rundown type, we can test 50 samples at each stimulus in the complete rundown test or about 200 at each stimulus in the case of the two stimuli test. Figure 3 shows a plot of the percentage failing against the probability of acceptance. On the same graph is plotted the results of the best single stimulus test, that at the specifcation stimulus. Figure 4 shows the amount of testing required using the specification stimulus which in this case would run in the neighborhood of 100,000 items as compared to about 400 with an increased severity test.

Another advantage obtained through increased severity testing is the ability to set up "safety-factors" for inspection tests. This generally cannot be done if a single stimulus type test is used.

Figure 5 is based on the sampling plan shown in Figure 4A and plots the probability of acceptance against the maximum stimulus where only 3 defectives in 10 million occur. From the graph, it is seen that practically no lot will be accepted whose maximum stimulus exceeds the specification stimulus by more than 1.25σ.

Let us consider the following problem:
A tensile specimen is being tested and it is desired that no more than 1 in 1000 will withstand a load of 4000 lbs. Twenty samples where tested at each of seven loads ranging from 500 lbs to 3500 lbs at 500 lb. increments. The results are tabulated:

Load - X (lbs)	No. Tested	No. Passing	Fraction	Passing - P
X_1 = 500	20	20	P_1	1.00
X_2 = 1000	20	19	P_2	.95
X_3 = 1500	20	18	P_3	.90
X_4 = 2000	20	14	P_4	.70
X_5 = 2500	20	4	P_5	.20
X_6 = 3000	20	1	P_6	.05
X_7 = 3500	20	0	P_7	0

Using the following form to simplify calculations, where

P_i = fraction passing

K_i = Std. Dev. factor

X_i = loads

Q_i = $1 - P_2$

f = interval of load

$X_{100\%}$ = interval all passing

x_i	P_i	k_i	$P_i q_i$	$k_i P_i$	$k_i - \Sigma k_i P_i$	$(k_i - \Sigma k_i P_i)^2$	$k_i - \Sigma k_i P_i)^2 P_i q_i$
1000	.95	1	.048	.95	-4.6	21.16	1.02
1500	.90	3	.09	2.70	-2.6	6.76	.61
2000	.70	5	.21	3.50	- .6	.36	.08
2500	.20	7	.16	1.40	1.4	1.96	.31
3000	.05	9	.048	.45	3.4	11.56	.55
	2.8		.56	9.0			2.57

$\Sigma P_i = 2.8$ $\Sigma P_i q_i = .56$ $\Sigma k_i P_i = 9.0$ $\Sigma (k_i - \Sigma k_i P_i)^2 P_i q_i = 2.57$

$f \Sigma P_i = 1400$ $\Sigma P_i q_i / n = \sigma_{\bar{x}}^2$ $(\Sigma P_i)^2 = 7.84$ $\sigma_{\sigma^2} = \sqrt{\frac{2.57}{n}}$

$x_{100\%} + .5f = 750$ $\sigma_{\bar{x}} = \sqrt{\frac{\Sigma P_i q_i}{n}}$ $\sigma^2 = 1.16$ $\sigma_{\sigma} = \frac{\sigma_{\sigma^2}}{2\sigma}$

$\bar{x} = 2150$ $\sigma_{\bar{x}} = \frac{f\sqrt{\Sigma P_i q_i}}{n}$ $\sigma = f(1.08)$ $\sigma_{\sigma} = f\frac{\sigma_{\sigma^2}}{2\sigma}$

$\sigma_{\bar{x}} = 85$ $\sigma = 540$ $\sigma_{\sigma} = 165$

The parameters multiplied by f, the interval size, connects the computational value to the actual value.

When the intervals are a fraction, change the fraction to its decimal equivalent and proceed as above. As can be seen, it is simpler to find all our parameters without using the interval size in computation but rather to adjust for it at the end of the computation.

At the 95% confidence level, the true mean critical stimulus, μ, lies between 1933 and 2317 lbs and at the 99% confidence level μ would lie between 1931 and 2369 lbs.

However, our interest lies in having at most 1 in 1000 specimens withstanding 4000 lbs load.

At the 99.9% level

$$\bar{X} + 3.09s = 2150 + 1670 = 3820$$

and $$s^2_{99.9} = s^2_{\bar{X}} + (3.09)^2 s^2 = 13225$$

giving $$s_{99.9} = 115$$

The probability of getting a sample value 3820 from a population having a mean of 4000 in approximately 1.74σ away from it and we can state that the test is significant at the 5% level; that is there is less than 1 chance in 20 of getting this value.

Since the aim of a test program is not solely to reduce sample size but also to avoid excessively restrictive assumptions, it is felt that tests of increased severity strike the balance. This was borne out earlier in the discussion where it was shown that 600 samples were necessary to insure rejection 5% of the time of lots having .1% defectives when testing at the specification stimulus. We saw that 32 samples were required testing at the 50% critical stimulus. However, certain assumptions had to be made namely, the critical stimuli are normally distributed for all lots and have the same standard deviation.

In actual practice using the complete rundown method, the number of samples required will lie somewhere in between 32 and 600.

However, the gain in information about the distribution of the critical stimuli obtained will more than compensate for the increased sample size compared to the single stimulus increased severity test. Sometimes, due to factors beyond our control, it is not feasible to test at equally spaced intervals.

If the intervals are not equally spaced, a first difference method can be used to estimate the parameters. For purposes of illustration a primer testing problem will be used.

Let $m_i = \frac{y_i + y_{i+1}}{2}$ $\quad m_0 = \frac{y_0 + y_1}{2}$

$d = m_i - m_0$ $\quad \bar{x} = \Sigma (p_i - p_{i+1})\left(\frac{y_i + y_{i+1}}{2}\right)$

$\beta = \alpha_{i+1} - \alpha_i$ $\quad \sigma_{\bar{x}}^2 = \Sigma \beta_i \sigma_{p_i}^2$

$\bar{x} = m_0 + \Sigma \beta_i q_i$ $\quad$ where $\sigma_{p_i}^2 = \frac{\Sigma p_i q_i}{n}$

$s^2 = \Sigma y_i q_i - (\Sigma \beta_i y_i)^2$ $\quad \sigma_s^2 = [\Sigma \alpha_i \cdot 2\beta_i (\Sigma \beta_i p_i)]^2 \sigma_{p_i}^2$

where q_i = fraction misfiring at height x_i

For ease of computation we tabulate the data as follows:

y_i	q_i	$y_i - \bar{x}'$	τ_i	$\tau_i - \bar{\tau}$
13	.10	-2	-1.28	-1.69
14	.60	-1	.25	- .16
15	.70	0	.52	.11
15.5	.80	.5	.84	.43
16	.80	1	.84	.43
16.5	.90	1.5	1.28	.87

$\sigma = \Sigma (y_i - \bar{x})(\tau_i - \bar{\tau}) = 1.37$

$\bar{x} = \bar{x}' - \sigma \bar{\tau} = 14.44$

1. $\bar{x}'$ = assumed mean; $\bar{x}$ = computed mean
2. τ_i obtained from "t" table

12		12.50		0		1
13	.90	13.50	.09	1	1.00	1
14	.40	14.50	.24	2	1.00	.5625
15	.30	15.25	.21	2.75	.75	.2500
15.5	.20	15.75	.16	3.25	.50	.2500
16	.20	16.25	.16	3.75	.50	.2500
16.5	.10	16.75	.09	4.25	.50	

$\sigma_{\bar{x}}^2 = \Sigma \beta_i \sigma_{p_i}^2 = .5506$ $\quad m_0 = 12.50$

PROBIT METHOD

The "Probit Method" of analysis is actually a means of transforming normal data where measurement is based upon only whether the measured characteristic is above or below a certain stimulus. The most common application of this method of analysis is in the biological sciences where lethality of varying dosages of drugs might be studied. In the field of ballistics it can readily be applied as well, even though it might be felt that the stimulus could be gradually increased until detonation occurred. However, any impulse applied to the primer that doesn't fire it, undoubtedly changes its sensitivity characteristics. This method depends on fitting a straight line to the observed data. However, since the variance of the independent variable is not constant but depends on "t" the usual means of fitting a straight line can not be used. Instead a method of successive approximations is employed.

A method of obtaining a first approximation for equally spaced intervals can be accomplished from the data accumulated from a "run down" experiment. Tabulating results of primer drop test data gives:

Height		Fraction Firing	t value
Trans.	Actual		"t" Tables)
-3	15"	.067	-1.50
-2	16"	.100	-1.28
-1	17	.200	- .84
0	18	.400	- .26
1	19	.500	0
2	20	.800	.84
3	21	.867	1.11
4	22	.967	1.84

From this table we get $\bar{X} = 18.599$

$\sigma = 1.989$

Using $t = \frac{h - x}{\sigma}$ $\qquad h = x + 18$

$$a = -\frac{.599}{1.989} = -.301$$

$$t = \frac{h - 18599}{1.989} = \frac{x + 18 - 18.599}{1.989}$$

$$t = \frac{x - .590}{1.989} = -.301 + .503x$$

$$b = \frac{1}{1.989} = .503$$

a useful means for obtaining a first approximation is the graphic method since it can be used for equally or unequally spaced intervals.

Given:

Charges (grains)	Number fired	Number successes	%Successes P	"t" from Table
60	3	0	.00	-1.28
120	3	2	.67	.44
180	3	2	.67	.44
240	3	3	1.00	1.28
300	3	[illegible]	1.00	1.28

When the interval is not equal (5,5,10,5,3) etc.... take the W value from the table and multiply by the n or a reduction of it.

From first approximation t = .44 + .84Y (See Graph Fig.7)

x	t	p	Q	$Q-p$	Z	w	η	wx	$w\eta$
-2	-1.24	1.00	.8925	-.1075	.1849	.3565	-.5814	-.7130	-.2073
-1	- .40	.33	.6554	.3254	.3683	.6005	.8835	-.6005	.5303
0	.44	.33	.3300	.0000	.3621	.5932	.0000	.0000	.0000
1	1.28	.00	.1003	.1003	.1758	.3428	.5715	.3428	.1956
2	2.12	.00	.0170	.0170	.0422	.1064	.4028	.2128	.0428
						1.9994		-.7579	.5616

q = 1-P
"Q", "Z", "W" are found in "Tables for Analysis of Experimental Data", when "t" is negative, subtract Q value found in table from 1.0000

"Z" and "W" is taken from the table regardless of "t" sign

$$\eta = \frac{Q-p}{Z}$$

$$\bar{x} = \frac{\Sigma Wx}{\Sigma W} = -.379 \qquad \bar{\eta} = \frac{\Sigma W\eta}{\Sigma W} = .2809$$

$$\Sigma Wx\eta = .1653 \qquad \Sigma Wx^2 = 2.7949$$

$$-\Sigma W\eta\bar{x} = \frac{.2129}{.3782} \qquad -\bar{x}\Sigma Wx = \frac{-.2873}{2.5076}$$

$$\delta b = \frac{.3782}{2.5076} = .1508$$

$$\bar{\eta} = .2809$$

$$-\bar{x}\,\delta b = .0572$$

$$\delta a = .3381$$

$$t = .44 + .84x$$
$$\frac{.3381 + .1508x}{t = .7781 + .9908x} = \text{second approximation}$$

x	t	p	Q	$Q-p$	Z	w	η	wx	$w\eta$
-2	-1.20	1.00	.8849	-.1151	.1492	.3703	-.5927	-.7406	-.2195
-1	- .20	.33	.5793	.2493	.3910	.6274	.6376	-.6274	.4000
0	.78	.33	.2177	-.1123	.2943	.5086	-.3816	.0000	-.1941
1	1.77	.00	.0384	.0384	.0833	.1880	.4610	.1880	.0867
2	2.77	.00	.0028	.0028	.0086	.0265	.3256	.0530	.0086
						1.7208		-1.1270	.0817

$\bar{x} = -.6522$ $\qquad \bar{\eta} = .0475$

$\bar{X} = -.6522$

$\bar{\eta} = .0475$

$\Sigma W X \eta = .1428$ $\qquad$ $\Sigma W X^2 = 2.4026$

$-\bar{X}\Sigma W \eta = .0533$ $\qquad$ $-\bar{X}\Sigma WX = -.7350$

$.1961$ $\qquad$ 1.6676

$$\delta b = \frac{.1961}{1.6676} = .1176$$

$\bar{\eta} = .0475$

$$\frac{-\bar{X}\,\delta b = .9767}{\delta a = .1242}$$

$t = .7781 + .9908 X$

$.1242 + .1176 X$

$t = .9032 + 1.1084 X$ = Third approximation

X	t	f	Q	Q-f	Z	W	η	WX	Wη
-2	-1.31	1.00	.9019	-.0951	.1691	.3325	-.5624	-.6650	-.1870
-1	- .21	.33	.5832	.2532	.3902	.6265	-.6439	-.6265	.4065
0	.90	.33	.1841	-.1459	.2662	.4714	-.5483	.0000	-.2585
1	2.01	.00	.0222	.0222	.0592	.1289	.4196	.1289	.0541
2	3.12	.00	.0009	.0009	.0031	.0104	.2903	.0208	.0030
						1.5697		1.1418	.0181

$\bar{X} = -.7274$ $\qquad$ $\bar{\eta} = .0115$

$\Sigma WX^2 = 2.1270$ $\qquad$ $\Sigma WX\eta = .0276$ $\qquad$ $\bar{\eta} = .0115$

$-\bar{X}\Sigma WX = -.8350$ $\qquad$ $-\bar{X}\Sigma W\eta = .0132$ $\qquad$ $-\bar{X}\,\delta b = .0229$

$.0408$ $\qquad$ $\delta a = .0344$

$$\delta b = \frac{.0408}{1.2965} = .0315$$

$t = .9023 + 1.1084 X$

$.0344 + .0315 X$

$.9367 + 1.1399 X$

The final approximation is determined if δb and δa is less than .01 of first approximation. Therefore, the final approximation is $t = .9023 + 1.1084 X$

To estimate the error associated with these parameters compute:

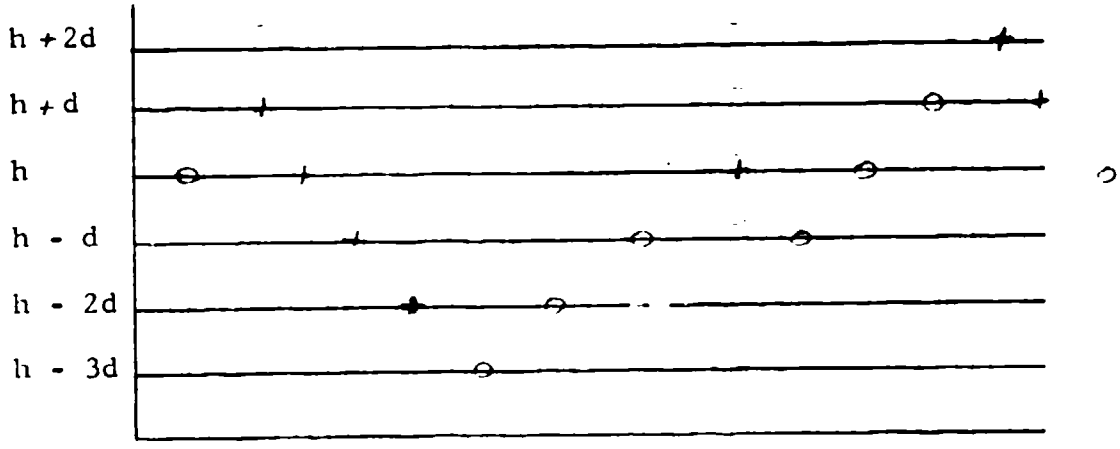
$$\sigma_a^2 = k\left[\frac{\Sigma W x^2}{\Sigma W \Sigma W(x-\bar{x})^2}\right]\cdot\frac{1}{\ell^2}$$

$$\sigma_b^2 = k\left[\frac{1}{\Sigma W (x-\bar{x})^2}\right]\cdot\frac{1}{\ell^2}$$

where k is the factor for reducing the sample size, η and 1 is the scale reducing factor. Here $k = \ell = .1$

$$\rho_{ab}\sigma_a\sigma_b = k\left[\frac{-\Sigma(Wx)}{\Sigma W[\Sigma W(x-\bar{x})^2]}\right]\cdot\frac{1}{\ell^2}\,;\; \chi^2 = \frac{1}{k}\left[\Sigma W\eta^2\right]$$

Another procedure for statistical analysis of sensitivity data is one that was used extensively by the Explosives Research Laboratory at Bruceton, Pa. This method is known as the "staircase" or "up and down" method, and quite often, as the Bruceton method. The difference between this method and the ones previously described lies in the fact that this method does not use a fixed sample size at each height. Instead, the height of drop, is changed by a fixed increment after each single specimen. If the explosive fired at h_n the height tested, then for the next test the height is reduced to h_{n-1}. (on the other hand, if it fails to fire, the height is increased by this fixed increment to h_{n+1}) This method insures a great number of tests being conducted at or near the mean height of fire, that is, at the height at which fifty percent fire. If we let + denote firing and ⊖ misfiring a plot of a test could look as follows



where n is the height and d is a fixed difference. The initial testing height is usually chosen on the basis of past experience.

The important advantages of this method are:

1. An accurate estimate of the mean, stronger than run-down test.
2. Computation of mean and variance is relatively simple.
3. Reduced sample size.

The disadvantages are:

1. Changing height of test for each specimen.
2. The estimate of the variance is weak compared to a run down test.

Plotting the results of 100 specimens gives the following picture:

See Figure

Where

i = reduced test heights

h_i = actual heights

$+$ = firing

$\bigcirc$ = misfiring

In estimating the mean and standard deviation either the +'s or O's are used depending upon which occur least.

The mean is obtained from

$m = c + d\left(\frac{1}{N}\Sigma i n_i + \frac{1}{2}\right)$ if the zeros are used and

$m = c + d\left(\frac{1}{N}\Sigma i n_i - \frac{1}{2}\right)$ if the +'s are used.

The standard deviation is obtained by computing

$$M = \frac{\Sigma i^2 n_i}{N} - \left(\frac{\Sigma i n_i}{N}\right)^2$$

and then going to the tables with this numbe. to find s. From s, we estimate $\sigma = d\,s$

The meaning of the terms are as follows:

c = normalized heights of lowest line = .928

N = number firing or misfiring (lesser) = 50

d = difference between log h_i

i = reduced height

n_i = number firing at reduced height i

Summarizing the information from Fig. 6 we have

i	n_i	$i n_i$	$i^2 n_i$
0	0	0	0
1	8	8	8
2	35	70	140
3	6	18	54
4	1	4	16
Σ	50	100	218

Since the +'s and O's are equal in number, we will use the formula for the mean based on +'s in this case -- although either could be used.

This gives

$$m = .928 + .093 \quad (100/50 - \tfrac{1}{2})$$

$$= 1.068$$

and $$M = \frac{50\ (218) - (100)^2}{50^2}$$

$$= 360$$

From Table I the value of s corresponding to a value of M = .360 is s = .625 and σ = .093 (.625) = .058

Heights at which a given percent of the specimens will fire can be estimated from the mean by subtracting or adding multiples of σ. Thus various percent heights can be estimated from $m \pm k\sigma$ by choosing the proper k.

Percent P	k
.01	-3.719
.1	-3.090
1	-2.326
5	-1.645
10	-1.282
25	- .675
50	0
75	.675
90	1.282
95	1.645
99	2.326
99.9	3.090
99.99	3.719

ABSTRACT

This report gives several methods of estimating the mean critical stimulus and its variance.

The types discussed are:

1. Testing at single specification stimulus.
2. Testing at a single stimulus greater than the specification stimulus.
3. Testing at two or three stimuli all greater than the specification stimulus
4. A complete "run down" test or probit testing.
5. The "Staircase" or "Bruceton" method which consists of varying the stimulus throughout the test.

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ADDENDUM

ACCURACY OF CALCULATIONS

There appears to be a great deal of misunderstanding regarding accuracy of calculations and significant numbers. Some of the confusion seems to stem from a misunderstanding concerning the meanings of accuracy and precision.

We deal primarily with two types of numbers, rational and irrational, with the rational numbers being either integral or fractional. Obviously, since we are dealing with measurements, our readings will be inaccurate after a given point, due to the limitations of our measuring devices. Because of this, we must discard some of our figures resulting from computations. However, we may also discard some figures if the accuracy of our results are only needed to a certain degree. In addition, certain numbers such as π, e, roots, logarithms can only be approximated to being irrational numbers.

For the reasons given above, we must express our results as "correct to the nth significant figure".

Definitions

Approximate number - An approximate number is one that differs from the exact number for which it stands. For example, $1/3 \sim .333$; $\pi \sim 3.14$; 546, 273, 812 ~ 546, 274, 000. The symbol ~ means "is approximately".

Significant figure - A significant figure is any digit from 1 through 9; a zero is significant except when it is used for the sole purpose of fixing the decimal point. Zeros at the end of a number such as 546, 273, 000 may or may not be significant. Therefore, a proper procedure to follow is to write numbers in a scientific form where the number is expressed as one whole number with the decimals to the proper number of significant digits and the magnitude powers of 10. For example, 5.46×10^4 is significant to three digits, but its magnitude is in the ten thousands.

The rules to follow in rounding off a number to n significant figures are as follows:

a. Discard all digits to the right of the nth digit.

b. Increase the nth digit by one if the n plus first digit is greater than 5.

c. Do not change the nth digit if the n plus first digit is less than 5.

d. If the n plus first digit is exactly 5, increase the nth digit by 1 if it is odd; let it remain unchanged if it is even. For example, in rounding off 2.565 to three significant figures gives 2.56 but 2.555 would round off to 2.56.

Therefore a number which has been rounded off to n significant figures may differ from the actual number by, at most, one integer in the nth place.

Measurements of Error

One measurement of error is the difference between the true value of a quantity and its approximate value and is known as the absolute error. For example, 1 inch may be read as 1.02 inch. Here, the absolute error is 0.02 inch.

For a number that is correct to n significant figures, its absolute error cannot be greater than 1/2 unit of the nth significant figure. This follows directly from the rounding off process. Thus, if 2.568 is correct to four significant figures, the true value must lie in the interval from 2.5675 to 2.5685.

Another measurement of error is known as the relative error and is defined as the ratio between the absolute error and the true value. Even though an absolute error is greater in magnitude, the measurement may be more accurate than one having a smaller absolute error. For example, in measuring a 2 inch block to the nearest thousandth of an inch, and one mile to the nearest foot, the absolute errors are 0.0005 inch and 6 inches respectively. However, the respective relation errors are $\frac{0.005}{2}$ or $\frac{1}{4000}$ and $\frac{1}{5280}$ or $\frac{1}{10,560}$, clearly showing that the measurement of the mile is more accurate.

The best estimate of error is the standard deviation which is a measure of the dispersion of the readings about the average. The formula for the standard deviation;

$$\sigma = \sqrt{\frac{\sum(X_i - X)^2}{n}}$$

where X_i is the individual readings, X is the average of all the readings and n is the number of individual readings. However, if a desk calculator is used the formula may be written

$$\sigma = \sqrt{\frac{\sum(x_i)^2}{n-1} - \frac{(\sum x_i)^2}{n(n-1)}}$$

In general, a number correct to n significant figures will be in the interval between $x + 3\sigma$ and $x - 3\sigma$.

Quite often, it is required to know how many figures to carry in computational work. In adding a column of not more than 20 figures, one more decimal place should be carried than is required in the final result. If a measurement is needed correct to the nearest hundredth, then the individual readings are taken to the nearest thousandth. Since the absolute error of each of the numbers will be ≤ 0.0005; for twenty numbers it will not exceed 0.01. Therefore, it will be possible for the second decimal to be in error by not more than one unit.

If there are more than 20 but less than 200 readings, carry two more decimals than are required in the final result.

When subtracting numbers, both should be rounded off to the same number of decimal places. For example, in subtracting 54.563 from 764.9 where each is correct to the total number of significant figures. It would be entirely wrong to write 764.900 - 54.563 because the last two places in 764.900 are not necessarily zero. The accepted way is to write 764.9 - 54.6. This type of error is often found in writing of tolerance limits, where the true dimension is given as $0.06 \pm 10\%$.

A serious error occurs in the subtraction of two nearly equal approximate numbers. In subtracting 55.563 from 55.436 which are each correct to five figures we obtain the result of 0.127, correct to only three significant figures. In cases where the numbers are extremely close, the result may be correct to only one significant figure, and even this may be in error by one unit. For this type of computation, in order to eliminate this occurrence, we must carry additional places. This can be done if the numbers are approximated such as π, $\sqrt{3}$, e, and so forth.

Supposing we had a problem in multiplication where one factor is without error and the other is an approximate number and we wish the absolute error to be less than some fixed constant. In a case of this sort, retain as many decimal places in the approximate factor as there are whole digits in the other factor plus the number of decimal places permitted in the absolute error. Let us consider the case of multiplying 291 by π where 291 is known without error. Let us assume that we wish the absolute error to be $\leq .01$. To obtain this magnitude of the absolute error, we retain 5 decimal places for π. If the desired absolute error has been 0.001, then 6 decimal places would have been retained.

In the case where both factors are approximate, retain as many decimals in the multiplicand as there are whole numbers in the limiting error. In the multipler, retain as many decimals as there are whole numbers in the multiplicand, plus the number of decimals in the limiting error. For example, in multiplying 30.87541 by 6.21832 so that the absolute error of the product is $\leq .01$ take 30.875 x 6.2183 and obtain 191.99.

In finding a product of two or more approximate numbers of different accuracies, the more accurate number is rounded off so that it contains one more significant figure than the leat accurate factor. The result should be given to as many significant figures as are contained in the least accurate factor. A more reliable procedure is given later.

In division, as in multiplication, if one of the numbers is more accurate, it should be rounded off so as to contain one more significant figure than the less accurate one. Again, the result should be given to as many, but not more, significant figures as are contained in the less accurate. Dividing 56.3 by $\sqrt{5}$ where the numerator is an approximate number which has been rounded off to one decimal place. In order to minimize the error of the $\sqrt{5}$, we take the value 2.236 as the square root of 5. Using the relative error, $E_r \leq \frac{.05}{56.3} < .0009$ the division $\frac{56.3}{2.236} = 25.2$ and $E_a < 25.2 \times .0009 < .023$. Since this error has no effect on the third place of the quotient, we can accept 25.2 as the correct result.

In averaging numbers where the number being used to obtain the average ≥ 10, one more place may be considered significant than was significant in the terms of the sum. Seldom should more places be retained in the average.

For example.

1.32	1.3
1.45	1 4
1.36	1 .4
1.01	1.0
1.28	1.3
1.09	1.1
1.29	1.3
1.30	1.3
1.27	1.3
1.01	1.0
12.39	12.4

Average 1.239 ~ 1.24 Average 1.24

The accuracy of a product can be found by use of the relative error. The absolute error is then found from:

absolute error = relative error x product of factors

For a series of products, the relative error is:

$$E\sim = \frac{\Delta\mu_1}{\mu_1} + \frac{\Delta\mu_2}{\mu_2} + \frac{\Delta^{\mu}\eta}{\mu_\eta}$$

with N equal to the product of $u_1 \cdot u_2 \cdot u_3 \ldots u_n$. Consider the product 349.1 x 863.4 with both factors correct to four figures. Therefore, $\Delta u_1 = \Delta u_2 = .05$ and $E\sim \leq \frac{.05}{349.1} \quad \frac{.05}{863.4} = .00020.$

Here, N ~ 301413. The absolute error is ~ 301413 x .00020 = 60. The true result must therefore lie between 301473 and 301353. However,

since from this we see that we can only trust 4 significant figures we write $349.1 \times 863.4 = 3.014 \times 10^5$.

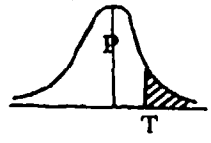
Let us consider the above problem from the standpoint that the true product must be between its maximum and minimum values. We then retain as many significant figures as coincide in the maximum and minimum values. The maximum value is $349.15 \times 863.45 = 3014.74$ and the minimum is $349.05 = 863.35 = -3013.52$. This points out that we can retain four significant figures. The effect of dropping right hand numbers in multiplicand and multiplier is shown below:

```
      3456786
      3134652
      6913572
     17283930
    20740716
   13827144
  10360358
  3456786
10360358
10825721148472
```

Table I

Areas and Their Standard Sampling Errors for the Normal Curve

$$Q = \int_T^\infty Z dx, \quad P = 1 - Q$$



T	Q	PQ	T	Q	PQ
.00	.5000000	.2500000	.32	.3744842	.2342458
.01	.4960106	.2499841	.33	.3707000	.2332815
.02	.4920217	.2499363	.34	.3669283	.2322919
.03	.4880335	.2498568	.35	.3631693	.2312774
.04	.4840466	.2497455	.36	.3594236	.2302383
.05	.4800612	.2496024	.37	.3556912	.2291750
.06	.4760778	.2494277	.38	.3519727	.2280879
.07	.4720968	.2492214	.39	.3482683	.2269775
.08	.4681186	.2489836	.40	.3445783	.2258441
.09	.4641436	.2487143	.41	.3409030	.2246881
.10	.4601722	.2484137	.42	.3372427	.2235101
.11	.4562047	.2480820	.43	.3335978	.2223103
.12	.4522416	.2477191	.44	.3299686	.2210893
.13	.4482832	.2473254	.45	.3263552	.2198475
.14	.4443300	.2469009	.46	.3227581	.2185853
.15	.4403823	.2464457	.47	.3191775	.2173032
.16	.4364405	.2459602	.48	.3156137	.2160017
.17	.4325051	.2454444	.49	.3120669	.2146811
.18	.4285763	.2448987	.50	.3085375	.2133421
.19	.4246546	.2443231	.51	.3050257	.2119850
.20	.4207403	.2437179	.52	.3015318	.2106104
.21	.4168338	.2430834	.53	.2980560	.2092186
.22	.4129356	.2424198	.54	.2945985	.2078102
.23	.4090459	.2417274	.55	.2911597	.2063857
.24	.4051651	.2410063	.56	.2877397	.2049456
.25	.4012937	.2402571	.57	.2843388	.2034902
.26	.3974319	.2394798	.58	.2809573	.2020203
.27	.3935801	.2386748	.59	.2775953	.2005361
.28	.3897388	.2378425	.60	.2742531	.1990383
.29	.3859081	.2369830	.61	.2709309	.1975273
.30	.3820886	.2360969	.62	.2676289	.1960037
.31	.3782805	.2351844	.63	.2643473	.1944678

Table I. Continued

T	Q	PQ	T	Q	PQ
.64	.2610863	.1929202	1.02	.1538642	.1301900
.65	.2578461	.1913615	1.03	.1515050	.1285512
.66	.2546269	.1897920	1.04	.1491700	.1269183
.67	.2514289	.1882124	1.05	.1468591	.1252915
.68	.2482522	.1866230	1.06	.1445723	.1236712
.69	.2450971	.1850245	1.07	.1423097	.1220576
.70	.2419637	.1834173	1.08	.1400711	.1204512
.71	.2388521	.1818018	1.09	.1378566	.1188522
.72	.2357625	.1801785	1.10	.1356661	.1172608
.73	.2326951	.1785481	1.11	.1334995	.1156774
.74	.2296500	.1769109	1.12	.1313569	.1141023
.75	.2266274	.1752674	1.13	.1292381	.1125356
.76	.2236273	.1736181	1.14	.1271432	.1109778
.77	.2206499	.1719635	1.15	.1250719	.1094289
.78	.2176954	.1703041	1.16	.1230244	.1078894
.79	.2147639	.1686404	1.17	.1210005	.1063594
.80	.2118554	.1669727	1.18	.1190001	.1048391
.81	.2089701	.1653016	1.19	.1170232	.1033288
.82	.2061081	.1636276	1.20	.1150697	.1018287
.83	.2032694	.1619510	1.21	.1131394	.1003389
.84	.2004542	.1602723	1.22	.1112324	.0988598
.85	.1976625	.1585920	1.23	.1093486	.0973915
.86	.1948945	.1569106	1.24	.1074877	.0959341
.87	.1921502	.1552285	1.25	.1056498	.0944879
.88	.1894297	.1535461	1.26	.1038347	.0930531
.89	.1867329	.1518637	1.27	.1020423	.0916297
.90	.1840601	.1501820	1.28	.1002726	.0902180
.91	.1814113	.1485012	1.29	.0985253	.0888181
.92	.1787864	.1468218	1.30	.0968005	.0874302
.93	.1761855	.1451442	1.31	.0950979	.0860543
.94	.1736088	.1434688	1.32	.0934175	.0846907
.95	.1710561	.1417959	1.33	.0917591	.0833394
.96	.1685276	.1401260	1.34	.0901227	.0820006
.97	.16602032	.1384595	1.35	.0885080	.0806743
.98	.1635431	.1367968	1.36	.0869150	.0793608
.99	.1610871	.1351380	1.37	.0853435	.0780600
1.00	.1586553	.1334838	1.38	.0837933	.0767720
1.01	.1562476	.1318343	1.39	.0822644	.0754970

Table I. Continued

T	Q	PQ	T	Q	PQ
1.40	.0807567	.0742351	1.78	.0375380	.0361289
1.41	.0792698	.0729861	1.79	.0367270	.0353781
1.42	.0778038	.0717504	1.80	.0359303	.0346393
1.43	.0763585	.0705279	1.81	.0351479	.0339125
1.44	.0749337	.0693186	1.82	.0343795	.0331975
1.45	.0735293	.0681227	1.83	.0336250	.0324944
1.46	.0721450	.0669401	1.84	.0328841	.0318027
1.47	.0707809	.0657710	1.85	.0321568	.0311227
1.48	.0694366	.0646152	1.86	.0314428	.0304542
1.49	.0681121	.0634728	1.87	.0307419	.0297968
1.50	.0668072	.0623440	1.88	.0300540	.0291508
1.51	.0655217	.0612286	1.89	.0293790	.0285159
1.52	.0642555	.0601267	1.90	.0287166	.0278920
1.53	.0630084	.0590383	1.91	.0280666	.0272789
1.54	.0617802	.0579634	1.92	.0274289	.0266766
1.55	.0605708	.0569020	1.93	.0268034	.0260850
1.56	.0594799	.0558539	1.94	.0261898	.0255039
1.57	.0582076	.0548195	1.95	.0255881	.0249333
1.58	.0570534	.0537983	1.96	.0249979	.0243730
1.59	.0559174	.0527906	1.97	.0244192	.0238229
1.60	.0547993	.0517963	1.98	.0238518	.0232829
1.61	.0536989	.0508153	1.99	.0232955	.0227528
1.62	.0526161	.0498476	2.00	.0227501	.0222325
1.63	.0515507	.0488932	2.01	.0222156	.0217221
1.64	.0505026	.0479521	2.02	.0216917	.0212212
1.65	.0494715	.0470241	2.03	.0211783	.0207298
1.66	.0484572	.0461091	2.04	.0206752	.0202477
1.67	.0474597	.0452073	2.05	.0201822	.0197749
1.68	.0464787	.0443184	2.06	.0196993	.0193112
1.69	.0455140	.0434425	2.07	.0192262	.0188566
1.70	.0445655	.0425794	2.08	.0187628	.0184108
1.71	.0436329	.0417291	2.09	.0183089	.0179737
1.72	.0427162	.0408915	2.10	.0178644	.0175453
1.73	.0418151	.0400666	2.11	.0174292	.0171254
1.74	.0409295	.0392543	2.12	.0170030	.0167139
1.75	.0400592	.0384545	2.13	.0165858	.0163107
1.76	.0392039	.0376670	2.14	.0161774	.0159157
1.77	.0383636	.0368918	2.15	.0157776	.0155287

Table I. Continued

T	Q	PQ	T	Q	PQ
2.16	.0153863	.0151496	2.57	.0050849	.0050590
2.17	.0150034	.0147783	2.58	.0049400	.0049156
2.18	.0146287	.0144147	2.59	.0047988	.0047758
2.19	.0142621	.0140587	2.60	.0046612	.0046395
2.20	.0139034	.0137101	2.61	.0045271	.0045066
2.21	.0135526	.0133689	2.62	.0043965	.0043772
2.22	.0132094	.0130349	2.63	.0042692	.0042510
2.23	.0128737	.0127080	2.64	.0041453	.0041281
2.24	.0125455	.0123881	2.65	.0040246	.0040084
2.25	.0122245	.0120751	2.66	.0039070	.0038917
2.26	.0119106	.0117687	2.67	.0037926	.0037782
2.27	.0116038	.0114692	2.68	.0036811	.0036675
2.28	.0113038	.0111760	2.69	.0035726	.0035598
2.29	.0110107	.0108895	2.70	.0034670	.0034550
2.30	.0107241	.0106091	2.71	.0033642	.0033529
2.31	.0104441	.0103350	2.72	.0032641	.0032534
2.32	.0101704	.0100670	2.73	.0031667	.0031567
2.33	.0099031	.0098050	2.74	.0030720	.0030626
2.34	.0096419	.0095489	2.75	.0029708	.0029709
2.35	.0093867	.0092986	2.76	.0028901	.0028817
2.36	.0091375	.0090540	2.77	.0028028	.0027949
2.37	.0088940	.0088149	2.78	.0027179	.0027105
2.38	.0086563	.0085814	2.79	.0026354	.0026285
2.39	.0084242	.0083532	2.80	.0025551	.0025486
2.40	.0081975	.0081303	2.81	.0024771	.0024710
2.41	.0079763	.0079127	2.82	.0024012	.0023954
2.42	.0077603	.0077001	2.83	.0023274	.0023220
2.43	.0075494	.0074924	2.84	.0022557	.0022506
2.44	.0073436	.0072897	2.85	.0021860	.0021812
2.45	.0071428	.0070918	2.86	.0021182	.0021137
2.46	.0069469	.0068986	2.87	.0020524	.0020482
2.47	.0067557	.0067101	2.88	.0019884	.0019844
2.48	.0065691	.0065259	2.89	.0019262	.0019225
2.49	.0063872	.0063464	2.90	.0018658	.0018623
2.50	.0062097	.0061711	2.91	.0018071	.0018038
2.51	.0060366	.0060002	2.92	.0017502	.0017471
2.52	.0058677	.0058333	2.93	.0016948	.0016919
2.53	.0057031	.0056706	2.94	.0016411	.0016384
2.54	.0055426	.0055119	2.95	.0015889	.0015864
2.55	.0053861	.0053571	2.96	.0015382	.0015358
2.56	.0052336	.0052062	2.97	.0014890	.0014868

TABLE I Continued

T	Q	PQ	T	Q	PQ
2.96	.0014412	.0014391	3.36	.0003897	.0003895
2.99	.0013949	.0013930	3.37	.0003758	.0003757
3.00	.0013449	.0013481	3.38	.0003624	.0003623
3.01	.0013062	.0013045	3.39	.0003495	.0003494
3.02	.0012639	.0012623	3.40	.0003369	.0003368
3.03	.0012228	.0012213	3.41	.0003248	.0003247
3.04	.0011829	.0011815	3.42	.0003131	.0003130
3.05	.0011442	.0011429	3.43	.0003018	.0003017
3.06	.0011067	.0011055	3.44	.0002909	.0002908
3.07	.0010703	.0010692	3.45	.0002803	.0002802
3.08	.0010350	.0010339	3.46	.0002701	.0002700
3.09	.0010008	.0009998	3.47	.0002602	.0002601
3.10	.0009676	.0009667	3.48	.0002507	.0002506
3.11	.0009354	.0009354	3.49	.0002415	.0002414
3.12	.0009043	.0009035	3.50	.0002326	.0002325
3.13	.0008740	.0008732	3.51	.0002241	.0002240
3.14	.0008447	.0008440	3.52	.0002158	.0002158
3.15	.0008164	.0008157	3.53	.0002078	.0002078
3.16	.0007888	.0007882	3.54	.0002001	.0002001
3.17	.0007622	.0007616	3.55	.0001926	.0001926
3.18	.0007364	.0007359	3.56	.0001854	.0001854
3.19	.0007114	.0007109	3.57	.0001785	.0001785
3.20	.0006871	.0006866	3.58	.0001718	.0001718
3.21	.0006637	.0006633	3.59	.0001653	.0001653
3.22	.0006410	.0006406	3.60	.0001591	.0001591
3.23	.0006190	.0006186	3.61	.0001531	.0001531
3.24	.0005976	.0005972	3.62	.0001473	.0001473
3.25	.0005770	.0005767	3.63	.0001417	.0001417
3.26	.0005571	.0005568	3.64	.0001363	.0001363
3.27	.0005377	.0005374	3.65	.0001311	.0001311
3.28	.0005190	.0005187	3.66	.0001261	.0001261
3.29	.0005009	.0005006	3.67	.0001213	.0001213
3.30	.0004834	.0004832	3.68	.0001166	.0001166
3.31	.0004665	.0004663	3.69	.0001121	.0001121
3.32	.0004501	.0004499	3.70	.0001078	.0001078
3.33	.0004342	.0004340	3.71	.0001036	.0001036
3.34	.0004189	.0004187	3.72	.0000996	.0000996
3.35	.0004041	.0004039	3.73	.0000957	.0000957

TABLE I Continued

T	Q	PQ	T	Q	PQ
3.74	.0000920	.0000920	4.12	.0000189	.0000189
3.75	.0000884	.0000884	4.13	.0000181	.0000181
3.76	.0000850	.0000850	4.14	.0000174	.0000174
3.77	.0000816	.0000816	4.15	.0000166	.0000166
3.78	.0000784	.0000784	4.16	.0000159	.0000159
3.79	.0000753	.0000753	4.17	.0000152	.0000152
3.80	.0000723	.0000723	4.18	.0000146	.0000146
3.81	.0000695	.0000695	4.19	.0000139	.0000139
3.82	.0000667	.0000667	4.20	.0000133	.0000133
3.83	.0000641	.0000641	4.21	.0000128	.0000128
3.84	.0000615	.0000615	4.22	.0000122	.0000122
3.85	.0000591	.0000591	4.23	.0000117	.0000117
3.86	.0000567	.0000567	4.24	.0000112	.0000112
3.87	.0000544	.0000544	4.25	.0000107	.0000107
3.88	.0000522	.0000522	4.26	.0000102	.0000102
3.89	.0000501	.0000501	4.27	.0000098	.0000098
3.90	.0000481	.0000481	4.28	.0000093	.0000093
3.91	.0000461	.0000461	4.29	.0000089	.0000089
3.92	.0000443	.0000443	4.30	.0000085	.0000085
3.93	.0000425	.0000425	4.31	.0000082	.0000082
3.94	.0000407	.0000407	4.32	.0000078	.0000078
3.95	.0000391	.0000391	4.33	.0000075	.0000075
3.96	.0000375	.0000375	4.34	.0000071	.0000071
3.97	.0000359	.0000359	4.35	.0000068	.0000068
3.98	.0000345	.0000345	4.36	.0000065	.0000065
3.99	.0000330	.0000330	4.37	.0000062	.0000062
4.00	.0000317	.0000317	4.38	.0000059	.0000059
4.01	.0000304	.0000304	4.39	.0000057	.0000057
4.02	.0000291	.0000291	4.40	.0000054	.0000054
4.03	.0000279	.0000279	4.41	.0000052	.0000052
4.04	.0000267	.0000267	4.42	.0000049	.0000049
4.05	.0000256	.0000256	4.43	.0000047	.0000047
4.06	.0000245	.0000245	4.44	.0000045	.0000045
4.07	.0000235	.0000235	4.45	.0000043	.0000043
4.08	.0000225	.0000225	4.46	.0000041	.0000041
4.09	.0000216	.0000216	4.47	.0000039	.0000039
4.10	.0000207	.0000207	4.48	.0000037	.0000037
4.11	.0000198	.0000198	4.49	.0000036	.0000036

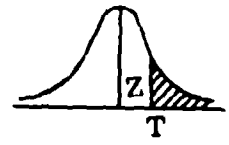
TABLE I Continued

T	Q	PQ
4.50	.0000034	.0000034
4.51	.0000032	.0000032
4.52	.0000031	.0000031
4.53	.0000030	.0000030
4.54	.0000028	.0000028
4.55	.0000027	.0000027
4.56	.0000026	.0000026
4.57	.0000024	.0000024
4.58	.0000023	.0000023
4.59	.0000022	.0000022
4.60	.0000021	.0000021
4.61	.0000020	.0000020
4.62	.0000019	.0000019
4.63	.0000018	.0000018
4.64	.0000017	.0000017
4.65	.0000017	.0000017
4.66	.0000016	.0000016
4.67	.0000015	.0000015

Table II

Ordinates, Probits, and Probit Weights Associated with the Normal Curve of Error

$$Z = \frac{1}{\sqrt{2\pi}} e^{-T^2/2}, \quad W = \frac{Z}{PQ}$$



T	Z	W	T	Z	W
.00	.3989423	.63662	.31	.3802264	.61472
.01	.3989223	.63660	.32	.3790305	.61331
.02	.3988625	.63653	.33	.3778007	.61185
.03	.3987628	.63641	.34	.3765372	.61035
.04	.3986233	.63625	.35	.3752403	.60882
.05	.3984439	.63604	.36	.3739106	.60724
.06	.3982248	.63579	.37	.3725483	.60562
.07	.3979661	.63549	.38	.3711539	.60396
.08	.3976677	.63514	.39	.3697277	.60226
.09	.3973298	.63475	.40	.3682701	.60052
.10	.3969525	.63431	.41	.3667817	.59874
.11	.3965360	.63383	.42	.3652627	.59692
.12	.3960802	.63330	.43	.3637136	.59506
.13	.3955854	.63272	.44	.3621349	.59316
.14	.3950517	.63210	.45	.3605270	.59123
.15	.3944793	.63143	.46	.3588903	.58925
.16	.3938684	.63072	.47	.3572253	.58724
.17	.3932190	.62996	.48	.3555325	.58520
.18	.3925315	.62916	.49	.3538124	.58311
.19	.3918060	.62832	.50	.3520653	.58099
.20	.3910427	.62742	.51	.3502919	.57884
.21	.3902419	.62649	.52	.3484925	.57664
.22	.3894038	.62551	.53	.3466677	.57442
.23	.3885286	.62448	.54	.3448180	.57215
.24	.3876166	.62341	.55	.3429439	.56986
.25	.3866681	.62230	.56	.3410458	.56753
.26	.3856834	.62115	.57	.3391243	.56516
.27	.3846627	.61995	.58	.3371799	.56277
.28	.3836063	.61870	.59	.3352132	.56034
.29	.3825146	.61742	.60	.3332246	.55788
.30	.3813878	.61609	.61	.3312147	.55538

Table II. Continued

T	Z	W	T	Z	W
.62	.3291840	.55286	1.03	.2347138	.42855
.63	.3271330	.55030	1.04	.2322970	.42517
.64	.3250623	.54772	1.05	.2298821	.42178
.65	.3229724	.54510	1.06	.2274696	.41839
.66	.3208638	.54246	1.07	.2250599	.41498
.67	.3187371	.53978	1.08	.2226535	.41157
.68	.3165929	.53708	1.09	.2202508	.40816
.69	.3144317	.63435	1.10	.2178522	.40474
.70	.3122539	.53159	1.11	.2154582	.40131
.71	.3100603	.52880	1.12	.2130691	.39788
.72	.3078513	.52599	1.13	.2106856	.39444
.73	.3056274	.52315	1.14	.2083078	.39100
.74	.3033893	.52029	1.15	.2059363	.38756
.75	.3011374	.51740	1.16	.2035714	.38411
.76	.2988724	.51449	1.17	.2012135	.38066
.77	.2965948	.51153	1.18	.1988631	.37721
.78	.2943050	.50859	1.19	.1965205	.37376
.79	.2920038	.50561	1.20	.1941861	.37031
.80	.2896916	.50260	1.21	.1918602	.36686
.81	.2873689	.49958	1.22	.1895432	.36341
.82	.2850364	.49653	1.23	.1872354	.35996
.83	.2826945	.49346	1.24	.1849373	.35651
.84	.2803438	.49037	1.25	.1826491	.35307
.85	.2779849	.48726	1.26	.1803712	.34963
.86	.2756182	.48413	1.27	.1781038	.34619
.87	.2732444	.48098	1.28	.1758474	.34275
.88	.2708640	.47782	1.29	.1736022	.33932
.89	.2684774	.47464	1.30	.1713686	.33589
.90	.2660852	.47144	1.31	.1691468	.33247
.91	.2636880	.46822	1.32	.1669370	.32906
.92	.2612863	.46499	1.33	.1647397	.32565
.93	.2588805	.46174	1.34	.1625551	.32224
.94	.2564713	.45848	1.35	.1603833	.31885
.95	.2540591	.45520	1.36	.1582248	.31546
.96	.2516443	.45191	1.37	.1560797	.31208
.97	.2492277	.44861	1.38	.1539483	.30871
.98	.2468095	.44530	1.39	.1518308	.30534
.99	.2443904	.44197	1.40	.1497275	.30199
1.00	.2419707	.43863	1.41	.1476385	.29865
1.01	.2395511	.43528	1.42	.1455611	.29531
1.02	.2371320	.43192	1.43	.1435046	.29199

Table II. Continued

T	Z	W	T	Z	W
1.44	.1414600	.28868	1.87	.0694333	.16180
1.45	.1394306	.28538	1.88	.0681436	.15929
1.46	.1374165	.28209	1.89	.0668711	.15681
1.47	.1354181	.27882	1.90	.0656158	.15436
1.48	.1334353	.27555	1.91	.0643777	.15193
1.49	.1314684	.27231	1.92	.0631566	.14952
1.50	.1295176	.26907	1.93	.0619524	.14714
1.51	.1275830	.26585	1.94	.0607652	.14478
1.52	.1256646	.26264	1.95	.0595947	.14244
1.53	.1237628	.25945	1.96	.0584409	.14013
1.54	.1218775	.25627	1.97	.0573038	.13784
1.55	.1200090	.25310	1.98	.0561831	.13557
1.56	.1181573	.24996	1.99	.0550789	.13333
1.57	.1163225	.24683	2.00	.0539910	.13112
1.58	.1145048	.24371	2.01	.0529192	.12892
1.59	.1127042	.24062	2.02	.0518636	.12675
1.60	.1109208	.23754	2.03	.0508239	.12461
1.61	.1091548	.23447	2.04	.0498001	.12249
1.62	.1074061	.23143	2.05	.0487920	.12039
1.63	.1056748	.22840	2.06	.0477996	.11832
1.64	.1039611	.22539	2.07	.0468226	.11626
1.65	.1022649	.22240	2.08	.0458611	.11424
1.66	.1005864	.21943	2.09	.0449148	.11224
1.67	.0989255	.21648	2.10	.0439836	.11026
1.68	.0972823	.21354	2.11	.0430674	.10831
1.69	.0956568	.21063	2.12	.0421661	.10638
1.70	.0940491	.20774	2.13	.0412795	.10447
1.71	.0924591	.20486	2.14	.0404076	.10259
1.72	.0908870	.20201	2.15	.0395500	.10073
1.73	.0893326	.19918	2.16	.0387069	.09890
1.74	.0877961	.19636	2.17	.0378779	.09708
1.75	.0862773	.19357	2.18	.0370629	.09530
1.76	.0847764	.19080	2.19	.0362619	.09353
1.77	.0832932	.18806	2.20	.0354746	.09179
1.78	.0818278	.18533	2.21	.0347009	.09007
1.79	.0803801	.18263	2.22	.0339408	.08838
1.80	.0789502	.17994	2.23	.0331939	.08670
1.81	.0775379	.17728	2.24	.0324603	.08506
1.82	.0761433	.17465	2.25	.0317397	.08343
1.83	.0747663	.17203	2.26	.0310319	.08182
1.84	.0734068	.16944	2.27	.0303370	.08024
1.85	.0720649	.16687	2.28	.0296546	.07869
1.86	.0707404	.16432	2.29	.0289847	.07715

TABLE II Continued

T	Z	W	T	Z	W
2.30	.0283270	.07564	2.69	.0107056	.03220
2.31	.0276816	.07414	2.70	.0104209	.03143
2.32	.0270481	.07267	2.71	.0101428	.03068
2.33	.0264265	.07122	2.72	.0098712	.02995
2.34	.0258166	.06980	2.73	.0096058	.02923
2.35	.0252182	.06839	2.74	.0093466	.02852
2.36	.0246313	.06701	2.75	.0090936	.02783
2.37	.0240556	.06565	2.76	.0088465	.02716
2.38	.0234910	.06430	2.77	.0086052	.02649
2.39	.0229374	.06298	2.78	.0083697	.02584
2.40	.0223945	.06169	2.79	.0081398	.02521
2.41	.0218624	.06040	2.80	.0079155	.02458
2.42	.0213407	.05915	2.81	.0076965	.02397
2.43	.0208294	.05791	2.82	.0074829	.02338
2.44	.0203284	.05669	2.83	.0072744	.02279
2.45	.0198374	.05549	2.84	.0070711	.02222
2.46	.0193563	.05431	2.85	.0068728	.02166
2.47	.0188850	.05315	2.86	.0066793	.02111
2.48	.0184233	.05201	2.87	.0064907	.02057
2.49	.0179711	.05089	2.88	.0063067	.02004
2.50	.0175283	.04979	2.89	.0061274	.01953
2.51	.0170947	.04870	2.90	.0059525	.01903
2.52	.0166701	.04764	2.91	.0057821	.01853
2.53	.0162545	.04659	2.92	.0056160	.01805
2.54	.0158476	.04556	2.93	.0054541	.01758
2.55	.0154493	.04455	2.94	.0052963	.01712
2.56	.0150596	.04356	2.95	.0051426	.01667
2.57	.0146782	.04259	2.96	.0049929	.01623
2.58	.0143051	.04163	2.97	.0048470	.01580
2.59	.0139401	.04069	2.98	.0047050	.01538
2.60	.0135830	.03977	2.99	.0045666	.01497
2.61	.0132337	.03886	3.00	.0044318	.01457
2.62	.0128921	.03797	3.01	.0043007	.01418
2.63	.0125581	.03710	3.02	.0041729	.01380
2.64	.0122315	.03624	3.03	.0040486	.01342
2.65	.0119122	.03540	3.04	.0039276	.01306
2.66	.0116001	.03458	3.05	.0038098	.01270
2.67	.0112951	.03377	3.06	.0036951	.01235
2.68	.0109969	.03297	3.07	.0035836	.01201

TABLE II Continued

T	Z	W	T	Z	W
3.08	.0034751	.01168	3.47	.0009689	.00361
3.09	.0033695	.01136	3.48	.0009358	.00349
3.10	.0032668	.01104	3.49	.0009037	.00338
3.11	.0031669	.01073	3.50	.0008727	.00328
3.12	.0030698	.01043	3.51	.0008426	.00317
3.13	.0029754	.01014	3.52	.0008135	.00307
3.14	.0028835	.00985	3.53	.0007853	.00297
3.15	.0027943	.00957	3.54	.0007581	.00287
3.16	.0027075	.00930	3.55	.0007317	.00278
3.17	.0026231	.00903	3.56	.0007061	.00269
3.18	.0025412	.00878	3.57	.0006814	.00260
3.19	.0024615	.00852	3.58	.0006575	.00252
3.20	.0023841	.00828	3.59	.0006343	.00243
3.21	.0023089	.00804	3.60	.0006119	.00235
3.22	.0022358	.00780	3.61	.0005902	.00228
3.23	.0021649	.00758	3.62	.0005693	.00220
3.24	.0020960	.00736	3.63	.0005490	.00212
3.25	.0020290	.00714	3.64	.0005294	.00206
3.26	.0019641	.00693	3.65	.0005105	.00199
3.27	.0019010	.00672	3.66	.0004921	.00192
3.28	.0018397	.00653	3.67	.0004744	.00186
3.29	.0017803	.00633	3.68	.0004573	.00179
3.30	.0017226	.00614	3.69	.0004408	.00173
3.31	.0016666	.00596	3.70	.0004248	.00167
3.32	.0016122	.00578	3.71	.0004093	.00162
3.33	.0015595	.00560	3.72	.0003944	.00156
3.34	.0015084	.00543	3.73	.0003800	.00151
3.35	.0014587	.00527	3.74	.0003661	.00146
3.36	.0014106	.00511	3.75	.0003526	.00141
3.37	.0013639	.00495	3.76	.0003396	.00136
3.38	.0013187	.00480	3.77	.0003271	.00131
3.39	.0012748	.00465	3.78	.0003149	.00126
3.40	.0012322	.00451	3.79	.0003032	.00122
3.41	.0011910	.00437	3.80	.0002919	.00118
3.42	.0011510	.00423	3.81	.0002810	.00114
3.43	.0011122	.00410	3.82	.0002705	.00110
3.44	.0010747	.00397	3.83	.0002604	.00106
3.45	.0010383	.00385	3.84	.0002506	.00102
3.46	.0010030	.00373	3.85	.0002411	.00098

TABLE II Continued

T	Z	W	T	Z	W
3.86	.0002320	.00095	4.25	.0000477	.00021
3.87	.0002232	.00092	4.26	.0000457	.00020
3.88	.0002147	.00088	4.27	.0000438	.00020
3.89	.0002065	.00085	4.28	.0000420	.00019
3.90	.0001987	.00082	4.29	.0000402	.00018
3.91	.0001910	.00079	4.30	.0000385	.00017
3.92	.0001837	.00076	4.31	.0000369	.00017
3.93	.0001766	.00073	4.32	.0000354	.00016
3.94	.0001698	.00071	4.33	.0000339	.00015
3.95	.0001633	.00068	4.34	.0000324	.00015
3.96	.0001569	.00066	4.35	.0000310	.00014
3.97	.0001508	.00063	4.36	.0000297	.00014
3.98	.0001449	.00061	4.37	.0000284	.00013
3.99	.0001393	.00059	4.38	.0000272	.00012
4.00	.0001338	.00056	4.39	.0000261	.00012
4.01	.0001286	.00054	4.40	.0000249	.00012
4.02	.0001235	.00052	4.41	.0000239	.00011
4.03	.0001186	.00050	4.42	.0000228	.00011
4.04	.0001140	.00049	4.43	.0000218	.00010
4.05	.0001094	.00047	4.44	.0000209	.00010
4.06	.0001051	.00045	4.45	.0000200	.00009
4.07	.0001009	.00043	4.46	.0000191	.00009
4.08	.0000969	.00042	4.47	.0000183	.00009
4.09	.0000930	.00040	4.48	.0000175	.00008
4.10	.0000893	.00038	4.49	.0000167	.00008
4.11	.0000857	.00037	4.50	.0000160	.00008
4.12	.0000822	.00036	4.51	.0000153	.00007
4.13	.0000789	.00034	4.52	.0000146	.00007
4.14	.0000757	.00033	4.53	.0000140	.00006
4.15	.0000726	.00032	4.54	.0000133	.00006
4.16	.0000697	.00031	4.55	.0000127	.00006
4.17	.0000668	.00029	4.56	.0000122	.00006
4.18	.0000641	.00028	4.57	.0000116	.00006
4.19	.0000615	.00027	4.58	.0000111	.00005
4.20	.0000589	.00026	4.59	.0000106	.00005
4.21	.0000565	.00025	4.60	.0000101	.00005
4.22	.0000542	.00024	4.61	.0000097	.00005
4.23	.0000519	.00023	4.62	.0000092	.00004
4.24	.0000498	.00022	4.63	.0000088	.00004
			4.64	.0000084	.00004
			4.65	.0000080	.00004
			4.66	.0000077	.00004
			4.67	.0000073	.00004

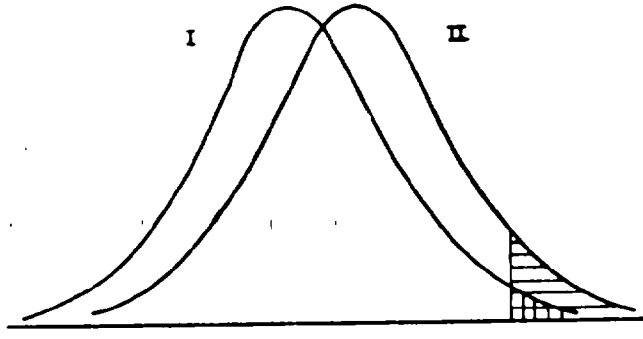
Table III

Table of s for Obtaining the Sample Standard Deviation

M	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
.30	.5102+239	.5316+168	.5518+113	.5711+70	.5897+37	.6077+13	.6253- 5	.6426-18	.6597-28	.6765-34
.40	.6932- 37	.7098- 39	.7263- 39	.7427-37	.7951-36	.7754-33	.7917-31	.8079-27	.8242-24	.8405-22
.50	.8567- 19	.8729- 16	.8892- 14	.9054-12	.9216-10	.9379- 9	.9541- 7	.9703- 6	.9866- 5	1.0028- 4
.60	1.0190- 3	1.0353- 3	1.0515- 2	1.0677- 2	1.0839- 1	1.1001 0	1.1164- 1	1.1326- 1	1.1488 0	1.1650 0
.70	1.1812 0	1.1974- 1	1.2135 0	1.2297	1.2459	1.2621	1.2783	1.2944	1.3106	1.3267
.80	1.3429	1.3590	1.3752	1.3913	1.4075	1.4236	1.4397	1.4559	1.4720	1.4881
.90	1.5043	1.5204	1.5365	1.5526	1.5687	1.5848	1.6009	1.6170	1.6331	1.6492
1.00	1.6653	1.6814	1.6975	1.7135	1.7296	1.7457	1.7618	1.7979	1.7939	1.8100
1.10	1.8261	1.8422	1.8582	1.8743	1.8904	1.9064	1.9225	1.9386	1.9546	1.9707
1.20	1.9867	2.0028	2.0188	1.0349	1.0509	1.0670	2.0830	2.0991	2.1151	2.1312
1.30	2.1472	2.1633	2.1793	2.1953	2.2114	2.2274	2.2435	2.2595	2.2755	2.2916
1.40	2.3076	2.3236	2.3397	2.3557	2.3717	2.3878	2.4038	2.4198	2.4358	2.4519
1.50	2.4679	2.4839	2.4999	2.5159	2.5320	2.5480	2.5640	2.5800	2.5960	2.6121
1.60	2.6281	2.6441	2.6601	2.6761	2.6921	2.7082	2.7242	2.7402	2.7562	2.7722
1.70	2.7882	2.8042	2.8202	2.8362	2.8523	2.8683	2.8843	2.9003	2.9163	2.9323
1.80	2.9483	2.9643	2.9803	2.9963	3.0123	3.0283	3.0443	3.0603	3.0763	3.0923
1.90	3.1083	3.1243	3.1403	3.1563	3.1723	3.1883	3.2043	3.2203	3.2363	3.2523
2.00	3.2683	3.2843	3.3003	3.3163	3.3323	3.3483	3.3643	3.3803	3.3963	3.4123
2.10	3.4283	3.4443	3.4603	3.4763	3.4923	3.5083	3.5243	3.5402	3.5562	3.5722
2.20	3.5882	3.6042	3.6202	3.6362	3.6522	3.6682	3.6841	3.7001	3.7161	3.7321
2.30	3.7481	3.7641	3.7801	3.7961	3.8121	3.8280	3.8440	3.8600	3.8760	3.8920
2.40	3.9080	3.9240	3.9400	3.9560	3.9720	3.9879	4.0039	4.0199	4.0359	4.0519
2.50	4.0678	4.0838	4.0998	4.1158	4.1318	4.1477	4.1637	4.1797	4.1957	4.2117
2.60	4.2277	4.2436	4.2596	4.2756	4.2916	4.3075	4.3235	4.3395	4.3555	4.3715
2.70	4.3874	4.4034	4.4194	4.4354	4.4514	4.4673	4.4833	4.4993	4.5153	4.5313
2.80	4.5472	4.5632	4.5792	4.5952	4.6111	4.6271	4.6431	4.6591	4.6750	4.6910
2.90	4.7070	4.7230	4.7390	4.7549	4.7709	4.7869	4.8029	4.8188	4.8348	4.8508
3.00	4.8668									

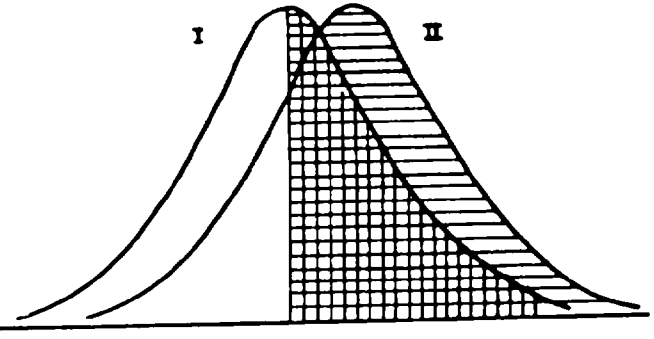
This table reproduced from AMP Report No. 101.R. *Differences when mean falls midway between testing heights. Interpolate for all other in between joints.

X_s = SPECIFICATION STIMULUS



AREA UNDER CURVE I FROM X_s OUT TO ∞ (AREA OF DEFECTIVES) =.1% OF TOTAL AREA.
AREA UNDER CURVE II FROM X_s OUT TO ∞ =1% OF TOTAL AREA.

X_i = INCREASED SEVERITY STIMULUS



AREA UNDER CURVE I FROM X_i OUT TO ∞ =50% OF TOTAL AREA.
AREA UNDER CURVE II FROM X_i OUT TO ∞ =78% OF TOTAL AREA.

FIGURE 1

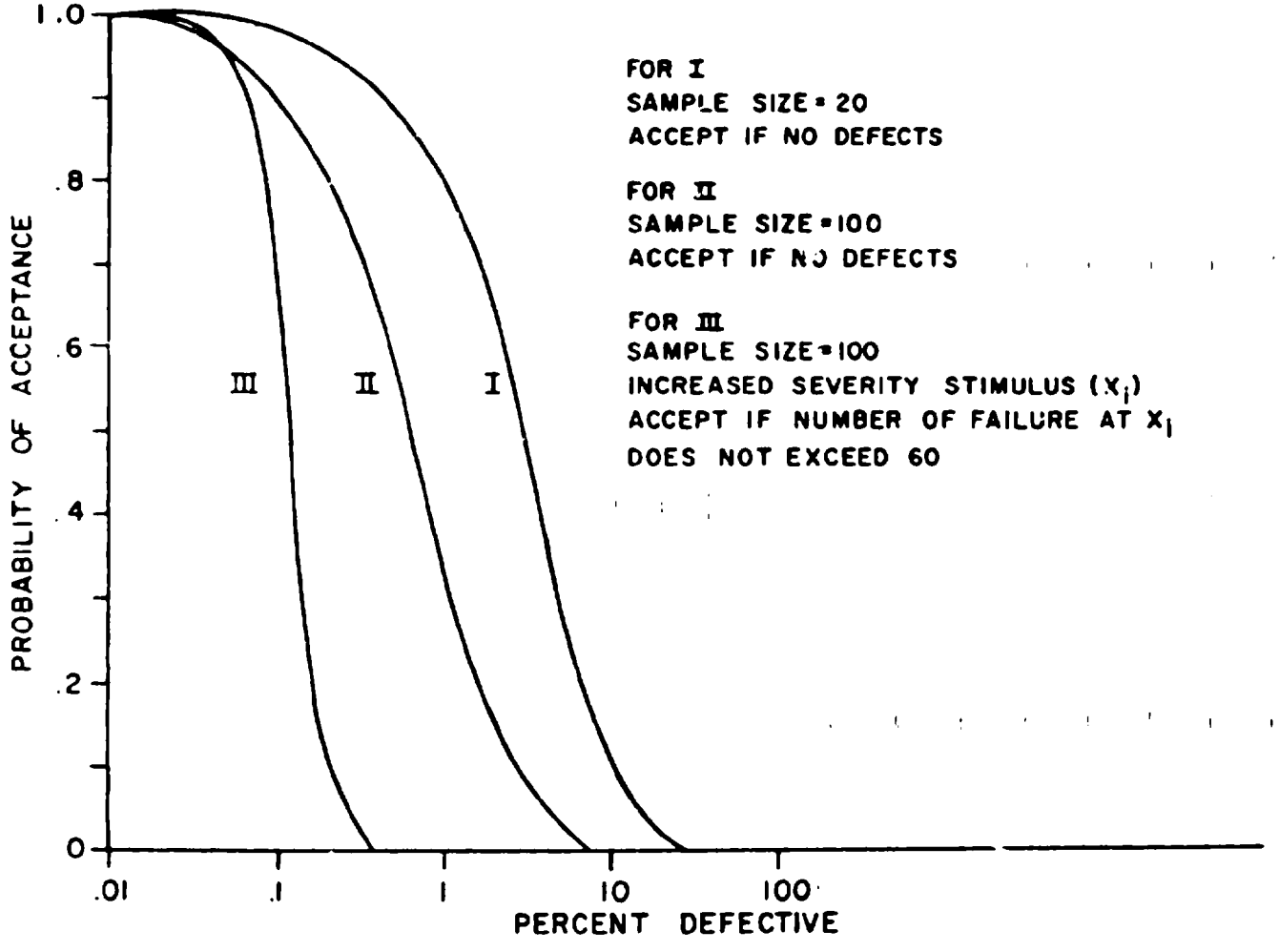


FIGURE 2. OPERATING CHARACTERISTIC CURVES FOR SINGLE STIMULUS TEST I AND II WITHOUT INCREASED SEVERITY. III WITH INCREASED SEVERITY.

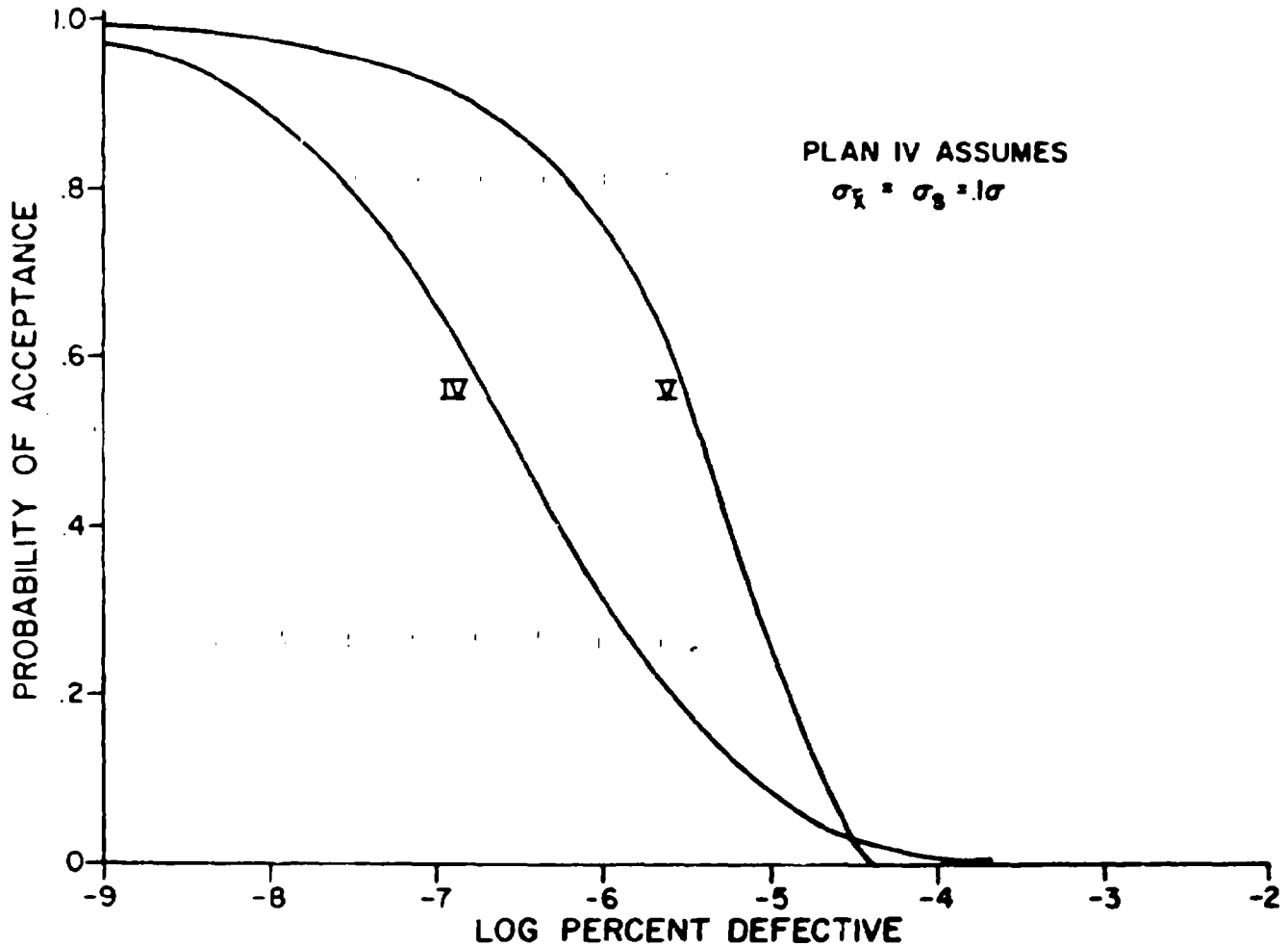


FIGURE 3. OPERATING CHARACTERISTICS CURVES FOR RUN DOWN TEST (IV) AND BEST SINGLE STIMULUS TEST (V)

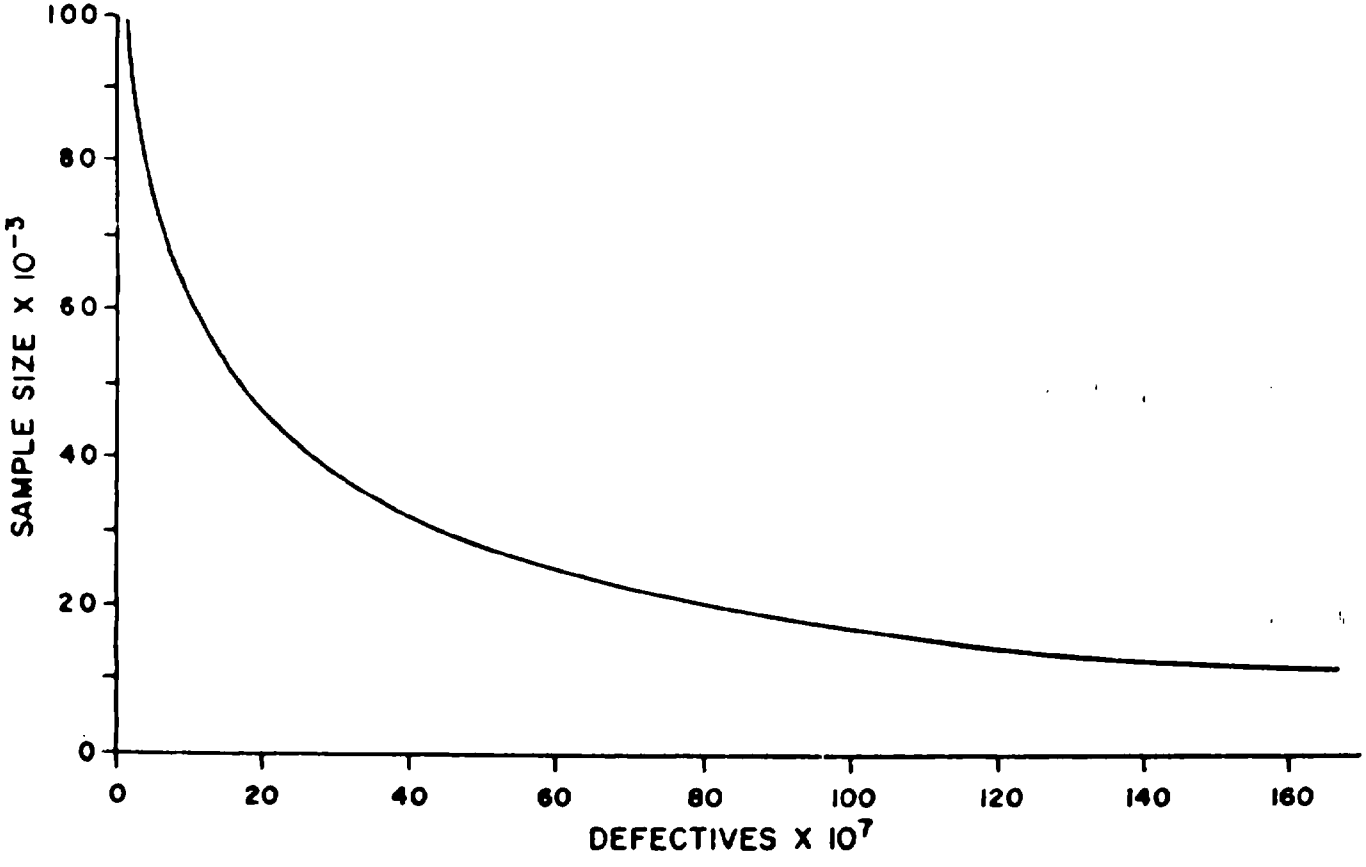


FIGURE 4. AVERAGE SAMPLE SIZE CURVE BEST SINGLE STIMULUS TEST METHOD

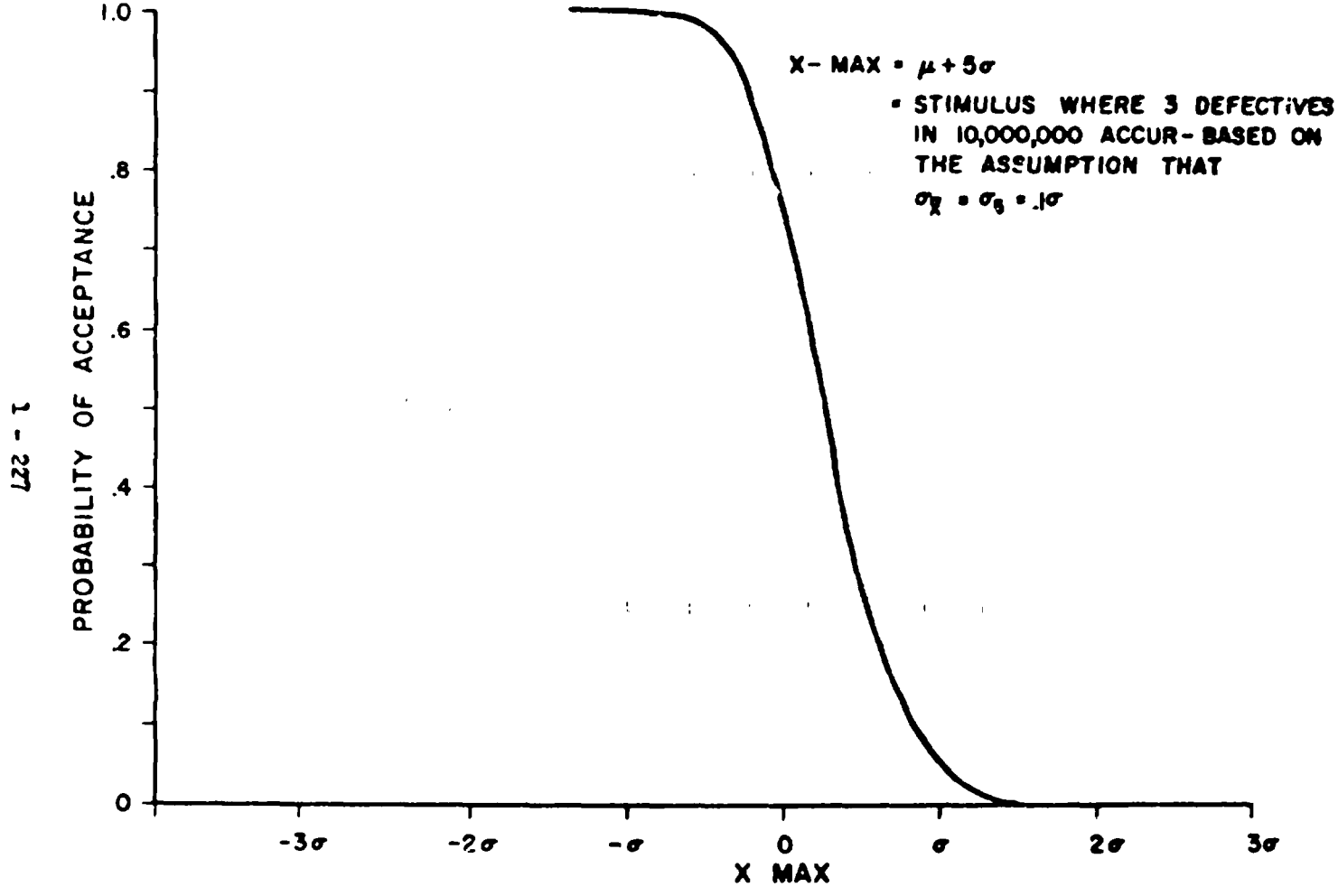
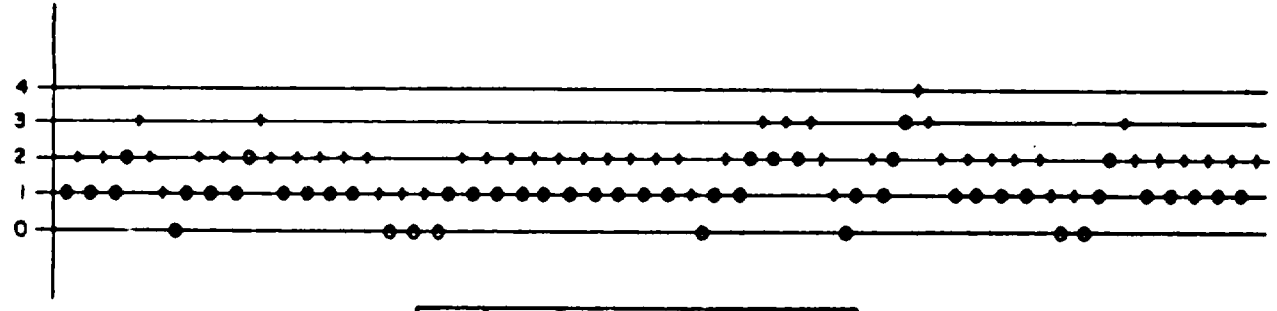


FIGURE 5. OC CURVE FOR RUN DOWN TEST

TEST RESULTS OF 100 SPECIMENS



i	h_i	LOG h_i*	FREQUENCIES	
			◆	0
4	20.0	1.300	1	
3	16.1	1.207	8	1
2	13.0	1.114	35	6
1	10.5	1.021	8	35
0	8.5	.928		8

*HEIGHTS CHOSEN SUCH THAT THEIR LOGARITHMS ARE EQUALLY SPACED.

FIGURE 6

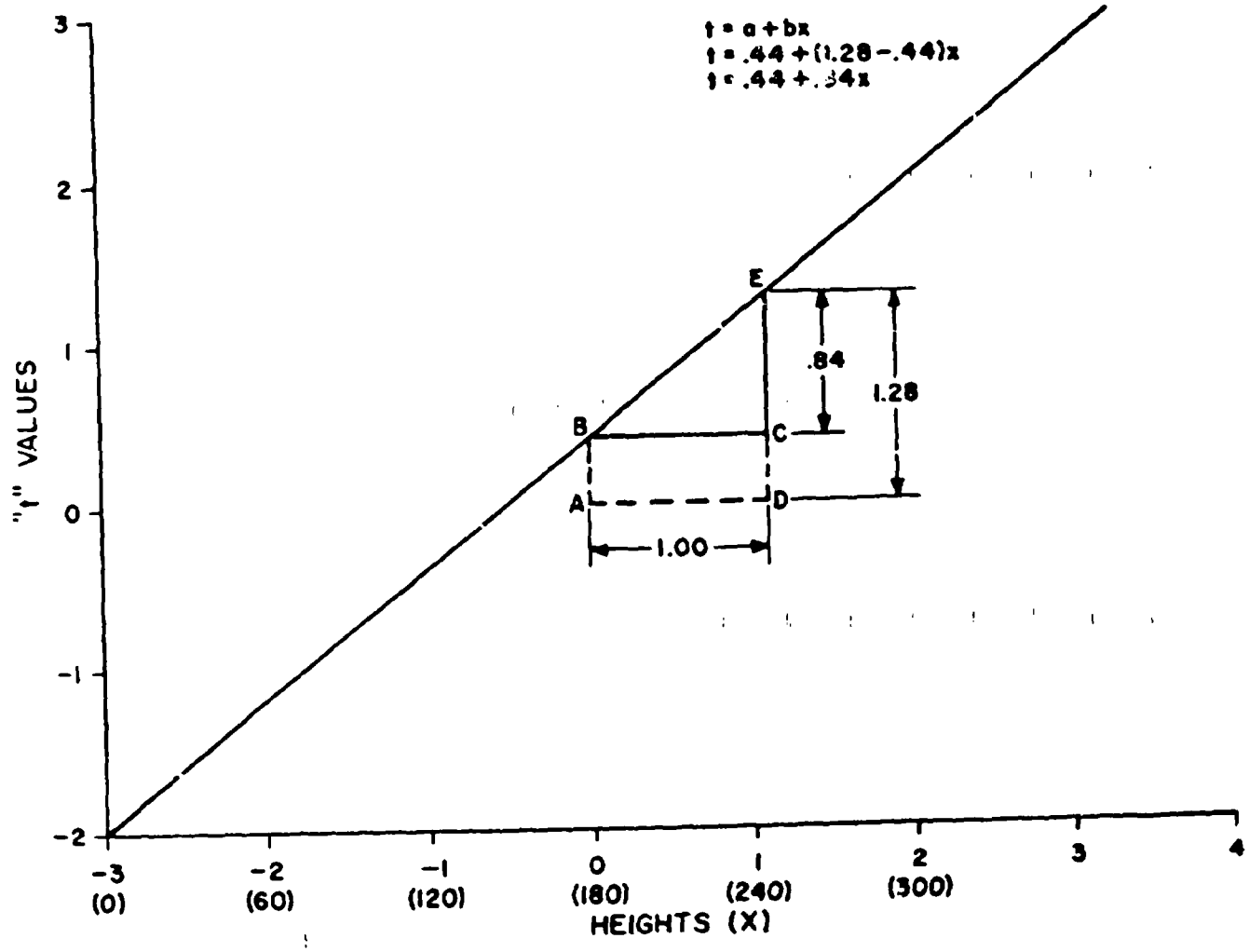


FIGURE 7. GRAPH FOR FIRST APPROXIMATION

BULLPUP, A ROUND OF AMMUNITION

R. D. GINTER, Senior BULLPUP Project Engineer, Bureau of Naval Weapons

For those of you who are not familiar with BULLPUP, or who might be thinking that the Bureau is shooting dogs into space, this is it. A 570 pound, air-to-surface missile, designed to provide effective close air support and ground interdiction capability to light attack aircraft. Visually guided by a radio command link, it is the only missile in the world which is never tested after it leaves the contractor's plant.

BULLPUP is an example of the tangible benefits which can be achieved in operational readiness and system cost reduction with high reliability. A reliability which is sufficiently high for the Navy to firmly commit the BULLPUP system to operate without the use of any missile test equipment. All BULLPUP missiles are "up" until actual flight proves differently. They are treated as a "round of ammunition". Under this "no-test-equipment" philosophy, BULLPUP has exceeded both specification requirements and our own optimistic expectations. Reliability in the Fleet is in excess of 90%.

It would be fitting if I could reveal a secret formula or magic procedure for insuring reliability in electronic-missile production. Unfortunately, BULLPUP has not discovered such a formula. Primarily, we have applied time-worn cliches, paid attention to the smallest detail and been adamant about stringent control of all factors comprising the entire system.

BULLPUP specifications have always required that the missile meet a particular reliability goal. This goal has been continually increased during development, evaluation and now production. All of these specifications recognized that continued testing of the missile during "ready service" stowage would reduce the total missile reliability. The specifications allowed a ½% reduction in reliability after each test. That reliability would be reduced due to continued testing was proven during the Navy Technical Evaluation. A block of 30 missiles was subjected to repeated operational tests. None failed on the first or second tests. Failures began to appear on the third and subsequent tests. Testing missiles in an attempt to prove them ready was actually causing them to fail.

For a missile like BULLPUP, it is impossible to design test equipment that will actually test all of the missile. Items such as the motor, fuze, warhead and flares, are not ammenable to test. These items comprise fully two thirds of the total missile volume. Thus, regardless of the quantity of the test equipment, the entire missile can never be tested. In addition, specific design improvements increased rather than decreased the number of items which cannot be tested. An example of this in BULLPUP was the change from an electric gyro to a "one-shot" spring-wound gyro. The batteries and pneumatic accumulator were also designed as "one-shot" items. In fact, the only major item remaining which could be tested was the receiver. The problem finally became one of insuring that the receiver reliability would be adequate for the intended usage of the missile.

The decision was made that instead of re-designing the test equipment for test of the receiver only, we would eliminate the test equipment. The BULLPUP Operational Evaluation was started without missile test equipment in early 1958. Portions of this evaluation were highly successful and other portions were not so successful. Approximately half way through the evaluation, the reliability dropped from an exceedingly high level to a very low level. The causes for this drop were eventually determined and remedied. It is significant that during all of the review to discover the cause for the reliability drop, only one discrepancy was ever discovered which would have been detected by the missile test equipment. So even our most serious reliability problem served to strengthen our conviction that the "no-test-equipment" philosophy was sound.

During all of the investigations associated with the drop in reliability, the extreme importance of stringent, detailed control became painfully evident. Each discrepancy which was discovered could have been prevented, if the proper controls had originally been applied. We were experiencing a number of the problems usually associated with increasing the production rate from a few per month to hundreds per month. Control became the single most important word in the BULLPUP vocabularly:

Control of Change
Control of Specifications
Control of Inspection Procedures
Control of Manufacturing Techniques
Control of Technical Improvements

We found that no deviation whatsoever could be allowed from the established minimum. If a minimum standard had not been set for a particular item, it had to be, immediately. The existance of an actual standard from which to measure had to be insured. In the event the standard was either too high or too low, this could be realistically modified later. The item of crucial importance was that no unit was ever passed through inspection which did not meet the established minimum.

These areas of detailed control are very standard and the normal reaction is that every competent manufacturer is thoroughly aware of them. The present BULLPUP philosophy is: That we are from Missouri. We will believe that any manufacturer has this detailed control after it has been demonstrated, but not before.

The control item which gave us the most difficulty and still does for that matter, is to insure that decisions are made at the proper level in both the contractor's organization and in the Government. Organizational control of decisions involves all of the other controls. It is mandatory that the total organization responsible for the delivery of a highly reliable missile to the Fleet be thoroughly aware of the objective for that missile. This objective is basically reflected in the specifications and test procedures. For the working level engineers, inspectors, etc., there is no such thing as acceptable unless it is above the specification or test minimum. Anything lower than the established minimum must be automatically unacceptable. We have found that human beings are very prone to place their own intrepretation on what should or should not be accepted based on their own individual intrepretation of what was needed for the program. This intrepretation appears to vary as the pressure to meet delivery deadlines varies. Organizational control of these decisions is one of the very important factors in insuring that a uniform production item is being delivered. I have been leading up to the word "uniform". Statistics are based on homogenous populations. If the population is not homogenous, the numbers derived from the best statisticians are merely numbers. They are not meaningful. The numbers become meaningful and capable of influencing intelligent decisions when the knowledge is definite and irrefutable that all units of production under consideration are in fact all above the established minimum. Without the knowledge that the statistical tests results are based on uniform production, decisions will probably be in error.

Still another area of control which is equally important is "Control of Technical Improvement". As you all know, any item can be improved to death. Possibly one of the hardest jobs in the management of any program is to actually stick to the decision that the product now being delivered is "good enough". At some point in any program, it becomes mandatory that the program management stipulate that the item is now GOOD. Additional engineering improvements will not be considered unless they are in fact significant improvements to the total system. In BULLPUP, we will not accept any improvement change which would cause us to depart from the "no-test-equipment" philosophy. We literally can't afford to. We can use a number of words to describe this phase of a program: Design Freeze, Final Optimization, etc. In BULLPUP, we have chosen to call it "good enough". The Navy has said that the BULLPUP missile in its present configuration is "good enough". It meets the original performance specifications established for it, plus a satisfactory margin. The problem now is to deliver Fleet usable units which meet the minimum standard of "good enough" with a high degree of reliability.

We know that BULLPUP will do its job. We know that it will do this job with a high degree of reliability. We know that the elimination of test equipment from the system has resulted in very substantial savings to the Government. There are no DOWN BULLPUP missiles, no missile maintenance problems, no test equipment, no maintenance training problems, no shortages of spares, etc. This list of NO's has been officially translated into dollar savings for the first year's outfitting as follows:

Missile Test Equipment	$3,000,000
Test Equipment Facilities	1,000,000
Training and Personnel Support	1,000,000
Spares	1,767,000
TOTAL SAVING	$6,767,000

a. Missile test equipment; 65 pieces at $45,000 each for a total of $3,000,000.

b. The facilities to house the equipment at Naval Ammunition Depots, Air Stations, Overhaul and Repair Stations and aboard three carriers was estimated at $1,000,000. Due to the space problem aboard the carriers, this item was both costly and time consuming.

c. Training costs including personnel maintenance and support was actually estimated at $3,000,000. However, to insure a conservative tabulation of the cost savings, this item was listed as only $1,000,000.

d. The amount of spare parts required to support the first year's production program was drastically reduced. Prior to the implementation of the "no-test-equipment" philosophy, 1.8 million dollars had been earmarked for spares. Due to the "no-test-equipment" philosophy, this order was reduced to merely $38,000. Both amounts were derived using the same basic provisioning techniques. As a matter of interest, this particular saving was used to significantly increase the follow-on procurement order of missiles. Thus, several hundred additional missiles were procured instead of spare parts. It was not possible to put all of the savings into additional missiles. However, the total $6,767,000 does represent a large amount of money released from spares support, test equipment, etc. which can be applied to the funding of other operational requirements.

I have been adamant about the necessity for a stringent control. We look toward the day when some of these extremes might be relaxed. At present, I cannot predict when this might occur. It will definitely not occur until a frozen design is in production at a stabilized rate. We are now in the process of building the production rate for BULLPUP to the highest in the missile history. After this has been successfully accomplished, we will face the problem of control relaxation. Speaking as a Government representative, I will indicate that unless this relaxation of control is accomplished with a reasonable decrease in unit cost, there would be little incentive for any Government agency to relax control for

the mere sake of relaxation.

BULLPUP has demonstrated the magnitude of tangible rewards obtainable through high reliability. We have learned again the extreme importance of strict, intelligent control. Fleet readiness has been increased at a significantly reduced cost. All operational aspects of the system have been simplified. We believe that other production missile systems can profitably adopt at least portions of the "no-test-equipment"/"round of ammunition" concept.

This sounds like I'm advocating something as impossible as being a "little bit pregnant". In this instance, I probably am. I'm advocating a different approach to the test equipment problem. During the definition of the operational missile system, start at the point of "no-test-equipment" and work back. Make each item of equipment justify its existence from the standpoint of total system operation cost. Allow nothing that is merely nice to have or easy to provide. Review the development test results and determine which equipment or portions of the equipment actually served a useful purpose. Do not allow the mere finding of a fault by the equipment to justify the item. Instead, make every conceivable effort to remedy the fault in design or in control of design on the production line, thereby eliminating the test equipment item.

We believe that if an approach similar to this is applied to missile systems producing large quantities of hardware, a very large amount of the present test equipment can be eliminated. Hense, probably you, too, are capable of being at least a "little bit pregnant". If not actually pregnant, at least you will be "well loved" for a tremendous increase in operational capability.

VERIFICATION OF FLIGHT RELIABILITY MISSILE GUIDANCE UNIT

L. N. St. James, Bell Telephone Laboratories, Inc.

The determination of the probability of success of a missile guidance unit can be approached in a number of ways. Perhaps the most direct and, from many standpoints a very appealing method, is to fly missiles and keep score of the results. Figure 1 has been taken from standard 10% consumer's risk sampling tables and can be used to determine the number of missiles that must be flown and the corresponding number that can fail. If 99% probability of success is required, for instance, 230 missiles must be flown with zero failures, 390 with not more than one failure, etc. This type of table provides a confidence of 90% that more than the indicated number of failures will be exceeded if the desired level of reliability is not attained. The procedure obviously involves sampling, so that the restrictions normally associated with a sampling process also apply. The sample must be randomly selected from, or otherwise justified as representative of, a homogeneous population which can be looked upon as very large.

Such a test program for a large missile would cost many millions. It could not be justified before the design had been proved in and it is not feasible to use this type of program to prove in a design because the sample itself would not be homogeneous even if some would authorize building it. The conclusion is inescapable: Proving by flight test alone that a guidance unit has attained a reliability objective of .99 just cannot be done when it will do any good.

Why is .99 a good level to choose rather than .90 or .95, which are still high? Two or three years ago, .95 was a very good level. Figure 2 shows the unconditional engagement reliability of a battery in terms of the number of targets engaged at any rate up to its maximum fire rate and at any time. This system is so designed that it can fire at least one more missile at any target in the event that the first fails. There are 21 missiles available and the unconditional probability of success falls off very little starting from .96 up to 17 targets. After that, it falls off very rapidly. This system assumes a .95 missile and the reason for its high engagement reliability is that it can engage any target at least twice if necessary. Remove this capability of a second engagement and the lower line results. There is no way of escaping the basic law that missiles, each with a probability of success of .95 engaging 17 targets, have a probability of getting them all

of .95[17] or .42. This, when added to the probability of success of the ground equipment, results in the lower line.

Figure 3 gives a diagramic version of the reliability function as it relates to the evolution of a system. Intended Function, at the top, embraces this concept. It also includes kind of targets, range, speed, environment of use, etc. Reliability enters at this point as a major design parameter before the system configuration can be sketched and the design objectives of the subsystems can be formulated. Referring back to the previous figure, the .92 capability could be obtained from a system that did not have a second shot capability. All that would be necessary, on paper anyway, would be to add a second system, use twice as many men and fire nearly twice as many missiles; hardly an economic solution. A .7 missile could be used at the expense of multiplying everything by 4 instead of by 2.

The Intended Function, then, requires a complete specification of the engagement and the probability of success required. If the economy of this country is to be kept intact, the design objective for such a relatively small and simple thing as a missile guidance unit must be in the .99 range.

It will be assumed at this point that the system configuration has been tentatively set and the design objective for the guidance unit has been derived including the required reliability. If the design objective for the guidance unit has been, in fact, adequately and completely specified at this point, those responsible for its design can forget the system concept. It is a relatively straightforward process of translating the design objective into detail design parameters and verifiable test requirements, in other words, Product Design. Shortly, models become available and they should be evaluated to determine their capability. Everyone does this. It is essential to know if it can be made to work at all. The thing frequently overlooked at this point, however, is an adequate determination of the reliability inherent in the design. As has already been shown, this cannot be done in flight; there are never enough of them and certainly there is no such think as a homogeneous population at this time. Assuming for the moment that it has been determined that the reliability inherent in the design is adequate, the information obtained provides the basis for a production evaluation test to be applied to a sample selected at regular intervals throughout the production period. This is necessary in order to secure

assurance that the production process realizes the full inherent design capability. Actually, our approach to both of these evaluation phases is very similar and based upon the same basic assumptions so it will only be necessary to cover one in detail.

The process found to be adequate is shown in Figure 4. In reference to the first item, the environments of shipment, handling and storage, there exists an abundance of information and what is even more important, they are relatively easy to meet. The second item, flight environment, is a real problem. Telemetry has been used for years but it has a limited band width and dynamic range and its reliability has never been particularly high. Far greater success can be expected from the flyable tape recorder system shown on Figure 5. In this system there are 12 available channels. Six are capable of recording vibration or sound up to 5000 cps and six are capable of recording high level transients from DC to 200 cps. The entire mechanical spectrum of shock, vibration and continuous acceleration is recorded along with the acoustic levels. Of course, the recorder tapes must be recovered but this has not been an insurmountable problem.

Returning to Figure 4, step 3 is in the nature of an exploration for design errors or oversights. One or two models is sufficient and they are run through all the environments. The causes of failures are usually obvious and corrective action is usually not too difficult. Higher than expected stress levels are frequently employed to afford some assurance that the corrective action has been adequate, but admittedly we do not know what different levels mean in quantitative terms. The experiment involved in item 4 can now be designed.

Before going into this, however, it might be well to examine a frequently proposed alternate procedure. Why not use the missile environment data and test each component, chassis and subsystem separately before building a system in order to insure that a margin of from 5 to 10 standard deviations between mean stress and mean strength actually exists. Conceivably this is possible but usually there is insufficient time for this method.

Figure 6 shows a guidance unit mounted in the forward section of its missile. This particular guidance unit is assembled into a low transmissibility magnesium casting and all the electronic packages are plug-in units, interchangeable between systems. For this test, accelerometers

were mounted in the areas found previously to be subject to high amplification. The entire assembly was mounted on a shaker and driven vertically with a sine wave to an amplitude of 2.5g with control at the base.

Figure 7 shows the levels observed at the base compared to the levels observed at a ring about 8 inches below the guidance unit mounting. Amplifications run over 10 to 1 in relatively narrow bands. Figure 8 shows the various levels observed at one rather critical point, a gyro mounting, in the guidance unit with g level control at the base, the ring 8 inches below the guidance unit and with the guidance unit mounted on a rigid fixture. We have made many more observations but these should suffice to indicate that the vibration levels experienced in a guidance unit are anybody's guess until a complete structure is available for test.

Returning to design evaluation, the purpose is to determine if the reliability inherent in the design is in the .98 to .99 range. Figure 9 is a breakdown of the problem that we find useful. Under pre-flight, shipment and handling involve shock and vibration, non-operating. Storage involves temperature extremes and humidity, again non-operating. Periodic checkouts involve operating time for the useful life of the guidance unit over a relatively wide temperature range. We have found that, if a long life is to be expected during this phase, the temperature range must be restricted to something reasonable, high temperature particularly shortens life. All these situations are known and methods for determining the probability of failure in any one of them can be devised.

Flight reliability involves a determination of flight environment and the probability of successful operation for the time of controlled flight, under that environment. One might argue that, as long as the flight reliability is as high as required, pre-flight reliability is unimportant. This is not true for two reasons. First, it costs money to repair electronic equipment and second, and more important, there is no good way of assuring that the reliability inherent in the design is preserved after numerous "field repairs".

The determination of the probability of failure in any of these situations involves establishing some pr bability model which represents the physical situation. The Poisson probability density function and the related exponential function have gained wide usage over the past few

years for life testing, failure prediction, etc. This is shown on Figure 10. It has two very important advantages over other distributions. First, it is easy to use and second, it assumes a constant failure rate. The second assumption is really vital since it implies that the probability of failure at any time is independent of its previous history as long as the Poisson process applies to this history. Therefore, if the Poisson process can be shown to represent an acceptable approximation to observed failure data in each environment involved, the order of subjecting units to successive environments is of no importance. Furthermore, if there is no evidence of physical interaction between environments, it can be assumed that interaction between environments applied simultaneously is unlikely. This justifies the assumption that the probability of success resulting from the simultaneous application of several environments equals the product of the probability for each applied separately. The problem, then, is to establish that the Poisson process is applicable to the critical environments involved in successfully delivering a missile from the factory to its target.

Figure 11 shows these critical environments and where they are found. It is interesting to note that the shock environment associated with rail transport across the country is frequently far more severe than shock associated with flight. The vibration environment associated with flight, however, is generally more severe than that experienced in any common carrier but it operates for a much shorter time. Transporting a unit in the back of a truck for several hundred miles, unprotected by a suitable shipping container, is almost sure to wreck it. This means that containers with suitable vibration isolation are usually necessary.

In the guidance unit I am going to discuss, we are concerned with shock during transportation, temperature extremes during storage, vibration and altitude during flight and ambient during checkout. We have found that high reliability and large temperature variations while operating are incompatible. Therefore, reasonable control of temperature during operation, within 40 or 50 degrees F, is mandatory. The probability of successful flight for this guidance unit has already been set as .985. The inherent design capability must be at, or better than, this level, manufactured product must meet this level, and guidance units in the field must be capable of meeting this level throughout their useful life. This last point is very important. It requires, as

already stated, that the need for field repair should be kept to a minimum by providing not only a high resistance to shipment, handling and storage but also a mean time between failures which will assure that only a small percentage of the units will fail as a result of the normal routine check-out during a 5 year period.

The prediction studies on this unit indicated a mean time between failures of 500 hours. If a biweekly check requiring 10 minutes operation is contemplated, it would be expected that 4% would require repair during a 5 year period. This is reasonable, and a life test can be set up to demonstrate that a mean time between failures of at least 500 hours has been attained. The Poisson function has gained general acceptance as applicable to life testing of complex electronic systems so it need not be discussed farther.

In the flight environment, it has been our experience that vibration is by far the most critical factor. This cannot be accepted as applicable to any electronic design in any missile structure but it has proven true in those we have been concerned with. It is also logical since the response of an assembly to a shock impulse is a highly damped wave starting at a high amplitude over a broad frequency band. It only excites resonances for a fraction of a second compared to a relatively continuous excitation due to vibration. The inference that immediately results is that the excitation during the vibration test should be preferably an actual tape produced from a combination of several flights or, as a compromise, band limited noise that approximates such a recording. With this decision made, it remains to be demonstrated that the Poisson process represents an acceptable approximation to the failure time distributions observed.

Several methods are available, the Kolmogrov-Smirnov test which is quite satisfactory with 20 or 30 failures or the Bartholomew test which appears to be very powerful with 200 or more failures. However, these tests do not give a picture and engineers usually like pictures. Figure 12 indicates the method we have found most convincing to engineers, although statistically it leaves something to be desired. The curves are boundaries of a 90% confidence interval plotted on either side of the 45 degree line which represents the mean time between failures of the unit under test. The unit is run on a shaker, in this instance at 2-1/2g level with a swept sine until 20 to 30 failures are

observed, the time of each failure being recorded. The times between failures are then ordered and the number of failures occurring at any time are plotted cumulatively against the expected number which is calculated from the Poisson Function. If all the points fall within the limit lines, the process can be considered sufficiently close to the Poisson for the latter to be used for estimating purposes. In this particular instance, 2 units were involved and some 30 hours of shaker time. In other instances, we have run considerably longer and the Poisson Model has always been applicable.

With this established, it is only necessary to run a test long enough to demonstrate that the mean time between failures required to give the desired probability of success in flight has been attained. The other environments involved in flight are altitude and continuous acceleration. Actually, we have never been able to run either of these tests long enough to demonstrate that a Poisson failure process is operating. We just do not get failures in a good design. However, we assume such a process.

The derivation of the criteria associated with the flight environments is shown in Figure 13. The required probability of success is .985. An equal probability of failure for each of the three environments of .01 was assumed and the criteria based upon that. In order to make such a criteria acceptable in production, it would be necessary to have a design capability much better than this. A .90 probability of acceptance of any one sample was assumed which means that the actual level has to be at least as good as .0043 shown in the third column. The total flight reliability then is .987 which meets the objective.

Figure 14 shows the criteria as they apply to a sample of 5 systems. For vibration, the test is run with random noise at g-level of $.01g^2$ per cycle. The test is run for 20 minutes in each of 3 mutually perpendicular planes. If no failures are observed, the mean time between failure for a single system is met at a 90% confidence level for a single unit and the test is over. A table is provided which gives the acceptance and rejection points associated with the 90% level. If no decision can be made up to 30 failures, the mean time obtained by dividing the total time by 30 is used for determining conformance.

The criteria for altitude and continuous acceleration are also based upon the time of exposure but only a

single rejection criterion is used. Failures are not expected and seldom observed in this area.

The pre-flight reliability criteria are shown on Figure 15. These criteria are combined in a manner similar to the flight reliability criteria and result in a pre-flight reliability of .95 for a 5-year period. The criterion for mean time on the life test is operated in the same manner as that for vibration, accept on 90% confidence of meeting the individual level, reject on 90% confidence of failing, or run until 30 failures are observed.

The shock test involves 10 drops at a response level of at least 100g between 100 and 700 cps in each of 3 planes, a total of 30 drops for each system. With 150 drops on 5 systems and allowing 3 failures in the total sample, we feel reasonably sure of meeting a probability of success of .98 or better. Actually, this drop test severity is likely to be equalled only 1% of the time in 3000 miles of rail transport. The temperature test uses the usual Mil-specification range of -80°F to 160°F but it is run for 10 cycles. Failures are not expected in this test but we have assumed a .01 probability of failure to be adequate. The rate of temperature change and time of dwell at the extremes are set to achieve this probability in actual service, storage or plane transportation. A sample of 5 meeting both the pre-flight and flight criteria supplies adequate assurance that the design is capable of meeting the .985 reliability objective required.

With the design capability established, the production control test can be set up by using the criteria for an individual system. It is not practicable in the usual small sampling of a production process to require criteria to apply to a group of several systems. The minimum sample size and distribution of the sample is given on Figure 16. This is an empirical rule and the best that can be said for it is that it has been proven by experience. This formula is applicable to contracts requiring production intervals of one year or less. For intervals of greater duration, this can usually be considered to apply on a per year basis.

NUMBER OF TESTS REQUIRED FOR A GIVEN PROBABILITY OF SUCCESS

90% CONFIDENCE

Probability of Success	Sample Size with 0 Failures	Sample Size with 1 Failure	Sample Size with 2 Failures
95	45	75	105
97	75	130	175
99	230	390	530

Figure 1

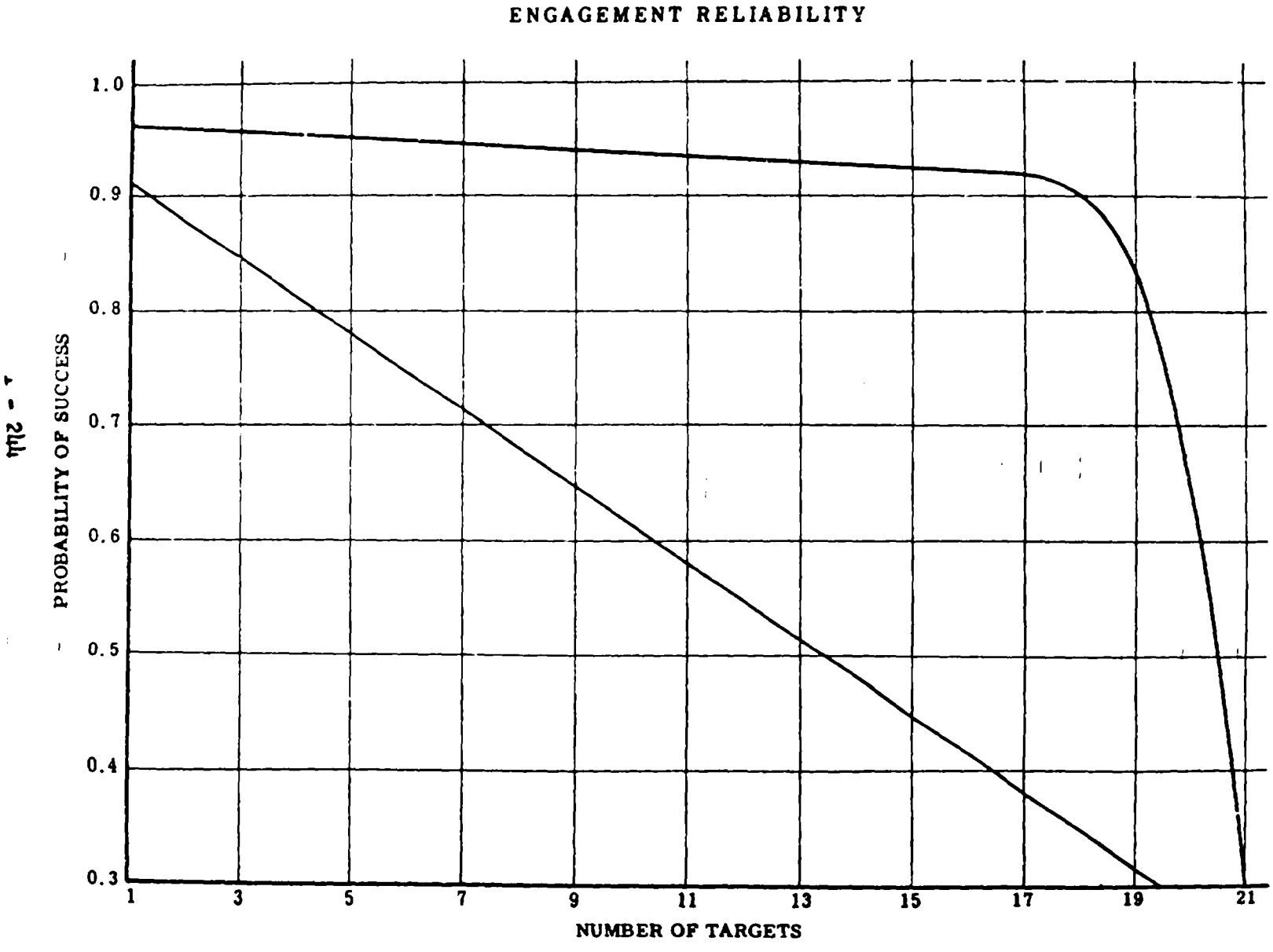

ENGAGEMENT RELIABILITY
PROBABILITY OF SUCCESS
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
1
3
5
7
9
11
13
15
17
19
21
NUMBER OF TARGETS

Figure 2

BELL TELEPHONE LABORATORIES

ENGAGEMENT RELIABILITY

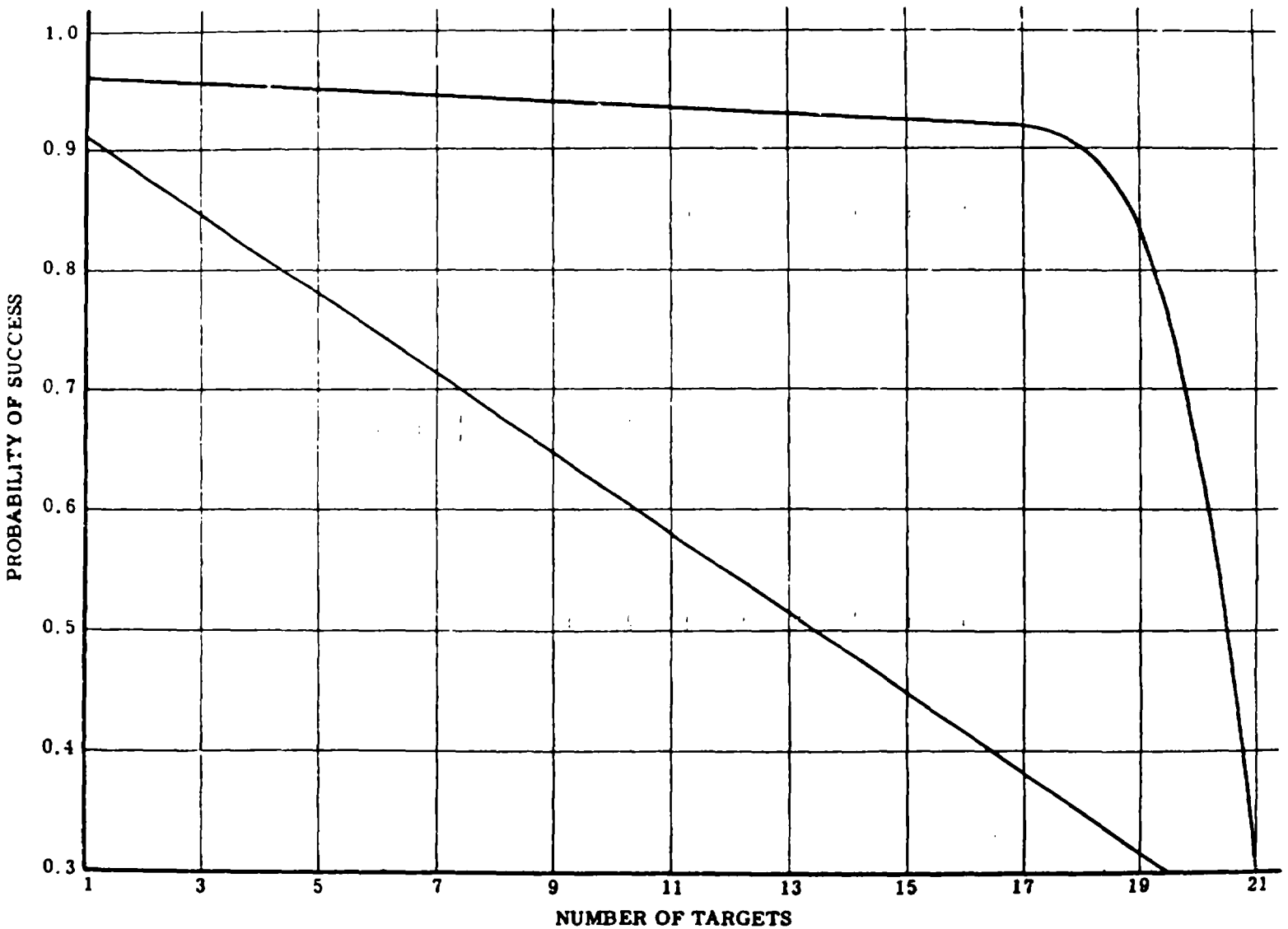


Figure 2

THE RELIABILITY CONCEPT

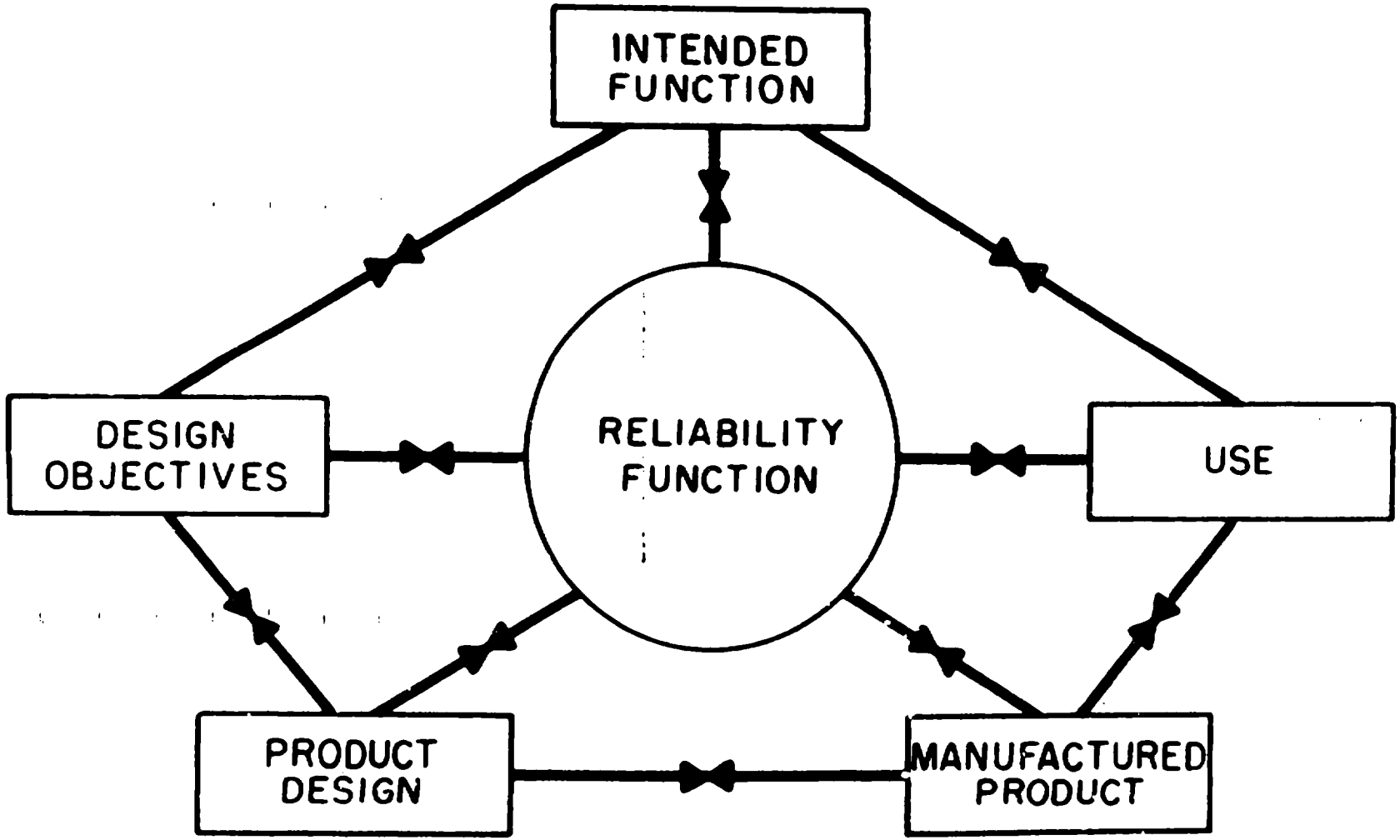


Figure 3

RELIABILITY EVALUATION PROCESS

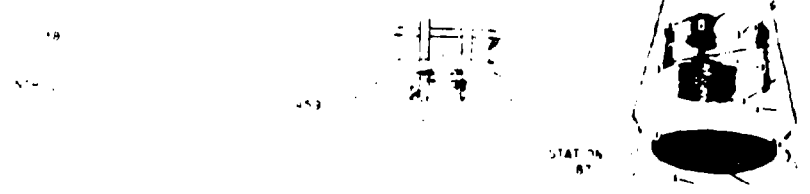
1. AN ESTIMATE OF THE ENVIRONMENTS ASSOCIATED WITH SHIPMENT, HANDLING, AND STORAGE.

2. A DETERMINATION OF THE ENVIRONMENT OF FLIGHT.

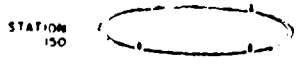
3. A PRELIMINARY EVALUATION OF THE SUSCEPTIBILITY OF MODELS OF THE GUIDANCE UNIT TO FAILURE IN THE SEVERAL ENVIRONMENTS INVOLVED.

4. AN EXPERIMENT TO DETERMINE THE DISTRIBUTION OF THE TIME BETWEEN FAILURES, THE FAILURE RATE, THE MODES OF FAILURE AND THE WEAKEST AREAS UNDER THE MORE CRITICAL ENVIRONMENT AND ON THE BENCH.

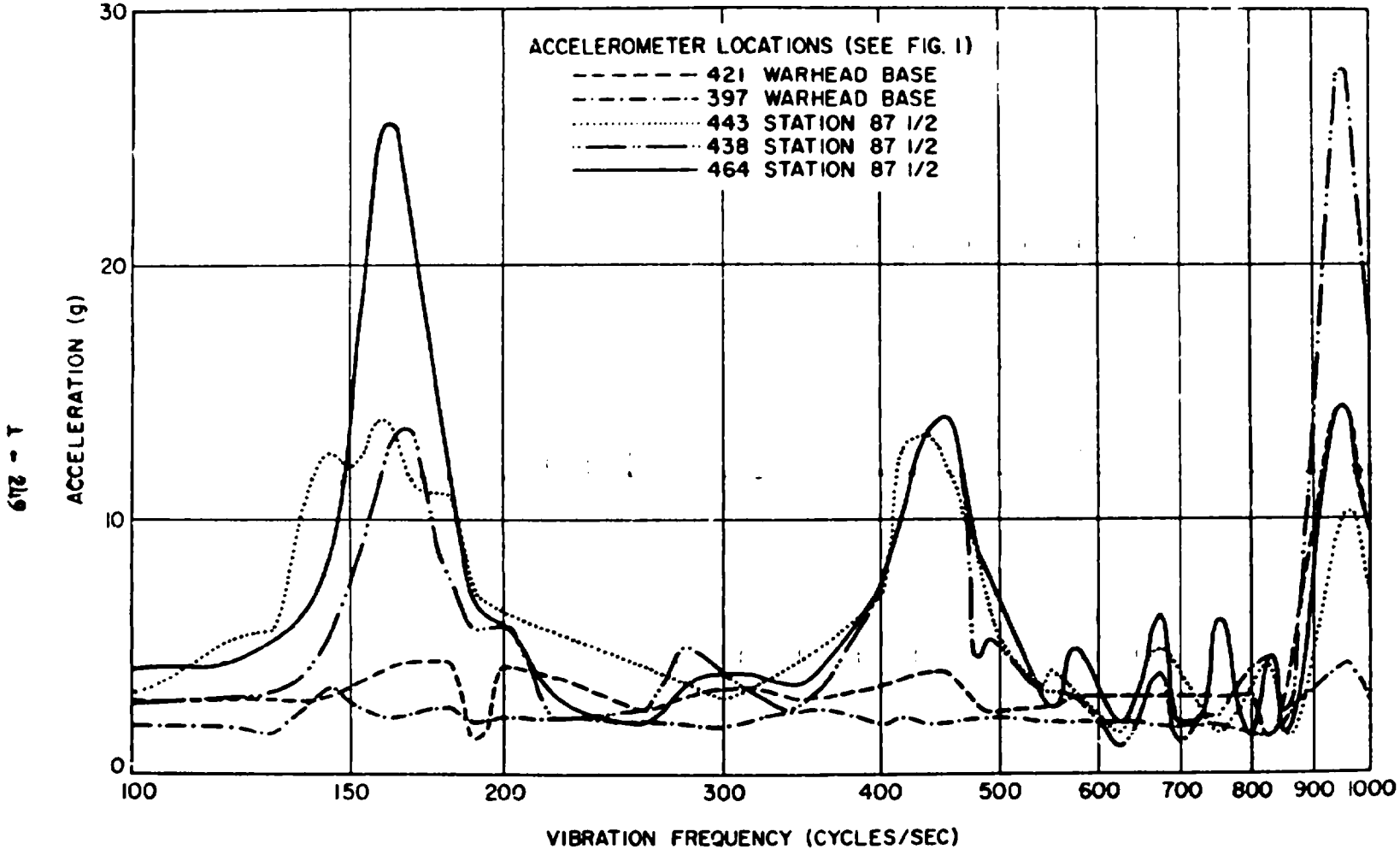
Figure 4



THRUST FIXTURE
SETUP



MISSILE SETUP



ACCELERATIONS AT WARHEAD BASE AND STATION 87 1/2,
MISSILE SECTION VIBRATION SETUP,
CONTROL AT WARHEAD BASE, 2 1/2g LEVEL

Figure 7

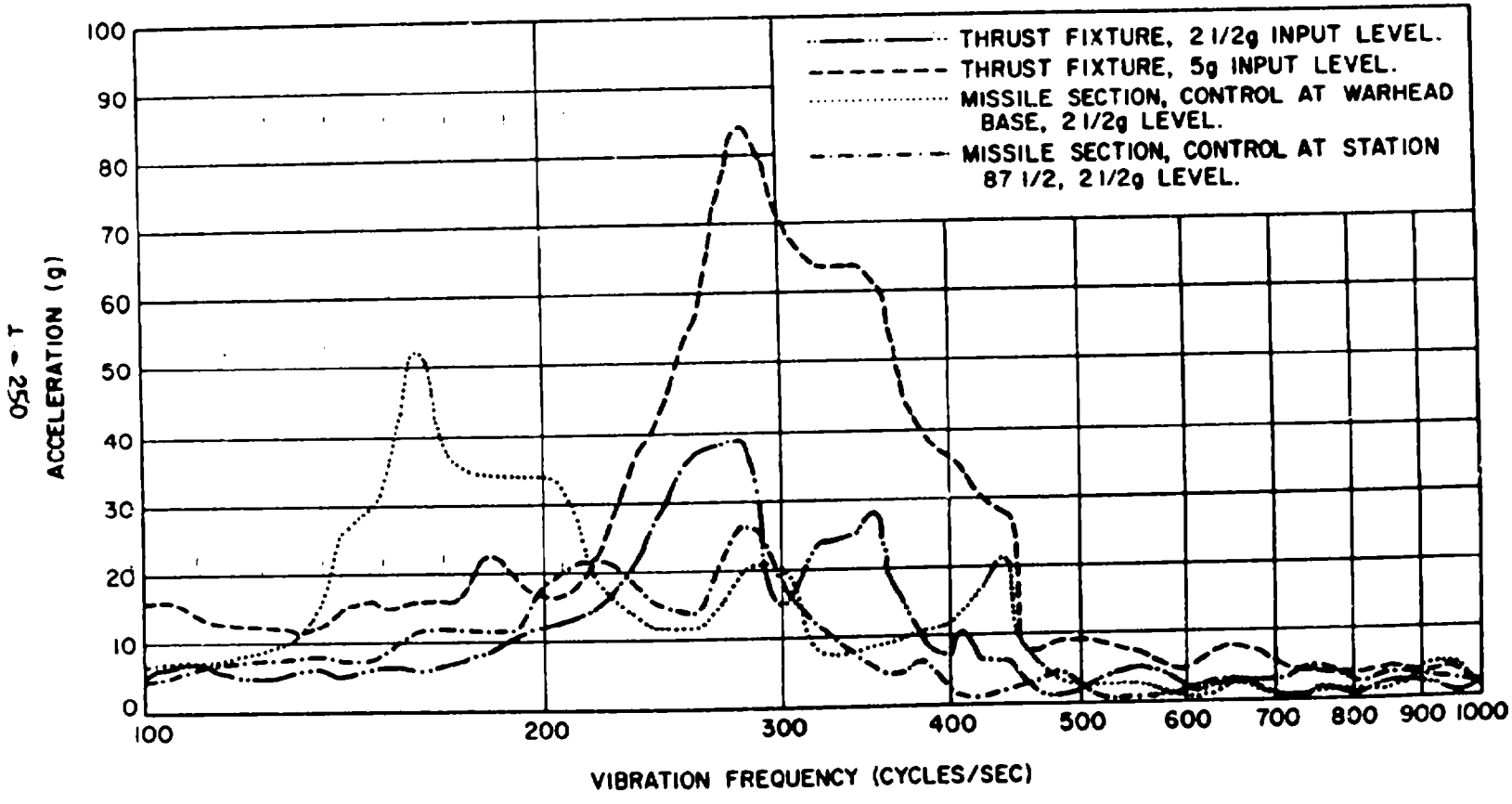


Figure 8

INTERNAL GS-19672 GUIDANCE SET ACCELERATIONS
AT MOUNTING FLANGE OF ROLL AMOUNT GYRO (OUTER POSITION),
ACCELEROMETER NO. 399, UNDER VARIOUS CONDITIONS.

GUIDANCE UNIT RELIABILITY

1. PRE-FLIGHT RELIABILITY
   - a. SHIPMENT
   - b. HANDLING
   - c. STORAGE
   - d. PERIODIC CHECKOUTS

2. FLIGHT RELIABILITY
   - a. FLIGHT ENVIRONMENT
   - b. OPERATION DURING CONTROLLED FLIGHT.

Figure 9

POISSON PROBABILITY DENSITY FUNCTION

$$P_{(n,\,t)} = \frac{\left(\frac{t}{\overline{T}}\right)^{n} e^{-\frac{t}{\overline{T}}}}{n!}$$

ADVANTAGES

1. EASY TO USE
2. ASSUMES CONSTANT FAILURE RATE

Figure 10

CRITICAL ENVIRONMENTS

ENVIRONMENT	WHERE FOUND
SHOCK	SHIPMENT
VIBRATION	HANDLING
	FLIGHT
TEMPERATURE EXTREMES	STORAGE
	SHIPMENT
ALTITUDE	FLIGHT
AMBIENT	CHECKOUT

Figure 11

TYPICAL ACCUMULATED DISTRIBUTION OF FAILURES

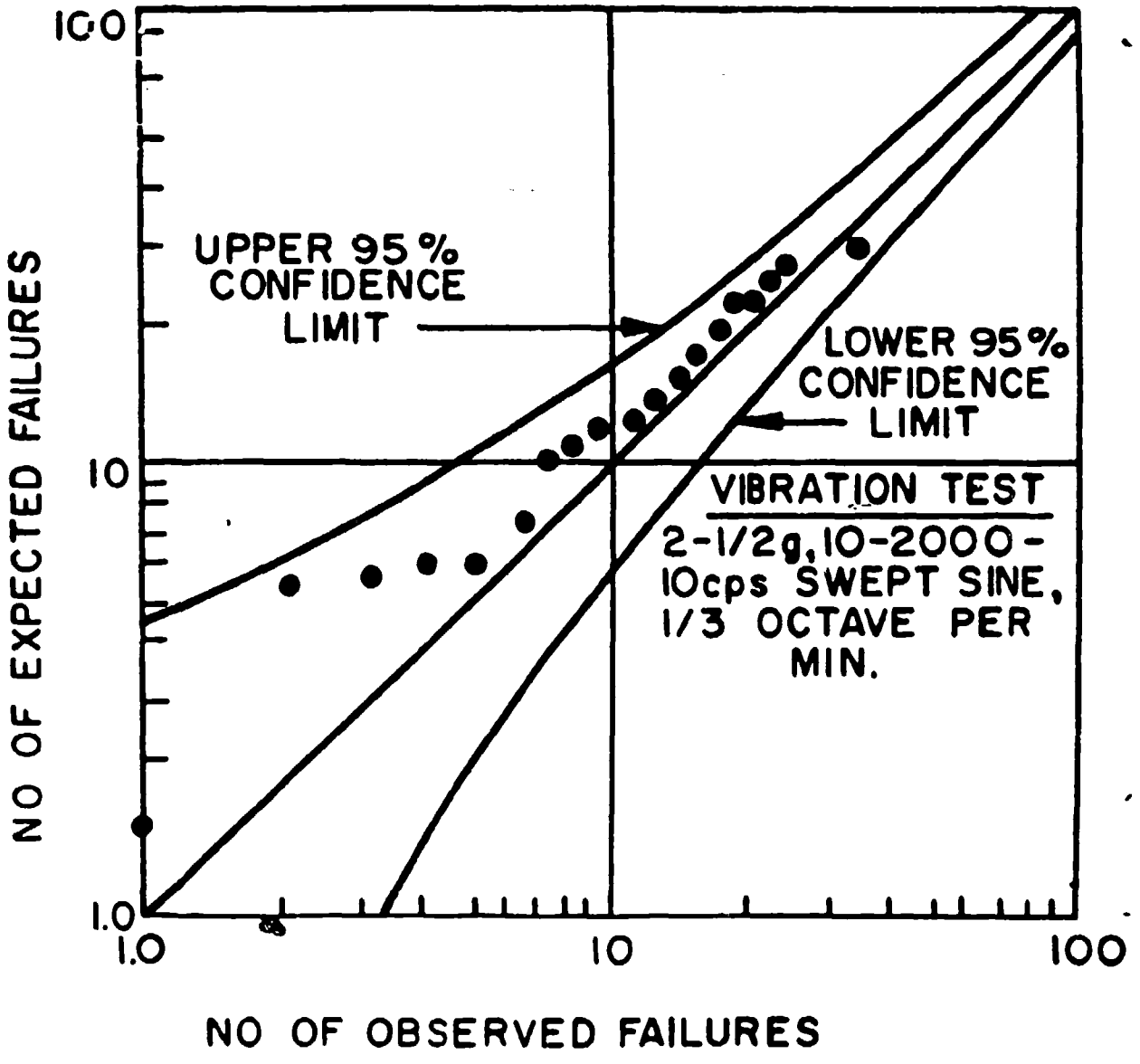


Figure 12

PROBABILITY OF SUCCESS IN FLIGHT

ENVIRONMENT	PROBABILITY OF FAILURE CRITERIA	PROBABILITY OF ACCEPTANCE	PROBABILITY OF FAILURE IN FLIGHT
VIBRATION	0.01	0.90	0.0043
ALTITUDE	0.01	0.90	0.0043
ACCELERATION	0.01	0.90	0.0043
PROBABILITY OF ACCEPTANCE OF 1 UNIT		0.73	
TOTAL PROBABILITY OF SUCCESS IN FLIGHT			0.987

Figure 13

DESIGN CAPABILITY VERIFICATION

PROBABILITY OF SUCCESSFUL FLIGHT 0.985

TOTAL SAMPLES — 5 SYSTEMS

VIBRATION

MEAN TIME BETWEEN FAILURES:

TOTAL SAMPLE	1 HOUR MINIMUM
EACH SYSTEM	25 MINUTES MINIMUM

ALTITUDE

TOTAL FAILURES IN SAMPLE	5 MAXIMUM
TOTAL FAILURES IN ANY SYSTEM	3 MAXIMUM

ACCELERATION

TOTAL FAILURES IN SAMPLE	2 MAXIMUM
TOTAL FAILURES IN ANY SYSTEM	1 MAXIMUM

Figure 14

DESIGN CAPABILITY VERIFICATION

PRE-FLIGHT PROBABILITY OF SUCCESS 0.95

TOTAL SAMPLE — 5 SYSTEMS

LIFE TEST

MEAN TIME BETWEEN FAILURES:

TOTAL SAMPLE	500 HOURS MINIMUM
EACH SYSTEM	220 HOURS MINIMUM

SHOCK

TOTAL FAILURES IN SAMPLE	3 MAXIMUM
TOTAL FAILURES IN ANY SYSTEM	2 MAXIMUM

TEMPERATURE

TOTAL FAILURES IN SAMPLE	5 MAXIMUM
TOTAL FAILURES IN ANY SYSTEM	3 MAXIMUM

Figure 15

PRODUCTION CONTROL TEST

SAMPLE SIZE

FOR ANY CONTRACT INVOLVING 1000 OR MORE GUIDANCE UNITS, THE TOTAL SAMPLE SIZE (N) SHALL BE

$$N = 6 + 1/2\sqrt{\frac{\text{NUMBER ON CONTRACT} - 1000}{10}}$$

ROUNDED TO THE NEAREST WHOLE NUMBER. FOR CONTRACTS OF LESS THAN 1000 THE MINIMUM NUMBER SHALL BE 6.

DISTRIBUTION OF SAMPLES

THE SAMPLE SHALL BE DISTRIBUTED APPROXIMATELY UNIFORMLY OVER THE PRODUCTION PERIOD.

Figure 16

RELIABILITY CONCEPTS APPLIED TO OBTAIN DESIGN SPECIFICATIONS FROM MEASURED ENVIRONMENTAL DATA

Elliot H. Kahn, The W.L. Maxson Corporation
Samuel Stempler, The W.L. Maxson Corporation

ABSTRACT

The Reliability Analysis Section of The W.L. Maxson Corporation has prepared a study on how raw measured environmental data was used in the preparation of a design specification. Such techniques are believed applicable and, indeed, desirable when starting a research and development project.

This article indicates how the vibration requirements for the structure of a unit were determined in a specific case: an aluminum alloy casting used as the primary structure in a critical guided missile safety and arming device. The Scope of Work listed limited measured data, giving steady-state loads, vibration, and shock loads. A review of this data indicated that the steady-state and shock loads were not critical compared with the vibration loads.

For the case in question, the vibration design levels are deemed to be influenced by four considerations:

1. Safety factors.
2. Probability of exceeding measured data.
3. Resonances in the structure.
4. Factors of ignorance.

These factors are discussed in greater detail, and a final recommendation for a vibration design specification is made.

RELIABILITY CONCEPTS APPLIED TO OBTAIN DESIGN SPECIFICATIONS FROM MEASURED ENVIRONMENTAL DATA

What reliability considerations are involved in using measured environmental data for the preparation of a design specification? The Reliability Analysis Section of The W.L. Maxson Corporation recently was required to answer this question for a project charged with the design of a device for a guided missile. The correction factors believed necessary before limited environmental data can be used reliably are presented herein. The techniques employed are believed applicable and, indeed, desirable when starting a research and development project.

Environmental requirements obviously must be included in contracts for military equipment. Equipment must operate or be capable of being stored under these environmental stresses. Often, the environments stipulated in the specifications referenced in the contract have been so generalized that no exact relationship can be found between them and the actual environment to which the equipment will be subjected. The limits specified are an attempt to insure that the equipment meets certain minimum standards of ruggedness, durability, and useful life. However, measured environmental data, when available, can and should augment the specification.

Paradoxically, the availability of actual environmental data may complicate the role of the reliability engineer in relation to the design engineer. This is so because the measured environmental data is often, of necessity, obtained from a statistically insignificant sample under conditions that aggravate the measurement problems, and should not be used directly. However, the data obtained from measured environments is necessary, and can be reasonably adjusted to enhance the probability of obtaining the desired reliability goal. This article indicates the manner in which the vibration requirements for the structure of a unit was determined in a specific case. Figure 1 illustrates how measured data could be used as a base upon which various factors can pyramid to "build" a good design specification.

We have taken the liberty of making a number of numerical simplifications without specifically noting them, because a rigorous mathematical treatment of the subject is not germane to the topic.

The background of the problem is as follows: an aluminum alloy casting is used as the primary structure in a guided missile adaption kit. The Scope of Work contained limited measured environmental data that stipulated steady-state loads, vibration loads, and shock loads. A review of this data indicated that the steady-state and shock loads were not critical, compared with the vibration loads.

In detail, the nature of the vibration specification was that the unit had to be capable of functioning with applied vibration levels up to a peak of 17g, which was the approximate flight and handling environment. Analysis of limited flight data indicated that the vibration had an rms value of 10g, with peaks of 17g actually observed. A high operational reliability (99.5 percent) was specified for the unit, with a much higher probability of functioning as a safety mechanism specified.

In evaluating techniques to adapt this data into a reliability design, it became apparent that Lusser, in "Reliability Through Safety Margins" (October 1958, Research and Development Division, Army Rocket and Guided Missile Division, Redstone Arsenal), had outlined most of the factors that lead to a selection of safety margins in a reliability

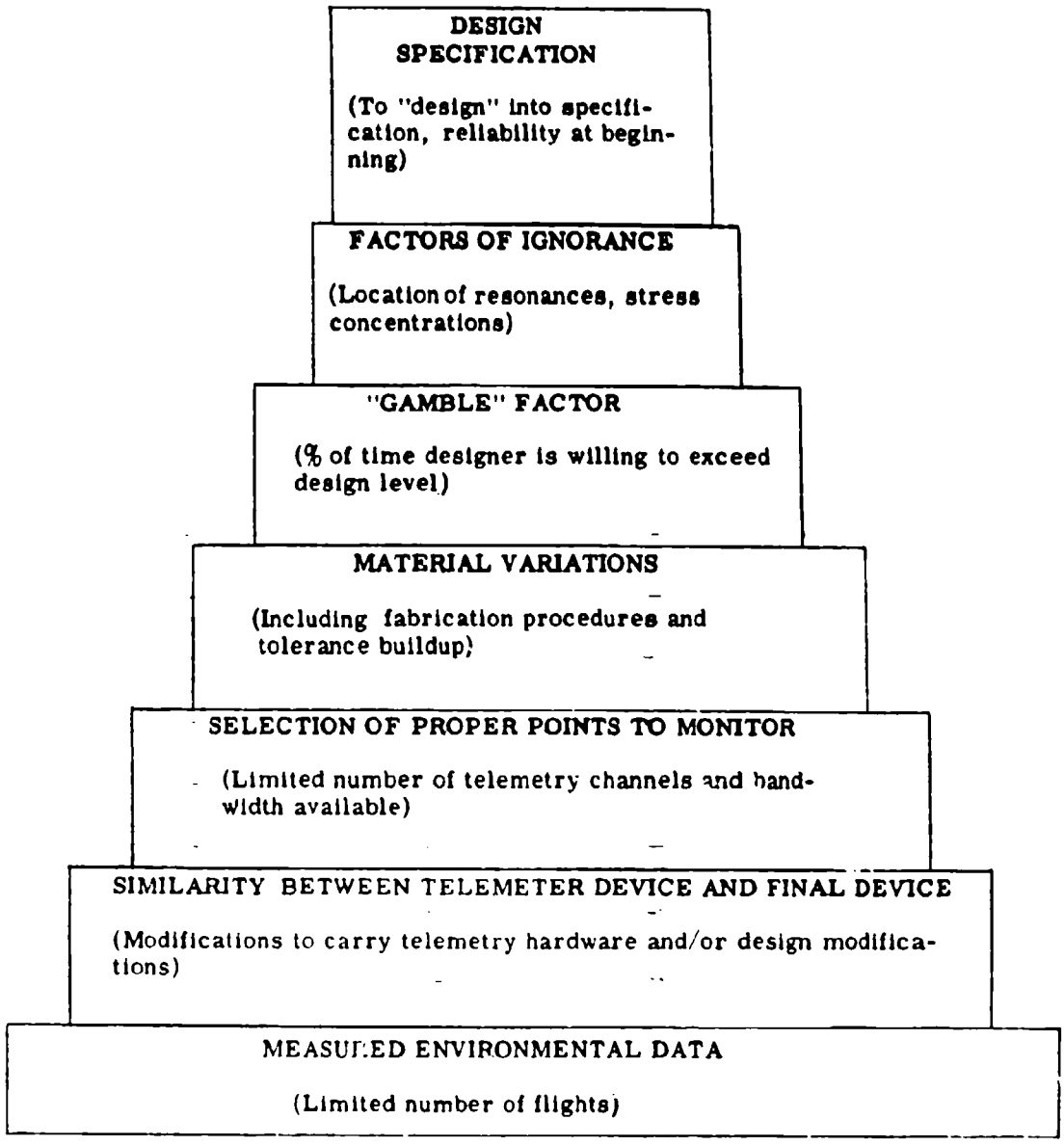


Figure 1. Some Factors to Be Considered in Building a Reliable Design Specification

specification. Although these principles may be rather provocative to the electrical engineer, they have been applied for many years in such civil engineering fields as traffic flow, flood control, and structural safety factors. Typical papers in the field include Freudenthal's "The Safety of Structures", Vol. 112, 1947 Transactions of the American Society of Civil Engineers, which reasserts the concept of safety factors; and various issues of highway and bridge specifications, which accept probability concepts in computing maximum design loads and arrangement of vehicles on a bridge. Naturally, a measure of risk is involved, and we are all aware of structures that collapse when subjected to conditions of severe overload. Generally, the failure rate allowed in these structures is based on economic principles. In military applications, operations research adds other considerations; and the designation of allowable failure rates is based upon the more involved factors that influence the nation's security. In some of our critical nuclear programs, these failure rates are so small that they actually may be interpreted as stating that no failure rate is tolerated (that is, absolute safety is required).

For the case in question, the vibration design levels were deemed to be influenced by four considerations.

1. Safety factors (which relate to the variations possible in the materials, fabrication processes, inspection procedures, and usage conditions).
2. Probability of exceeding measured data (purely on a statistical basis).
3. Resonances in the structure (and other factors associated with the absence of a laboratory-controlled experiment, which actually relates measured data to what is happening in the unit).
4. Factors of ignorance (which, paraphrasing Freudenthal, relates to the limitations in our intellectual concepts in understanding and describing what is happening).

Applications of the above-mentioned considerations affected the design specifications as follows:

1. Safety Factors.

It has been reported (reference A) that the fatigue strength for aluminum alloy (castings) has a scatter band ± 20 percent about the average value. Generally, statisticians consider the "limits of consideration" to be at the three-sigma point (reference B).

Let σ = sigma = standard deviation

S_{av} = average strength

S_{dl} = strength required at design level

Then, 20 percent of S_{av} = the three-sigma point, or $\sigma = \frac{0.2 S_{av}}{3}$

A reliability code is being prepared by one of the Arsenals (reference C) which contains the requirement that the contractor shall prove that a safety margin of at least five sigma is available.

Therefore, the design point should be 5σ away from the average strength, or

$$S_{dl} = S_{av} - 5\sigma = S_{av} - 1/3\, S_{av}$$

$$S_{dl} = 2/3\, S_{av}$$

The ratio of $\frac{S_{av}}{S_{dl}} = 1.5$

The average strength should be 1.5 times the strength required.

On this basis, the vibration design level should be increased from the specified 17g by a 1.5 factor to 25.5g.

For similar computations, a family of curves is available (reference D) which relates the safety factor, for various ratios of S_{av} to S_{dl}, to the sigma safety margin.

When one discusses safety factors for machines, aircraft, and structures, typically, a safety factor of only 1.5 is specified (reference C). Although it has been developed from specifications for structures, this low safety factor merely allows for the known variations of the basic materials, not for the many additional uncertainties and contingencies that always affect the components of even seemingly simple military equipment.

2. Probability of Exceeding Measured Data.

Assuming that the vibrations are random and the vibration levels have a normal distribution, the probability of exceeding the rms value of the vibrations can be determined. If one stipulates that the design level of vibration should not be exceeded more than one percent of the time, then the design level should be approximately 2.6 times the expected rms level. Therefore, the design for the problem posed above should required (10) x (2.6), or 26g, if we are not to exceed our design level of vibration more than one percent of the time. With the aid of tables available in most books on statistics, the design levels can be specified on the basis of their not being exceeded for whatever percentage of time the designer believes to be significant. Actually,

fatigue damage is cumulative, and a detailed application of Miner's approach could be followed. This would integrate the damage caused by the different vibration levels for the portion of the mission time present. A brief summary of the approach is given in reference E.

3. Resonance.

It should be fully expected that several points in the unit will experience amplification of applied vibration levels due to resonances. However, it is almost impossible to calculate resonance effects for a structure as complicated as a typical missile casting.

The nature of the design led to the presumption that an amplification factor of at least 1.5 was almost certain to be present at points within the unit. Consequently, requiring components and the structure to be designed for such amplification is entirely reasonable, and does not represent an ultra-conservative or over-designed approach. This magnification factor is not based on any theoretical work but is merely what we have found on similar units in the past.

4. Factors of Ignorance.

There are several additional considerations to the problem. Broadly, they may be lumped into what has been termed factors of ignorance. For example, if the most highly stressed points are not affected by resonance, the previously computed factor of 1.5 (which raised the vibration level to 25.5g to allow for material variations) is valid. However, if this stress is subjected to a 1.5 magnification because of resonance, the correct design vibration level is 38.3g. Naturally, it is perfectly valid to question the probability of obtaining a location with a high-resonance condition combined with low material strength.

Similar questions arise as to the probability of detecting major flight loads in a limited flight program with limited pickups, and the ability to determine the relationship between the data obtained from a telemetry missile and an actual missile having the unit installed. Obviously, if all these conditions were included (presuming they could be evaluated, even by an rms technique) the final design levels would be much higher than the levels specified.

It must be recognized that it is impossible (and not valid) to compound probability on probability without some overall evaluation of the statistical aspects. This evaluation should cover specification requirements, flight data, materials, experience (on the basis of design standards), possible reduction in reliability elsewhere (because of excessive weight and volume allocated to the structure at the expense of

other components), and so forth. Accordingly, based on such considerations as material variations, probability of exceeding a specified "g" level, and resonances observed in similar devices (past experience), a factor of 1.5 times the maximum observed flight load of 17g was selected to obtain design levels for the device. It was felt that the design would be jeopardized, in the light of current experience, if this safety factor of at least 1.5 were not used. On the other hand, it was also felt that the designer should be aware that a safety factor as low as 1.5 could be questioned for adequacy, since nothing had been allowed for factors of ignorance.

In performing this analysis, it was recognized that only elementary numerical computations were used, rather than more sophisticated approaches to the probability distribution. Although not necessarily valid, the stated reason is that the factors of ignorance are so great (particularly at the start of a research and development program)that it was not considered worthwhile to go into the subject more deeply.

Actually, the application of reliability factors to the design levels was questioned on the basis that other sections of the missile were not being designed to increased levels. In a way, this did make the adaption kit "stronger" than the missile. However, the adaption kit is expected to perform its function even while the missile may be structurally failing in flight. And the device must perform with a reliability greater than that expected of the rest of the missile.

Consequently, in discharging its responsibility of determining design and test specification criteria for this device, the Reliability Analysis Section of Maxson combined the measured environmental data and the required reliability into a compatible specification for design purposes.

Three levels of environmental severity were specified. These levels, Type A, Type B, and Type C, were defined as follows (quoting directly from the prepared design specification):

Type A: "Type A Environment (Contract Minimum Value): These levels are directly abstracted from the contract. Every item must be capable of withstanding these levels".

Type B: "Type B Environment (Design Target Value): These levels represent environments which may exceed those specified in the contract. All components and subassemblies must be capable of withstanding these environments. The completed unit must be exposed to these environmental levels, and the effects evaluated, before a design can be considered to meet the reliability provisions of the contract. Items subjected to Type B environment are not suitable for stockpiling or delivery to the customer."

Type C: "Type C Environment (Destruction Value): The margin of safety inherent in the design must be established by exposure to these destructive environments. These environments exceed the Type B environments. The levels stated in this specification are based upon the capabilities of presently available test equipment. Should increased capability become available, then advantage should be taken of the opportunity to induce greater environmental stress. The Type C environment is applicable to components, subassemblies and the completed unit. Items subjected to the Type C environments are not suitable for stockpiling or delivery to the customer."

It is intended that each of the different levels of environmental stresses will help achieve the objectives outlined below.

The Type A environment is the formal test environment, which must be met before the customer accepts any equipment.

The Type B environment permits all subassemblies to be tested and evaluated in parallel programs without waiting for final assembly. It permits a minimum amount of intensification of the contractually specified environments (which apply to the system) to allow for such quantities as vibration magnification, equipment heating, and other related items. It is recognized that the individual components and subassemblies must have a greater reliability than that required of the system as a whole. Consequently, component specialists, who must select specific components and vendors, can use the Type B environments as a basis for negotiating with outside sources.

The Type C environment is self-explanatory and is in the spirit of Lusser's recommendation to determine safety margins for all equipment. Should, for one reason or another, the operating requirements for the system change, knowledge of the safety margins would be invaluable. Evaluation and determination of changes (if any) could be rapidly made.

In our approach to this problem, we have felt that reliability is applicable to all aspects of the design, both electrical and mechanical. Indeed, an engineering solution that excludes reliability considerations anywhere is incomplete and should be treated as such.

APPENDIX

Subsequent events tend to justify the approach described in this article. A missile, containing the first deliverable adaption kit (which was designed using the approach described) broke apart shortly after launch. Telemetered information indicates that the safety and arming functions of the device were fulfilled as designed. Who knows what

the environment was at the time? Yet this was prec[illegible] the time that the equipment had to perform.

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QUALITY CONTROL AND MISSILE SYSTEMS ACCEPTANCE TESTING

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Missile Systems Acceptance Testing as established in the Redstone and Jupiter Missile Programs, refers to the Electro-Mechanical Tests performed on the Missiles and Ground Support Equipment as a part of the Quality Control function. These tests are run at the component level prior to installation, and at the component, sub-system and complete systems level after installation. Quality Control Engineers write the detailed test procedures used for these tests and Quality Control personnel perform them. The tests accomplish three main objectives; they assure quality of manufacture, functionability of the system, and compatibility between the missile and its firing equipment.

Assuring quality in the product is accomplished by testing each valve, relay, computer, actuator, distributor, gyro, etc., before assembly into a panel or black box to see that it performs to design specifications. Then it is tested again after assembly into the panel or black box, and again in final checkout after installation in the missile or in a vehicle. These later tests insure that no damage has resulted during assembly and that its new environment does not deter the components' ability to meet the original design specifications.

It should be established that Chrysler Missile does not do 100% inspection or testing. A better figure to use would be 400% as a minimum on most functional components, and 600% or 800% on many others. Statistical sampling is used only at receiving inspection on large lots of raw material or large quantities of small hardware and components (screws, rivets, resistors, etc.) and in-process inspection of some fabricated non-functional parts.

Assuring functionability in the missile is accomplished by verifying that the missile will perform properly during flight. By establishing test methods which duplicate or simulate conditions encountered in actual flight, the tests are a double check on the missile system design. This is especially important during the R & D phase of the project where the design is constantly changing in an effort to improve reliability and performance. But the early tactical version also undergoes modifications which result from the conditions encountered in field use, and added safety and reliability features. Each change in the missile design must be checked thoroughly to insure that it will accomplish the desired result and to verify that each modification does not cause interference with any of the other systems aboard the missile.

In the final checkout testing, the missile goes through a launch countdown and simulated flight as the final test, operating every component except firing up the engine. The stabilized platform is set in a gimballed turn tilt stand which can rotate it in any direction to simulate missile flight and check the response of the control system as error signals are introduced.

Assurance of compatability with the actual launching equipment is accomplished by designing the final checkout equipment functionally identical to the portable launching equipment which checks out and fires the missile in the field. Many of the tests performed in checkout are also identical with those performed in the field previous to firing. Many panels used in the checkout station can be interchanged with panels in the field equipment. As the missile design is modified, the test equipment, procedures and specifications used in checkout must be changed to accomodate the design. These changes are at the same time incorporated into the missiles, ground support equipment, and procedures used in the field. In this manner the design of the launching equipment remains up to date and is compatible with the missile as modifications are incorporated.

As a further check on compatibility the actual ground support equipment for each launch site is assembled and mating tests with each missile are performed at the contractor site. These tests, under field environment, further insure the compatibility of missile and ground equipment.

Functionability, quality, and compatibility are the goals established for acceptance testing, but why? It is a simple matter of reliability. For simplicity, break total reliability down into three main factors, design reliability, manufacturing reliability, and field reliability.

Design reliability is the establishment of component and system parameters and specifications which when integrated will define a weapons system capable of delivering a given payload to within a specified target area. It is the configuration established on paper and proven in lab environmental testing and initial R & D firings.

Manufacturing reliability is the assurance that the product conforms to the specifications established by the design. This is Quality Control, the evaluation of the hardware to see that it is built to the design specifications.

But complete 100% reliability of design and of manufacture is not enough. Field reliability, competant, trained personnel and procedures are required to complete the reliability of the system. Proper hookup of equipment, accruate laying or aiming, correct preset values, exact sequence of operations all are required.

Thus it is the product of the three factors, design reliability, manufacturing reliability, and field reliability which determines the overall reliability of the missile weapons system. In establishing Acceptance Testing criteria which determines the functionability of the system, a partial verification of design reliability results. Repeated tests to insure quality, establishes manufacturing reliability. A constant check for compatibility of equipment and procedures plays a major role in securing field reliability. Therefore, the continued effort to maintain high functionability, quality, and compatibility standards in acceptance testing has played a major role in establishing the Redstone and Jupiter as two of the most reliable of this nation's Weapons Systems.

Before going into detail on the exact nature of the testing and test equipment, it should be established how this function fits into the Quality Control organization. The Branch Manager of Quality Control reports directly to the Missile Division General Manager. He is on the same level as the Manufacturing Manager, Production Control Manager and Chief Engineer. Reporting to the Branch Manager of Quality Control are five line sections. These consist of a Quality Control Engineering Section which is responsible for the planning of inspection operations, three inspection sections covering Receiving Acceptance, In-Process Inspection, and Final Acceptance Testing; and a Quality Assurance Section which is responsible for the measuring of quality achievement. There is also a Material Review Department which deals with the disposition of material which deviates from specifications.

Quality Control Engineering is a phase of engineering that is associated strictly with Quality Control. These are the people who plan all the activities that are conducted by the Quality Control Branch. During the design and prototype phases of the missile program, Quality Control engineers work closely with product design engineering groups in order to develop inspection and test methods, and design and procure necessary test equipment. Each component of the missile system is evaluated to determine the most economical and reliable method for controlling its quality. Inspection points are established by Quality Control concurrently with the preparation of manufacturing routing sheets by Master Mechanics.

Quality Control Engineers investigate potential suppliers prior to the placing of purchase orders in order to assure their ability to produce quality components. Suppliers' quality control facilities, techniques, and past quality performance records are thoroughly evaluated and provisions are made for test samples, material certifications, and source inspection as necessary.

In addition to this, a very important function of Quality Control Engineering is to correct quality problems to see that they are not repeated. This involves the investigation of problems reported by Quality Assurance Section as a result of the occurence of repetitive defects. They will determine the exact cause of the problem, and take the necessary steps to correct the problem by initiating a change in inspection method or recommending a change in production process or change in the design specification.

The most important function of Quality Control is that of inspection. The Receiving Acceptance Inspection Section is responsible for the inspection and test of all parts produced by any of our suppliers. In some cases our people are stationed at the suppliers' own plant in order to assure that parts produced by the supplier meet the highest quality requirements. In general, primary reliance is placed on the supplier's own quality control system for assuring the maintenance of high quality. At the present time, there are permanent supplier liaison representatives stationed at 20 of the most important subcontractors and vendors. These representatives verify the performance of the supplier's quality control

trends, pin-pointing quality problem areas, and reporting trouble spots so that appropriate corrective action can be taken either by design, production, or inspection.

In order to continually evaluate the activities of our own quality control system, the Quality Assurance Section also is responsible for performing quality audits. These consist of spot checks of the efficiency of our inspection and test operations and audits of our conformance to our established quality control procedures. These audits act as a valuable check to insure that our quality control program functions continuously to guarantee the high quality of the missile systems.

When the missile is brought into the final checkout area, for final Acceptance Tests, pneumatic lines which connect the missile and the ground air supply are hooked up. Through these lines the air storage batteries or spheres as they are called are pressurized. This pneumatic pressure is used during flight to operate valves, float the gyros, for attitude control of the missile, and pressurization of the fuel tanks. Electrical harnesses connecting the ground consoles with the missile are hooked up. It is through the use of the switches and the meters on the ground consoles that the tests are performed. Other equipment is connected, such as interrupter boxes, dummy plugs, interrupter harnesses, gauges, and meters which simulate various conditions that would occur during flight and monitor pressure, current, and voltage at the various points within the missile system. For example, due to the safety requirements the fuel and oxidizer tanks are not pressurized in this area, actual ignition and mainstage burning cannot be accomplished, launching ring lift-off is not accomplished, but must all be simulated. These are accomplished by jumpering certain connections in missile circuitry, installing a time delay relay to simulate ignition delay, and using a pneumatically operated fixture to disconnect the electrical connections at the tail plugs as in lift-off. To provide error signals to the control system the stabilized platform is installed in a turn-tilt stand which can deflect the stable table into any prescribed orientation and, thus produce corresponding output signals.

The circuitry in the test equipment is designed such that most of the components aboard the missile can be operated individually. For instance; a valve, computer, radar beacon, blower motor, etc., can be turned on or off at will without going through automatic launch sequencing. After each of these components is tested individually it is then tested in conjunction with the other components and interconnecting harnessing within its system. After each of the systems have been checked for proper operation all the systems are operated together in a final simulated flight test. An example of this progressive testing is the operation of the main fuel valve. The valve would be tested as a component to determine that it functioned correctly. Then it would be operated as part of the automatic launch sequence overall test with only the propulsion system operated. During the simulated flight test it would be checked again in conjunction with the guidance system, measuring system, and tracking system. The simulated flight test would determine that there were no signals from one system which would interfere with any

system by continuous surveillance. When necessary, they may also perform direct inspection of the supplier's products and have the authority to accept, reject or request rework of nonconforming material produced by the supplier. They also assist our suppliers in correcting any quality problem areas. By assuring the performance of all necessary inspections and tests at the supplier's location, it is thus possible to reduce the amount of inspection necessary when parts are received at Missile Division.

The bulk of the parts and components which we purchase are procured from smaller vendors and subcontractors where the volume of parts procured makes it more economical to perform the inspection and acceptance right at Missile Division. These items are thoroughly inspected and tested upon receipt to assure that all quality requirements are met. The amount of inspection performed is generally covered by the nature of the part, as well as the past quality performance of the supplier involved. Even where inspection acceptance is performed at Missile Division, close liaison is maintained with the supplier to inform him of his quality performance and of problem areas requiring correction. Where necessary, both the supplier liaison people and the Quality Control Engineers work closely with the vendor to assist him in improving his Quality Control system in order to prevent recurring discrepancies.

All parts fabricated and assembled within the Missile Plant are inspected and tested by our In-Process Inspection Section. This involves all types of dimensional and mechanical inspection, pressure testing and electrical functional tests. Inspection is performed continuously during the fabrication and build-up process. During the assembly, inspections are performed at predetermined points where a high possibility of error may exist in order to completely control the build-up process. At the completion of the missile assembly, a final inspection is performed on the entire missile including pressure testing, continuity and installation resistance check of harnesses and optical alignment inspection. The missile is not released to the Final Acceptance Testing or Final Checkout operation until the completeness and acceptability of the entire assembly has been verified.

The Final Acceptance Testing is responsible for performing a complete functional system test of the entire missile. During this test, the missile is put through the complete sequence of operations normally performed prior to launching and simulated flight test. A similar type of test is performed on all units of Ground Support Equipment before they are delivered. The majority of the Acceptance Testing is performed by this section.

Another very important phase of the Quality Control Program is carried out by the Quality Assurance Section which is responsible for continuously monitoring and measuring our product quality. Quality data, in the form of inspection and test records, and reports of defects and failures are fed into our Quality Analysis Group from subcontractors, vendors, in-plant inspection, and field locations. This data is systematically categorized and stored by means of automatic data processing equipment and extracted for statistical analysis. This data represents a complete historical quality record which is used in determining quality

other of the systems. For example, poor installation or a floating ground on one of the connections in the propulsion system might allow stray current to appear in the Guidance System and introduce incorrect control movement. During the test, all of the radio frequency gear is operated to insure that there is no stray noise from rotating equipment nor harmonics of tracking signals to interfere with the telemeter signals nor the operation of other tracking or range safety equipment.

The simulated flight test is the final test run on the missile. After the test results are thoroughly evaluated and it is verified that the missile performed properly, it is then released to be packaged, weighed, and shipped. At this time, it need only be erected, armed, and fueled in order to be ready to fire.

R & D Missiles are flown to Cape Canaveral for firing. Earlier missiles were given a receiving inspection test in the hangar prior to erection on the pad. However, later missiles were delivered directly to the pad for the final mating of the missile to the firing equipment and series of tests prior to launch.

The tactical Jupiter Missiles are mated to the actual Ground Support Equipment which will form a launch complex in the field. These mating tests assure the compatibility of the system equipment and procedures and point out any problems which might result in deployment. After mating, each system is packaged and shipped overseas.

The final acceptance testing of the ground support equipment follows the same criteria as the missile testing. Each vehicle goes through a complete pressure, electrical and mechanical test prior to and after a lengthy road test. This insures that the equipment which launches a missile in the field will be reliable as the missile itself.

Thus the final stage in the manufacture of a Guided Missile System is accomplished. The Final Acceptance Testing is the final buyoff as the government accepts the equipment. The detailed procedures and specifications used in this area have certainly made a great contribution toward the proven flight reliability of both the Redstone and Jupiter Systems.

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WORK SMARTER, NOT HARDER TO ACHIEVE RELIABILITY

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High reliability and quality requirements are synonomous with any missile program. It is therefore extremely important to maintain control over manufacturing and assembly processes to assure that the reliability and quality commitments are either met or bettered. Most companies try to assure meeting these commitments by standardizing inspection instructions (such as classification of characteristics), tightening up of acceptable quality levels, and increasing the number of as well as quality of their measuring equipment. While this is necessary, it is not all that must be done to assure meeting the high quality and reliability levels expected of the missile industry.

Basically, we have found four areas wherein the expenditure of a little effort on the part of quality control and reliability organizations pay dividends out of all proportion to the time spent. These four areas have been recognized by many as problem areas. The first is measurement problems of correlation and repeatability of equipment and the standardization and definition of what is to be measured. This is perhaps one of the biggest problems for any quality control organization. It becomes increasingly important to the company and the government as we subcontract and purchase components and sub-assemblies from two or more suppliers.

The second area is quality reporting. Quality reporting need not be expensive but must define quality in terms that management can readily understand. As quality control reports quality, or lack of it, to manufacturing management and to top management, it is essential that they have a feeling of what poor quality or poor reliability means. The easiest way to do this is to hit them in the pocketbook by reporting quality in terms of cost.

The third area is the problem of adequately staffing inspection and test operations so that the maximum efficiency is obtained from them. Needless to say many of you have experienced the situation where throwing extra people into inspection and test only accomplished a screening operation and a poor one at that. But have any of you cut down inspection or test time without cutting down the quality or reliability of your product?

The last but by no means the least important area is a proper evaluation of changes in any product or process through the use of a properly designed statistical study. This is especially important in the missile area where you have small production runs and tremendously high costs. A goof here costs money. It also slows down production and may lead to your replacement as a missile contractor by some other organization which has a more efficient method of evaluating changes in both products and designs.

Now that we have highlighted the four major areas, let's examine each one in detail to see what is necessary to obtain the maximum quality and reliability with your present organization by working smarter, not harder.

Measurement Problems

We have found from our experience with vendors and our own internal experience that there are three basic problems associated with measuring equipment. The first is the definition of what is to be measured. While this may sound extremely trivial, nevertheless when you send a vendor a blueprint and tell him you want a certain dimension, you may run into more difficulties than you expect. This is an especially big problem in areas where items are being measured in millionths of an inch such as air bearing gyros. In order to solve this it is necessary that you spell out, for critical dimensions, exactly what you want measured, how you want it measured, the type of equipment to be used, the number of measurements to be taken, and where they should be taken. Once you have done this the question then arises, does your basic program of measurement control really give the necessary protection? To ascertain the effectiveness of your control program, the following questions must be answered:

(1) What is the precision or repeatability of the measuring equipment in use?

(2) Do different operators using the same measuring equipment obtain the same readings?

(3) How many of the disagreements between in-process and final inspection, between incoming and supplier's final inspection, and between final inspection and purchaser's inspection are the result of poor repeatability or lack of correlation of equipment?

Measuring equipment graduated in ten-thousandths of an inch, often is incapable of repeating within one graduation. In addition, readings taken on the same part with two "identical" measuring machines often differ by more than one graduation. Therefore, along with a basic control program, a manufacturing organization must conduct continuing

studies of the correlation and repeatability of measuring equipment which they and their suppliers use. Also, suitable inspection programs must be devised which will insure that tolerances will be held should the repeatability of measuring equipment be poor and which cannot be improved by adjustment or recalibration.

An Example

Shop-produced components and purchased components of a gyro assembly did not fit together properly because of the differences in measuring equipment and operating personnel at the two sources of manufacture, even though each was maintaining tolerances within its own operations. The supplier of purchased material graded bearings (for inside and outside diameter) into four classes - A, B, C, and D - for each dimension. Each class had a 50 millionths inch spread in dimension and each bearing was identified with two letters: AA, AD, BC, and so on. At assembly of the gyro, the bearings were matched by their code letter to shop-manufactured parts. Parts which went together on paper did not on the assembly bench. When shop supplied parts were reinspected, the same measurements were obtained as before, however, bearings labeled AA were found upon reinspection to be BA, AB, or BB.

The supplier graded each bearing, put it in a heat-sealed bag, and then into a box marked with the grade. To check grading each bag had to be opened, the bearing measured, cleaned and relubricated, and repacked in another heat-sealed bag. A risk of contamination occurred because of this. Still another problem arose - the frequency distribution of bearings from our inspection was not the same as from the supplier. This meant that the supply of a particular bearing grade needed for assembly was insufficient.

Our approach to this problem was to determine the repeatability of both shop and supplier measuring equipment, the average difference in measurement between us, and from this the correction factor which would enable the supplier to correctly grade readings to shop measurements. An experiment was designed to enable measurement differences to be properly assigned to the following:

(1) Different measuring machines used

(2) Different setting rings used

(3) Different operators (two from the supplier and two from our shop)

Four different size bearings were used, one for each class. It was assumed that a significant difference would be found between them. If no significant difference were found, there would be no sense to grading. To determine the precision of the measurements, it was necessary to

include a repeatability study in the experiment. In the repeatability study each test condition was repeated at random times during the course of the experiment. This gave two complete sets of data for the experiment. Analysis of the difference between these two sets of data permitted determination of repeatability. The results of this experiment for the inside diameter measurements are in Figure 1.

Similar data were obtained for the outside diameter measurements. The analysis for both sets of data was performed in the same manner. There were two steps involved in this analysis: determining the repeatability of measurements and determining significant causes of measurement difference.

Determining Repeatability

Repeatability was determined by taking the difference or range between measurements obtained under identical conditions. The average range over all measurements constituted our estimate of repeatability.

Formal statistical techniques assume that repeatability is relatively constant throughout an experiment. In this case this assumption could be verified by using a range control chart where 95% of the individual ranges should fall in the interval from 0 to 2.48 $\bar{R}$, where $\bar{R}$ was the average range. For the values shown in Figure 1 the interval was 0 to 28.8. The ranges were plotted on a control chart, Figure 2. This chart showed that all the points were within the control limits. However, repeatability of the first sixteen points (our equipment) appeared to be much better than the repeatability of the second sixteen points (supplier equipment). When the average repeatabilities of the machines were compared, by a variance ratio test, a significant difference in repeatability was found. Further analysis showed that there was no significant difference in repeatability between the two shop operators or the two supplier operators. Based on this variance ratio test, it was concluded that the repeatability of the supplier's equipment must improve if bearings were to be graded properly. This is true, of course, even if no other differences existed between our measurements and those made by the supplier.

Significant Causes of Differences

To determine whether significantly different measurements were obtained from the different measuring equipment, different operators or different setting rings, the average value of the measurements under each condition was compared to the average measurement for the experiment by the use of a control chart.

The extent of random variation of the average measurement from the over-all average should be within limits calculated as follows:

$$U = \bar{\bar{X}} + \frac{t_a \bar{R}}{1.128 \sqrt{n}}$$

$$L = \bar{\bar{X}} - \frac{t_a \bar{R}}{1.128 \sqrt{n}}$$

Where U is upper control limit, or UCL, L is the lower control limit, or LCL. $\bar{R}$ is the grand average from Figure 2, t_a is Student's "t", $\bar{\bar{X}}$ is the average of all the measurements, and n is the number of readings used to obtain the average measurement for a level of a variable. For the data shown there were two sets of limits, one set for the variables with two levels (machine, setting rings) and one set for the variables with four levels (bearings, operators). By plotting these limits a control chart was obtained for main effects (Figure 3). A common grand average was used for determining the upper and lower control limits for the machine setting ring, and bearing effects. However, as the operator effect was nested within the machine effect, operator 1 was compared against operator 2 for both the shop and the supplier by using the average measurement obtained at the shop and the supplier respectively. The control limits around these averages are the same distance from the average as the control limits around the bearing effect.

If a point falls outside the control limits, it indicates that the effect of different levels of that variable cannot be attributed to experimental error (repeatability). This effect is then said to be significant. On the other hand, if no point falls outside the control limits, the difference in levels of that variable is due to experimental error (repeatability) and the effect of that variable is not significant. Figure 3 showed that the effects of the machine and bearing were significant. No interactions were significant.

Two methods to improve grading procedure were recommended to the supplier. Either the same type of measuring equipment should be used by him as that used in our shop, or the basic difference between shop measurements could be subtracted from his measurements before grading the bearings. In addition, it was recommended that the supplier use the average of two measurements for those bearings whose initial measurement was within twenty millionths of the grading tolerance.

Since our first step in this direction we have expanded our study of measurement problems to cover all critical material. We have found many instances where there was a lack of correlation between our measuring equipment and our vendor's measuring equipment. We have also found instances where excellent correlation existed between our measuring

equipment but because of poor repeatability we rejected good parts or accepted bad ones. To remedy this situation we have conducted correlation and repeatability studies with our vendors and have effected corrective action wherever necessary.

Our Test Department has recently initiated a program whereby repeatability checks will be performed by the calibration section. As most test equipment is expensive, any equipment that does not have sufficient repeatability to distinguish between acceptable and rejectable material will be used for the measurement of less critical material, wherever possible. If this is not possible and if we cannot obtain replacement equipment, we resort to selective double inspection. This is a procedure whereby parts whose measurements are within plus or minus $\bar{R}$ (the average repeatability of the measuring equipment) from the tolerance limit will be inspected twice. The average of these two measurements is then used as the criterion for acceptance or rejection.

Quality Reporting

One of the biggest problems faced by a quality control organization is how to successfully report quality. As most quality reports deal with past history, it is obvious that we should have a rational way of determining the quality level experienced. Many people have their own schemes for reporting quality. Some base it on the percent defective and others on the defects per unit of the inspected material. These methods, while reporting one measure of the quality level, do not convey it in terms that top management understands. If an item or a department or a plant has a quality level of 1% defective, does this cost the company more than one with a quality level of 5% defective? Management is paying for a quality product, therefore, they are interested in knowing how much of this payment is lost by the production of poor quality material. Thus, one of the first characteristics of good quality reporting is to report the quality level in terms that management can understand and that can be used by shop management to obtain better quality.

The second characteristic is that the quality information should be based upon records that are currently available. Almost all plants have a Cost Accounting Department where you can obtain realistic figures of the time spent on a given job as well as the time required to rework the job because of poor quality. The cost of scrapping material is also determined by most Cost Accounting Departments. This is all the basic information you need. Most of this information is reported to management each month, but this reporting does not include any analysis that is immediately useful to detect quality trends.

The third characteristic any effective quality reporting system should have is that it must be inflation-proof. If we report our quality in terms of dollars and cents, we can expect that the steady upward creep of inflation will render invalid any long term quality comparisons.

However, if it takes two hours to make a part using a particular setup today, it will take two hours to produce that same part using the same setup two years from now. Therefore, the hours spent to produce, rework, or the hours lost in scrapping a given part or assembly are a most effective measure of quality.

Now how is this information used? Figure 4 shows Ford's Manufacturing Quality Level Report. This report has been in use for over one year and has been well received by management, by our prime contractors, and by the government representatives stationed at our plant. The report is simple, straightforward, and takes a minimum of time to prepare. If you will look at any given block on the report, you will see that we report three figures - scrap hours, rework hours, and production hours. These figures are all obtained from Cost Accounting. Our measure of quality is

$$M.Q.L. = \frac{\text{Scrap} + \text{Rework}}{\text{Scrap} + \text{Rework} + \text{Production}} \times 100$$

This is the Manufacturing Quality Level.

The rework hours are charged to the department that caused the rework and do not necessarily reflect on the department that did the rework. Thus, if a high percentage of rework is caused by drilling, it may be that the Bench Mechanics Department spent a large number of hours removing broken drill bits. Nevertheless, the hours spent by Bench Mechanics on drilling rework are charged to the Drilling Department.

The production hours for drilling and jig boring added together give the production hours for the Drilling Department. The same applies for the scrap and rework hours. Time lost in scrapping or reworking items for which no one department can be held responsible is entered in the shop total slot for either scrap or rework hours. Thus, the figures shown in the scrap and rework slots of the shop total box will be greater than the sum of all the scrap and rework hours shown for the four departments underneath it.

This report is used by almost all divisions of the company. The shop manager receives copies of the rework cards and scrap tickets which indicate, wherever possible, the employee responsible for producing the poor quality material. The shop manager's office maintains a record of the amount of rework and scrap produced by each employee. This is used by shop management to rate the employees, to determine if additional training is needed by an employee, and to warn the employee when excessive quality failures have been charged against him. Furthermore, this report is used by the shop manager to rate the effectiveness of his managers and foremen in maintaining the quality of their production output.

Quality Control uses this report to assist them in determining causes of repetitive defects. Consistent rejects which require either rework or scrap are analyzed to determine whether additional in-process checks

or an increased overage is required (provided there are no other possible corrective actions which will remedy this condition). This report also assists Quality Control in assigning inspection coverage to areas that have shown a consistently poor quality level. The policy is to assign the inspectors to in-process work so as to avoid the production of scrap or rework material rather than to increase the end of the line inspection which merely sorts the good from the bad.

In order to inform the shop personnel of their quality performance a Quality Level Chart is posted in each foreman's area depicting the quality results for a given month. (See Figure 5.) The lower part of this chart shows the desired quality level for the particular area. The total height of each line on the chart indicates the actual quality level produced and is the same as that shown on the Manufacturing Quality Level Report. When these charts were started almost every employee spent some time looking at them and asking his foreman questions about them. The foremen had been briefed and were able to supply the shop personnel with answers that they could understand.

The benefits of this report to the company were obvious. It supplied realistic quality information that could be used by all divisions at a very nominal cost. Since its inception, we have noticed a consistent improvement in the quality level of the shop as a whole as well as in many of the individual areas within the shop. Our conclusion, therefore, is that this report has been beneficial to us and would be beneficial to you.

Adequate Inspection and Test Coverage

The question of adequate inspection and test coverage is one that cannot be merely decided by rule of thumb such as the practice of utilizing one inspector for every seven operators in the shop or one tester for every five assemblers regardless of the type of work performed. In doing this we run one of two risks, either we will have insufficient coverage so that our reliability and quality levels will deteriorate or we will be paying too much to obtain a very small increase in our quality and reliability levels.

Rather than use a rule of thumb, we decided to measure the efficiency of inspection and test operations in various areas. The results of this are shown in the attached chart (Figure 6) which plots quality efficiency versus the ratio of inspectors and testers to manufacturing personnel. From this you will note that we have never achieved 100% efficiency. If any of you claim to have achieved it, you are kidding yourself. You

may have come close to it but in this business a miss is still expensive. From this chart you see that it is relatively easy, on paper, to obtain better than a 90% inspection efficiency. However, to achieve 99% or 99.9% inspection efficiency would be extremely difficult. Even using a 1 to 1 ratio the best efficiency was approximately 96%. This can be attributed to the fact that many inspection and test operations are extremely tedious and require the evaluation of hundreds or even thousands of check points where the decision to accept or reject is based upon the inspector's judgment. One inspector may say it is good and another may say it is bad, etc.

Now how can this be overcome so as to increase our inspection and test efficiency without bankrupting the organization. There are two ways of doing this. The first and most important is to assure that classification of characteristics or inspection instructions spell out in detail exactly what you will accept and what you will not accept. The realm of all grey area decisions should, wherever possible, be removed from the hands of inspectors and placed in the hands of the supervisors. It is far easier to control the supervisors than the inspectors and testers in a given plant. This is the first step. Without doing this, the second step may not produce any results at all. The second step involves selecting the best combination of inspection to production ratios and following this up with an audit inspection to evaluate the efficiency of your inspection and test organizations. The cost of this can be plotted as a function of your total test organization or your increase in efficiency and an appropriate cutoff point selected by management. The combination of these two will give you the optimum coverage in any one inspection and test area. A third item which should be looked into is the use of automatic testing equipment such as attribute measuring devices instead of variable type devices. Again, the cost of these items should be balanced out against the increased inspection and test efficiency. The above three items can effectively be handled by Quality Control or reliability organization within your company.

Cutting Inspection Costs

Based on the previous discussion, you will probably find that there are many areas which require increased inspection coverage. If you look through the records you maintain, you will also find that there are many areas where inspection costs can be cut. We have found parts that take three hours to manufacture may take ten hours to inspect. Sounds ridiculous doesn't it, yet it happens. If nothing is done about it, you soon find that you are priced out of business. Yet you cannot simply eliminate inspection. To do so would be sheer folly for you would also be out of business because of the poor quality produced. To solve this problem, namely bringing the inspection time in line with the shop time as well as maintaining exacting

quality requirements, we reviewed inspection records by a technique known as error analysis and came to the conclusion that inspection costs could be reduced by using the right amount of inspection at the right place and at the right time. Let us look at a typical example where error analysis has been applied and see the benefits that have accrued from it.

Cam Cost Cut

Ford Instrument Company produces various types of cams - two dimensional and three dimensional, empirical function cams and mathematical function cams, cams that have 200 inspection points and cams that have 14,000 inspection points. The majority of our cams are used in analog computers produced by Ford and by many other companies. We pride ourselves on the quality of our cams. For a while, however, our pride was dimmed somewhat by the ever increasing cost of our cams. When we manufactured cams on the job shop basis, 100% inspection of all points on a cam was considered a routine operation. However, when we received contracts for volume production of cams we were faced with a problem. We had to cut our cam inspection cost or else loose the business. In Figure 7 we show you a typical cam produced by Ford. It is a magnetic variation cam which feeds correction factor into a compass to assure that the proper magnetic variation is added to or subtracted from the heading so that the pilot always has a true magnetic heading. This cam contains approximately 3,000 check points. These 3,000 points cover the magnetic variation between the latitudes of 70° north and 70° south. As this is not a simple cam based on a mathematical function but based upon data supplied by the U.S. Coast and Geodetic Survey, the surface of the cam is very irregular. For this reason it was felt that 100% inspection was an absolute must. However, we soon found out that the inspection records for this cam showed a remarkably consistent pattern. In Figure 8 we present the average readings and spread for the different points on this cam. You will note that we seem to have peaks and valleys in the circled areas. This pattern consistently repeated itself from cam to cam. Using a well known principle of Pareto that a very few points contribute most of the variation, we analyzed the cam and found that approximately 36 points had deviations large enough to warrant continual inspection. We instituted a sampling plan using these 36 points (Figure 9). However, to make sure that the quality was maintained we not only plotted the results of inspection of these 36 points but periodically audited a cam, that is did 100% inspection on it. The results of this 100% inspection verified the adequacy of the plan. It was felt that we could reduce our sample size from each cam to every third cam. Doing this maintained our protection and at the same time permitted a minimum of inspection.

In terms of cost savings the cam inspection procedure was phenomenally successful. For a modest investment in time (approximately 40 hours for the initial analysis) a saving of 31 hours per cam was possible. On another cam which contained 14,000 inspection points, which you can well realize is not only a large number of inspection points but would be an exceedingly tedious job for an inspector to go through, the savings were far greater. This technique has been extended to all items manufactured at Ford Instrument Company. Furthermore, we have never received an unfavorable comment from any of our customers or from our own assembly areas. This proves that inspection costs can be cut while still upholding quality and reliability.

The Proper Evaluation of Product Changes

The proper evaluation of product changes involves many divisions within the company. In order to properly evaluate changes in products or processes the sound application of some common statistical techniques is required. The two most useful are the design and analysis of experiments and the correlation study. These statistical studies are not the type that you can tell the Engineering or Manufacturing Divisions that they must use. You must first sell them on why they should use them. The biggest selling point for their use is that you can investigate many variables with a minimum number of tests.

A Review of Experimental Designs

An experiment is designed to determine if there is any significant change in output, performance, yield, etc., as we go from one level of a variable to a second level of that variable. Most of the time the engineer is interested in the effect upon a process or an assembly of a variable acting by itself. However, the engineer must also be aware of the fact that variation in an experimental setup may be due to the interaction between two or more variables. (Interactions between three or more variables are rare and, furthermore, are usually hard to explain.) The predominant interaction that we must worry about is that between two variables.

Therefore, the basic problem in the design of an experiment is to be able to determine which of the many effects are significant and which two variable interactions are significant. Now what type of experiment is best suited for this? There is no one best experiment that will serve all purposes. However, if you confine yourself to two levels of each variable, the fractional factorial experiment yields a maximum amount of information for a minimum amount of testing. In Figure 10 we illustrate a "master" fractional factorial experiment. If we use variables A through D, we can measure their effect plus any interaction between them by using the first eight tests. If we have eight variables to investigate, we will use letters A through H and tests one through sixteen. Again, we will be able to measure the

effect of each variable as well as the effect of different interaction groups of two variables. If we have sixteen variables, we will use all tests shown in this figure to achieve the same results. It has been our experience that we seldom encountered experiments that required an evaluation of more than sixteen variables at one time, therefore, we have limited the set of experiments shown in Figure 10.

Now what about using the Latin or Graeco-Latin square type experiments. If you stop to think for a second, you will realize that the Latin and Graeco-Latin squares, which are merely special cases of a fractional factorial, would not serve our purpose. As we increase the number of variables, we also increase the number of levels of each variable, thereby, showing a rapid increase in the total number of tests required to measure the effects under investigation. Furthermore, as we increase the number of levels, we encounter problems in trying to obtain these levels for each variable. It would be possible to design fractional factorial experiments in which we can measure the effect of seven variables in eight tests, fifteen variables in sixteen tests, thirty-one variables in thirty-two tests and so forth. However, by doing this we would only be able to measure the effect of the variable acting by itself (assuming all interactions are nonexistent). We would lose all information on interactions. As interactions can be important in many of our engineering applications, it is felt that it is best not to run the risk of having a significant interaction escape our detection.

With the above background in mind, we designed a series of fractiona factorial experiments, where each variable is used at two levels, enabling the engineer to determine which main effect and which of several interaction groups are significant. The table in Figure 11 contains the best combination of experiments for any given number of variables (up to sixteen). Through the use of experiments contained in this table, the engineer can obtain the maximum amount of information with a minimum amount of testing. He will be able to detect any main effects that are significant. If he should find any interaction group significant, he can either determine why only one interaction in that group could logically be significant or perform additional tests using this first experiment as part of a larger experiment to pick out which interaction in the group was significant.

The column labeled Interaction Group in Figure 11 is used as follows: The engineer selects the underlined interaction for analysis. If this interaction is not significant, this means the remaining interactions in the bracket are also nonsignificant because they are confounded with each other and with the underlined interaction. However, should this interaction be significant, then the engineer must ask the following question, which one of those interactions is really significant? As they are all confounded with each other, we

rely upon the use of engineering judgment as well as statistical evidence at hand. How is this done? Let us assume that interaction AB was found significant in the sixteen variable experiment. The engineer may have reason to believe that interaction CD, EF, and GH are not possible. Therefore, this would leave us with interaction AB, JK, and LM to evaluate. By seeing what tests have been previously run on this interaction, he would then know what additional tests must be run to obtain a measure of their effect. Another factor to consider in the analysis is that an interaction can be statistically significant but have no engineering significance. This occurs when the points of an interaction fall outside the statistical limits but are still inside the over-all tolerance limits. When this happens, we need not worry about the significance of the interaction.

In order to determine the significance of the main and interaction effects, it is necessary to repeat some tests. The column labeled Repeat Tests tells which tests should be re-run to obtain this measure of experimental error. Thus, if we are running an experiment with sixteen variables, we would want to repeat eight of the thirty-two tests. These eight tests should be re-run at random times during the course of our experiment. The difference between readings on these repeated tests is our measure of the experimental error and is used to determine the significance of our effects.

The advantages of using the Master Experimental Design are obvious. (1) We get a maximum amount of information for our experimental dollar; (2) we know the extent of confounding in our experiment before the experiment is run; (3) if we need to pick out responses that may be non-linear, we can always use our fractional factorial as the basis for further investigation using response surface techniques. The analysis of any fractional factorial experiment is straightforward, furthermore, the analysis of a fractional factorial experiment will easily yield a regression equation relating the change in output to the change in the input variable.

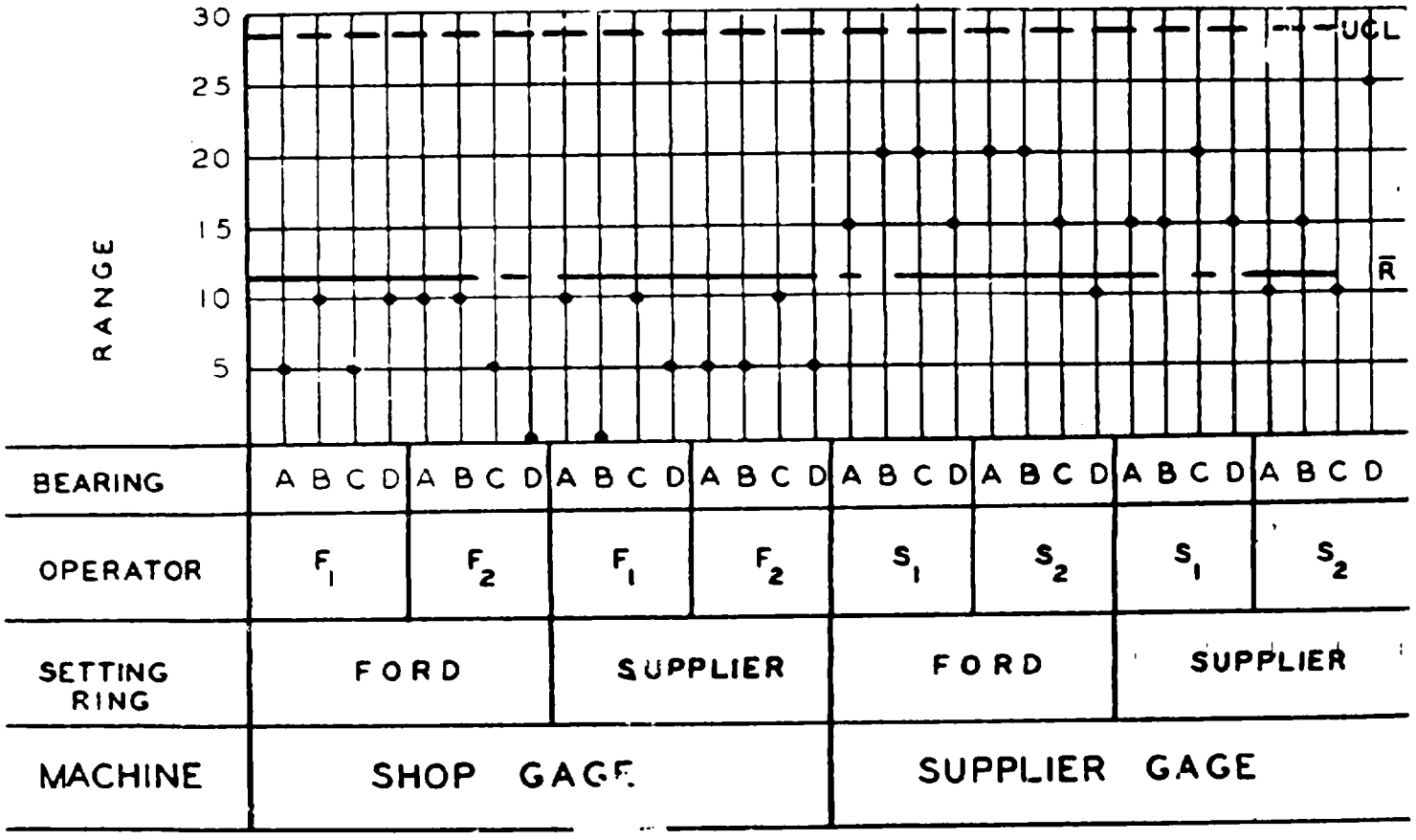
Summary

What we have shown is not impossible, takes little if any extra effort, and is being used by many of your competitors. Let's get the most missile per dollar by working smarter, not harder.

MACHINE		SHOP GAGE A				SUPPLIER GAGE B			
SETTING RING		FORD		SUPPLIER		FORD		SUPPLIER	
OPERATOR		F_1	F_2	F_1	F_2	S_1	S_2	S_1	S_2
BEARING	A	5	0	10	10	30	20	20	20
		0	10	0	5	15	40	35	30
	B	50	50	50	60	70	60	60	60
		40	60	50	65	50	80	75	45
	C	100	95	100	100	115	110	95	115
		95	100	110	90	95	95	115	110
	D	150	145	155	155	165	155	165	155
		140	145	160	150	180	165	150	180

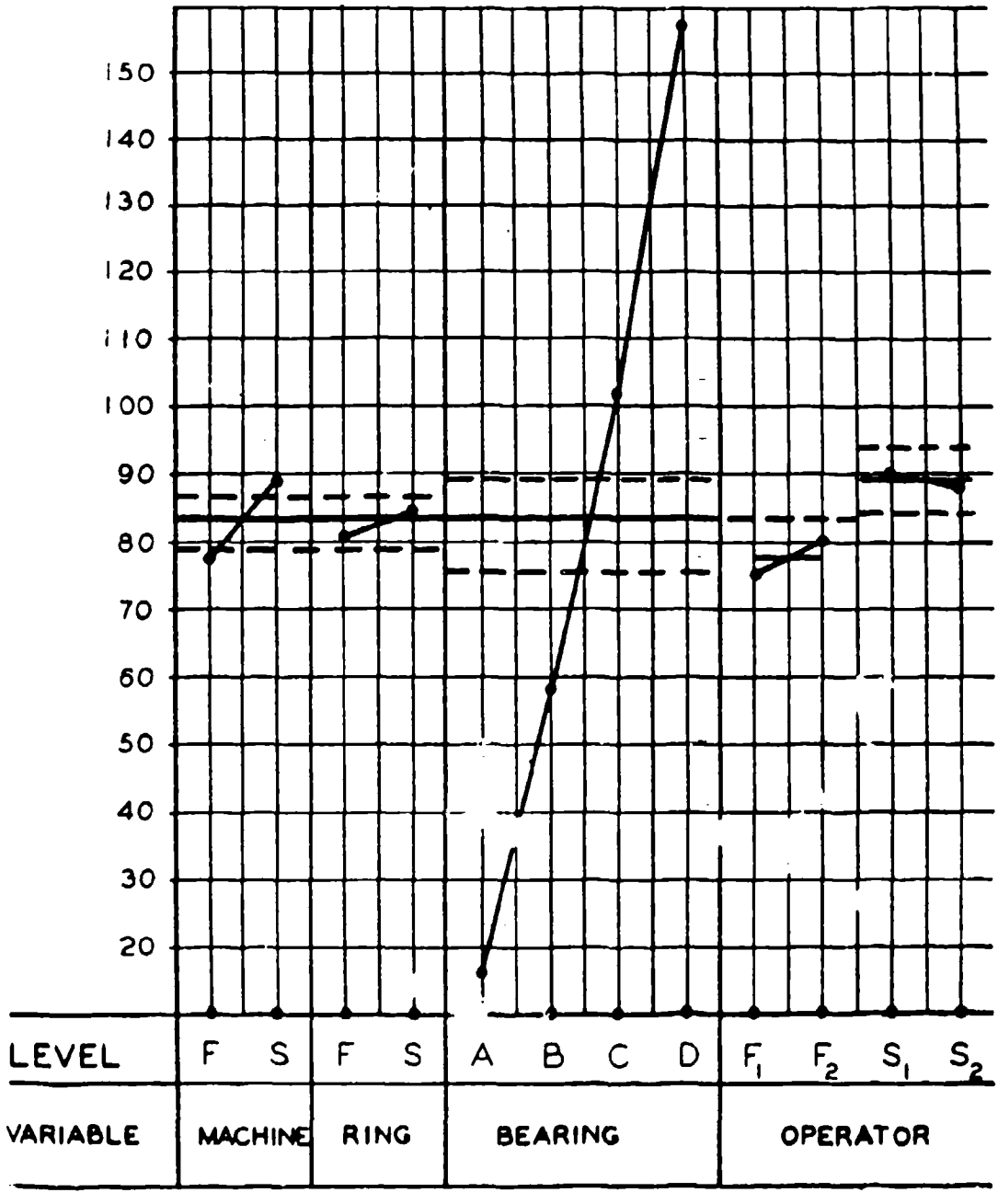
BEARING INSIDE DIAMETER MEASUREMENTS (CODED).

FIG. 1



CONTROL CHART FOR RANGES

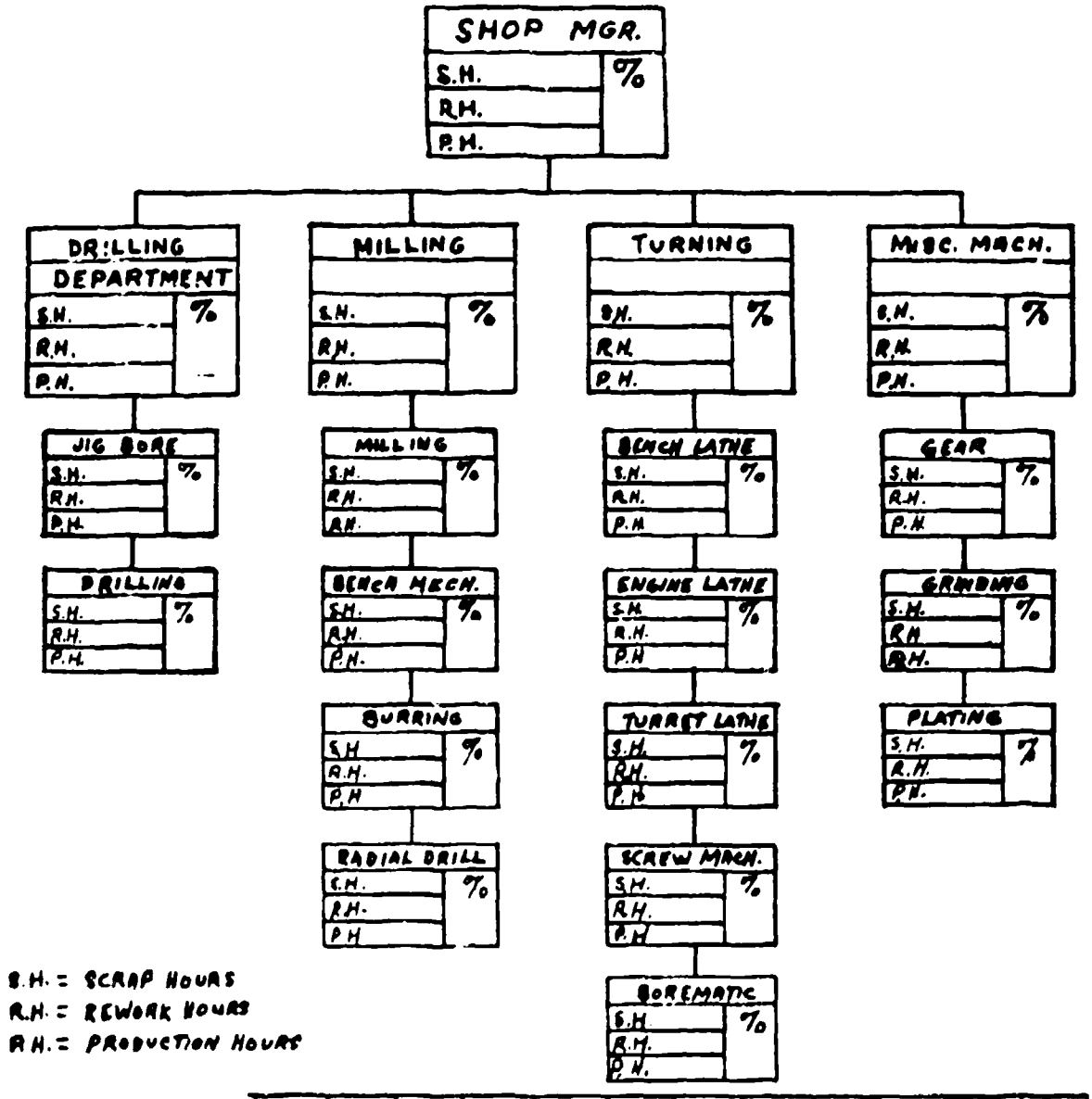
FIG 2



CONTROL CHART FOR MAIN EFFECTS

FIG. 3

MANUFACTURING QUALITY LEVEL REPORT



QUALITY LEVEL (%)

FIG. 4

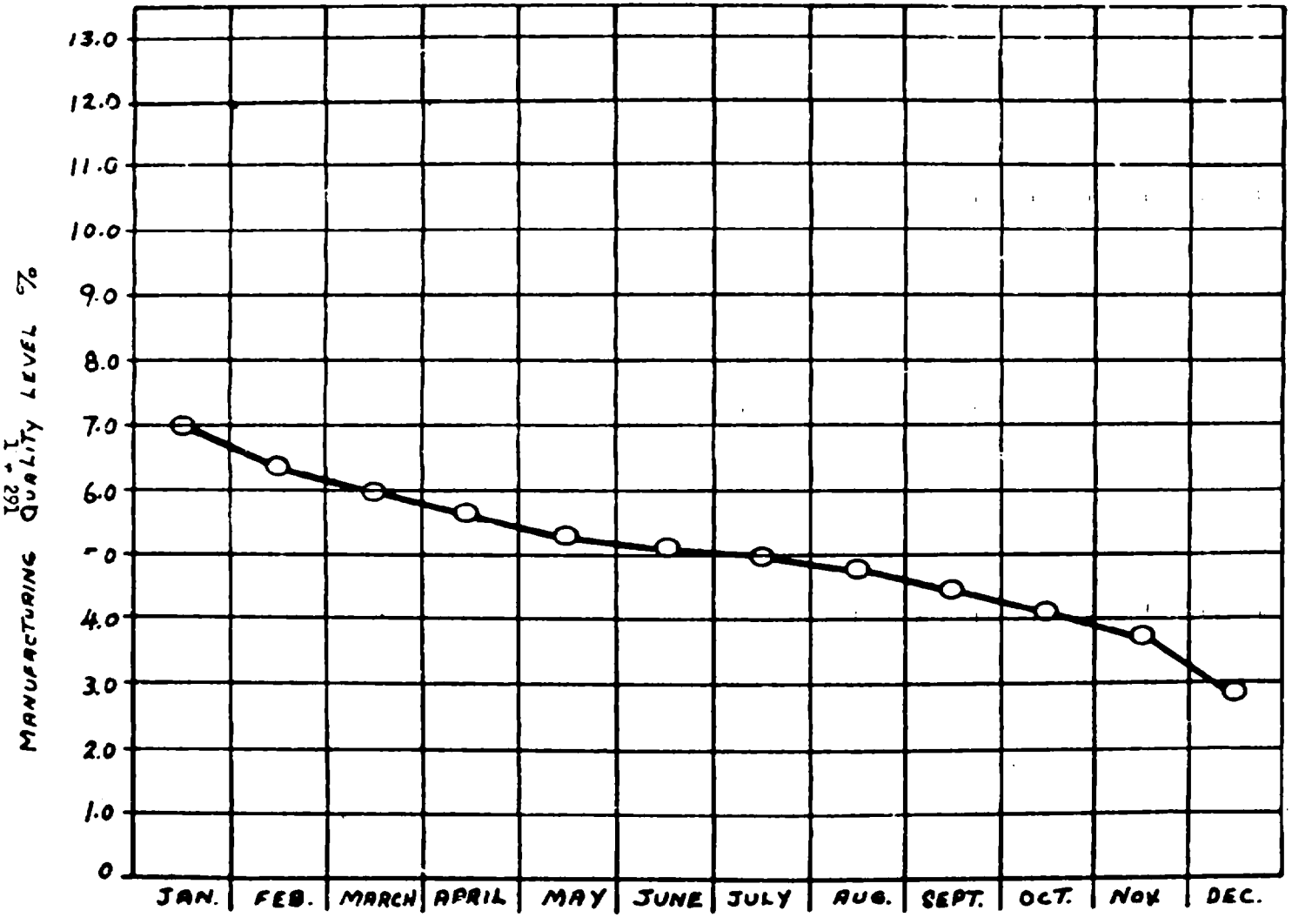

MANUFACTURING QUALITY LEVEL %
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
JAN.
FEB.
MARCH
APRIL
MAY
JUNE
JULY
AUG.
SEPT.
OCT.
NOV
DEC.

FIG. 5

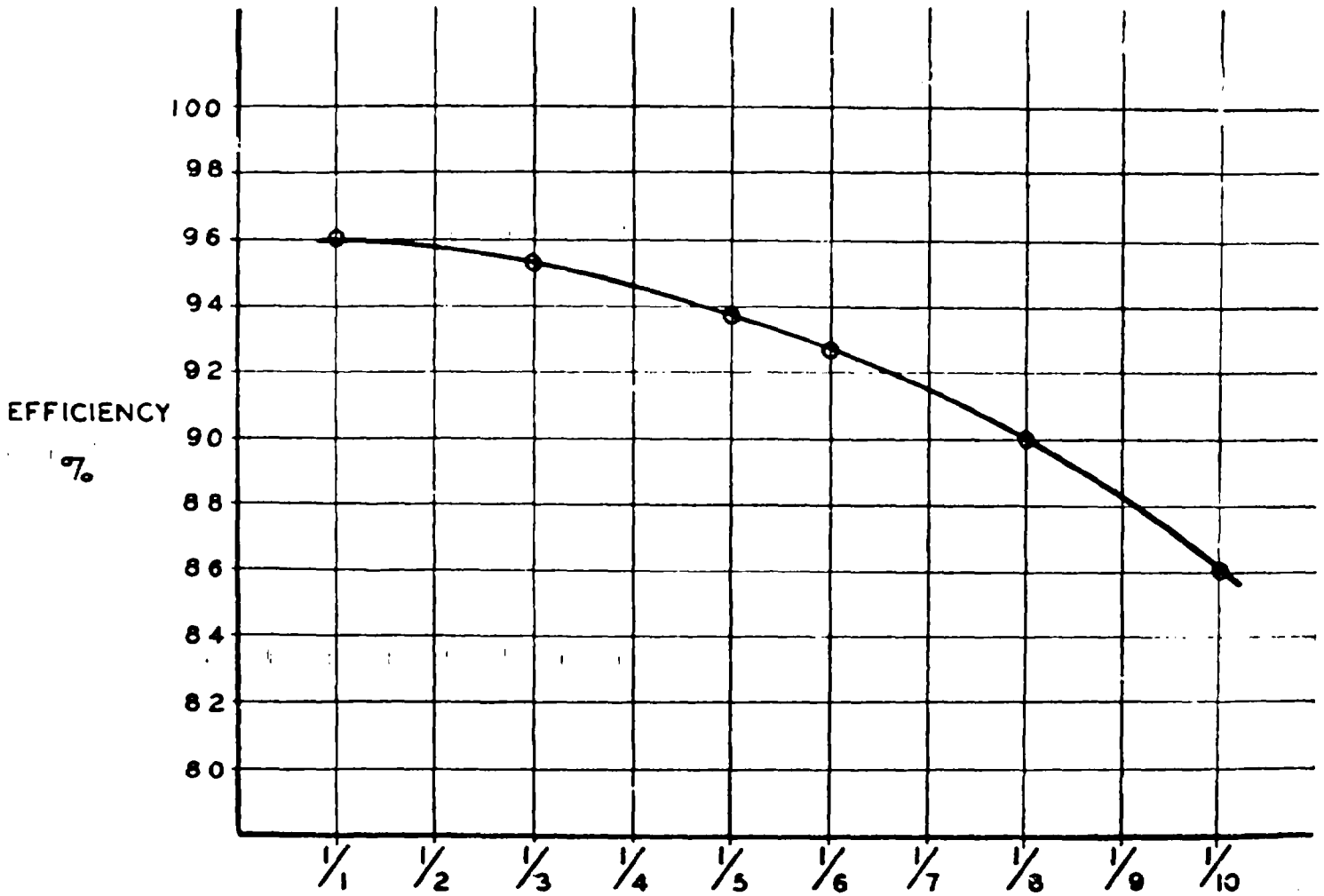

EFFICIENCY
%
100
98
96
94
92
90
88
86
84
82
80
1/1
1/2
1/3
1/4
1/5
1/6
1/7
1/8
1/9
1/10
RATIO OF INSPECTORS (TESTERS) TO SHOP (ASSEMBLY) PERSONNEL.

FIG. 6

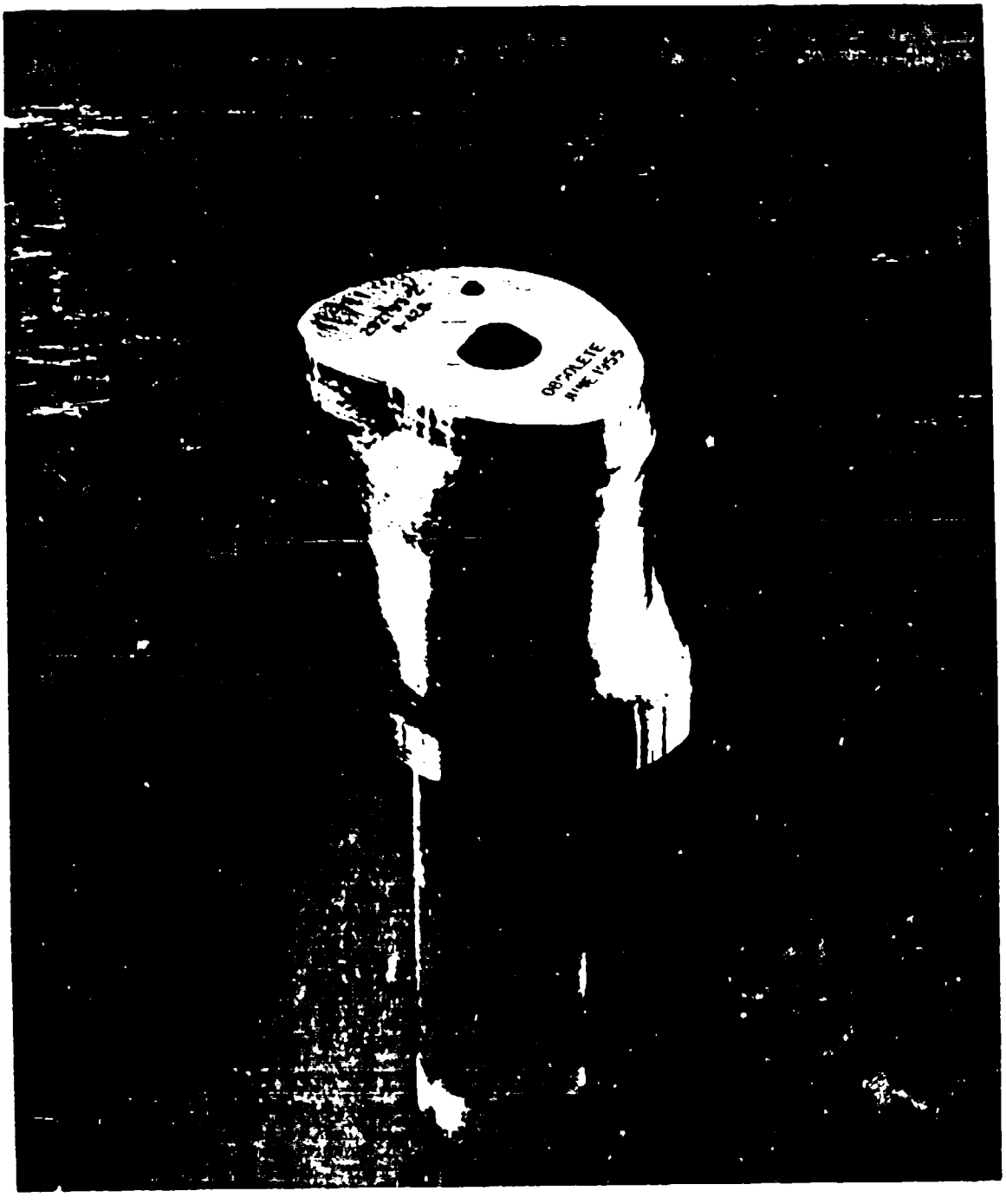


FIG. 7

CAM ERROR CHART

LONGITUDE EAST \ LATITUDE	70°N	65°N	60°N	55°N	50°N	45°N	40°N	35°N	30°N	25°N	20°N	15°N	10°N	5°N	0°	5°S	10°S	15°S
0°	0	+1	+1	+2	0	0	+1	+1	0	+1	+2	+5	+3	+3	+1	0	-1	-1
4°	+1	+3	+5	+4	+1	0	+1	-1	+1	+3	+4	+7	+5	+2	+1	+1	0	-1
8°	+1	+4	+8	+4	0	+1	+1	-1	0	+1	+1	+4	+2	+1	+1	-1	0	+1
12°	0	+3	+6	+4	+1	+1	0	-1	-1	0	+1	+2	+1	+1	0	-1	-1	-1
16°	0	+1	+4	+2	0	0	-1	0	-1	-1	0	+1	0	-1	-1	-3	-2	-2
20°	-1	0	+1	0	+1	-1	-3	-3	-2	-3	-1	0	-1	-2	-3	-4	-3	-3
24°	-1	+1	0	+1	0	-2	-5	-7	-6	-5	-3	-1	-1	-2	-4	-6	-5	-3
28°	0	-1	+1	0	-1	-4	-7	-8	-7	-5	-2	-1	-1	-1	-1	-2	-3	-2
32°	0	+1	+1	+1	-1	-2	-4	-7	-5	-4	-2	0	+1	0	-1	-1	-1	-1
36°	+1	+1	+3	+1	0	-1	-2	-5	-2	-1	0	+1	+2	+1	0	-1	0	0
40°	0	+1	+2	+1	+1	-1	-1	-2	0	+1	+2	+5	+4	+2	+1	0	-1	+1
44°	-1	0	+1	+1	+1	+1	+1	0	+1	+2	+4	+6	+5	+4	+2	+1	0	+1

AVERAGE DEVIATION FROM NOMINAL
IN TEN THOUSANDTHS OF AN INCH
(ALL POINTS HAVE APPROX. SAME SPREAD)

FIG. 8

QUALITY CONTROL DIVISION
FORD INSTRUMENT COMPANY
DIV. of SPERRY RAND CORP.

CAM SAMPLING PLAN

INSPECTOR: _____
DATE: _____

DWG. #_____ JOB #_____ PIECE _____ MACH. #_____

	SHIFT.	DEGREE OF ROTATION	CUTTER ADJUSTMENT	SPEED OF ROTATION
LAST CAM				
THIS CAM				

LATITUDE	LONGITUDE	DIAL READ.	SPREAD
60°N	8°E		
60°N	164°E		
55°N	96°E		
50°N	128°E		
45°N	160°E		
45°N	160°W		
40°N	114°W		
40°N	70°W		
35°N	28°E		
35°N	68°E		
30°N	112°E		
25°N	176°W		
20°N	120°W		
15°N	4°E		
15°N	44°E		
10°N	96°E		
0°	168°W		
0°	100°W		

LATITUDE	LONGITUDE	DIAL READ	SPREAD
5° S	24°E		
5° S	132°E		
10° S	172°W		
10° S	116°W		
20° S	64°W		
25° S	4°W		
30° S	40°E		
30° S	92°E		
35° S	132°E		
35° S	176°W		
35° S	104°W		
40° S	44°W		
50° S	4°E		
50° S	52°E		
55° S	100°E		
60° S	148°E		
60° S	144°W		
65° S	68°W		

Operating Procedure for Cam Checking

After zeroing the cam at its specified latitude and longitude readings, the perpendicular distance from the center line to the surface of the cam is observed on the indicator affixed to the plunger.

Acceptance Criteria

After the specified points have been inspected, the cam may be accepted if the following conditions are met:

1. All points must be within tolerance.
2. The difference between the highest and lowest spread must be within two thousandths of an inch.

FIG. 9

PREPARED BY: STAT SERVICES SECTION

TEST NO.	VARIABLE															
	A	B	C	D	E	F	G	H	J	K	L	M	N	O	P	Q
1	−	−	−	−	+	+	+	+	−	−	−	−	+	+	+	+
2	−	−	+	+	−	−	+	+	−	−	+	+	−	−	+	+
3	+	+	−	−	−	−	+	+	−	−	+	+	+	+	−	−
4	+	+	+	+	+	+	+	+	−	−	−	−	−	−	−	−
5	−	+	−	+	+	−	+	−	−	+	−	+	+	−	+	−
6	−	+	+	−	−	+	+	−	−	+	+	−	−	+	+	−
7	+	−	−	+	−	+	+	−	−	+	+	−	+	−	−	+
8	+	−	+	−	+	−	+	−	−	+	−	+	−	+	−	+
9	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
10	−	−	+	+	+	+	−	−	−	−	+	+	+	+	−	−
11	+	+	−	−	+	+	−	−	−	−	+	+	−	−	+	+
12	+	+	+	+	−	−	−	−	−	−	−	−	+	+	+	+
13	−	+	−	+	−	+	−	+	−	+	−	+	−	+	−	+
14	−	+	+	−	+	−	−	+	−	+	+	−	+	−	−	+
15	+	−	−	+	+	−	−	+	−	+	+	−	−	+	+	−
16	+	−	+	−	−	+	−	+	−	+	−	+	+	−	+	−
17	−	+	−	+	−	+	−	+	+	−	+	−	+	−	+	−
18	−	+	+	−	−	+	+	−	+	−	−	+	+	−	−	+
19	+	−	−	+	−	+	+	−	+	−	−	+	−	+	+	−
20	+	−	+	−	+	−	+	−	+	−	+	−	+	−	+	−
21	−	−	−	−	−	−	−	−	+	+	+	+	+	+	+	+
22	−	−	+	+	−	−	+	+	+	+	−	−	+	+	−	−
23	+	+	−	−	−	−	+	+	+	+	−	−	−	−	+	+
24	+	+	+	+	+	+	+	+	+	+	−	+	+	+	+	+
25	−	+	−	+	+	−	+	−	+	−	+	−	−	+	−	+
26	−	+	+	−	+	−	−	+	+	−	−	+	−	+	+	−
27	+	−	−	+	+	−	−	+	+	−	−	+	+	−	−	+
28	+	−	+	−	−	+	−	+	+	−	+	−	−	+	−	+
29	−	−	−	−	+	+	+	+	+	+	+	+	−	−	−	−
30	−	−	+	+	+	+	−	−	+	+	−	−	−	−	+	+
31	+	+	−	−	+	+	−	−	+	+	−	−	+	+	−	−
32	+	+	+	+	−	−	−	−	+	+	+	+	−	−	−	−

MASTER EXPERIMENTAL TABLE

FIG. 10

NUMBER OF VARIABLES	NUMBER OF TESTS	NUMBER OF REPEATED TESTS	TOTAL	Interaction Groups (assuming all variables used)
2 - 4	8	4	12	AB (CD) AC (BD) AD (BC)
5 - 8	16	4	20	AB (CD, EF, GH) AC (BD, EG, FH) AD (BC, EH, FG) AE (BF, CG, DH) AF (BE, CH, DG) AG (BH, CE, DF) AH (BG, CF, DE)
9 - 16	32	8	40	AB (CD, EF, GH, JK, LM, OQ, NP) AC (BD, EG, FH, JL, KM, NQ, OP) AD (BC, EH, FG, JM, KL, NO, PQ) AE (BF, CG, DH, JN, LQ, MO, KP) AF (BE, CH, DG, KN, MQ, JP, LO) AG (BH, CE, DF, LN, JQ, MP, KO) AH (BG, CF, DE, MN, KQ, JO, LP) AJ (BK, CL, DM, EN, FP, GQ, HO) AK (BJ, CM, DL, EP, FN, GO, HQ) AL (BM, CJ, DK, EQ, FO, GN, HP) AM (BL, CK, DJ, EO, FQ, GP, HN) AN (EJ, FK, HM, BP, CQ, DO, GL) AO (EM, FL, HJ, BQ, CP, DN, GK) AP (EK, FJ, HL, BN, CO, DQ, GM) AQ (EL, FM, HK, BO, CN, DP, GJ)

FIG. 11

ONE HUNDRED PERCENT PRODUCTION TESTING OF CRITICAL COMPONENTS

ARTHUR E. WOOD, JR.
LEACH CORPORATION
LEACH RELAY DIVISION

THE REQUIREMENT:

The electrical systems of air-borne vehicles have always required components of high performance and high reliability, capable of withstanding the environments of flight.

The present day missile, which subjects its components to environments considered impossibly severe a few years ago, and its demand for the highest possible degree of reliability requires that steps be taken to further improve both performance and reliability.

THE SOLUTION:

A positive step toward these ends is the performance of environmental testing on a production basis.

The fact that extremes of environment exist in missile applications is well known. Components may be exposed to high or low temperatures, vibration shock, acceleration and vacuum in addition to the deteriorating effects of humidity, dust, or corrosive atmosphere.

NORMAL PROCEDURE:

In most instances in component manufacture, performance characteristics and environmental capabilities are considered during design stages and are subject to study and proof testing prior to the start of production.

Initial production is then subjected to a program of formal qualification testing to the requirements of one or more applicable performance or environmental specifications. The results of these tests are compiled in the form of certified reports which are available for the customers' use in evaluating capabilities or for obtaining use approval from the military.

At this point, normal quality control procedures are applied to production of the device with acceptance and periodic destructive testing included.

CRITICAL COMPONENTS:

Through environmental testing of 100% of relays destined for use in critical circuits, it is possible to provide a far greater assurance of performance than can be obtained through normal quality control procedures

and do much to enhance the reliability of a complex system exposed to extremes of environment.

THE TESTS:

Depending upon conditions of application, the extent of the test program applied varies with different relays and customer requirements.

One production test program includes the measurement of relay operate values, dielectric strength and insulation resistance, coil resistance, and contact resistance under load while subject, in turn, to high temperature (+ 85 °C), low temperature (-55 °C), vibration (10G to 2000 CPS), and sustained acceleration (15G).

Any relays exhibiting variations in characteristics outside narrow limits are rejected.

In addition, each relay is required to withstand a specified value of shock without contact disturbance and to demonstrate integrity of hermetic seal at the conclusion of environmental exposure.

Another type of testing involves energizing and de-energizing the relay for several thousand operations while monitoring contacts for proper functioning during each individual operation. Relays displaying a single instance of excessive contact resistance are rejected.

It has been found that the small quantity of relays disposed toward contact discontinuity generally exhibits the tendency within the first 2,000 operations and it is possible to eliminate such units by monitored cycling. It has also been found that relays of the "contaminant-free" type (capable of meeting the "Minimum Current" requirements of MIL-R-6106C) display about 1/20 the miss rate of relays of conventional construction.

Other test programs include portions or combinations of the aforementioned evaluations. For example, vibration plus operational tests are performed on a number of relay types.

EXPERIENCE:

In the course of testing over approximately a three-year period, a wide range of failure rates have been experienced. Certain relay types have displayed zero failure rates.

In other cases, relays which were tested close to their ultimate capabilities have displayed temporary rates in excess of 50% when some characteristic was not adequately controlled. Such an occurrence of course signals the need for immediate remedial action.

In general, rejection rates of the order of a per cent are experienced. (Figure 4)

THEORY:

Production environmental testing is merely an extension of normal acceptance testing procedures in which characteristics are measured under room conditions.

The concept has basis in the generally accepted relationship of failure rates of manufactured devices to time or cycles of use. The form of a plot of this relationship is a "U" with higher failure rates existing in the initial period of life, then dropping to a lower constant value until the point of wear-out is reached, at which time the curve of failure rate again rises sharply. (Figure 1)

Production testing serves to eliminate those units which would cause the initial levels of failure.

Verification of the shape of this life curve has been obtained through testing of over 25,000 relays.

WHAT THE PROGRAM OFFERS:

In addition to the obvious advantage of providing relays which have already demonstrated their capabilities in the extremes of environment of their intended application, a program of this type can also offer other contributions to overall component reliability.

In the normal production and sale of relays, there is almost no feedback of specific reliability (or unreliability) information relating to performance in actual application. Because of this, evaluation of relay designs and their extension by improvement and modification into new designs (the advancement of the state of the art) must be based upon the testing performed on a relatively small number of units during development and qualification. Because of the small quantity of data which such testing generates and because defects of low probability of occurrence may not even be demonstrated, a program of environmental testing of production quantities of units offers a source of information on performance which can be of great value to the designer and, through product improvement, to the user.

Failures which occur in the course of production environmental testing are analyzed and causes reported to the engineering department. In the experience of Leach, a number of very subtle design changes resulting in improved product reliability have been suggested by data accumulated during production testing.

In addition, data is provided for control of process as the searching evaluation of environmental testing gives immediate indication of the existence of defect producing situations.

A LIMITATION:

If satisfactory levels of reliability are to be achieved in the application of any component, it is absolutely necessary that the conditions of environment to which the component is to be subjected are properly specified. No amount of testing in one level of environment will insure reliability if actual environments differ and are in excess of component rating.

An example of such a situation is to be found in a recent missile failure. A relay which had been produced and tested (by the user) to meet exacting standards was subjected in the application environment to shock accelerations of two and one half times the specified relay capability. In this situation, contact disturbance resulted in destruction of the missile. The means of prevention of this failure lay not in component test but in correct evaluation of environment, prior to, rather than after the occurrence.

NOT A LIMITATION:

The fear that production testing may "wear out" a device is not valid, if designs are adequate to the rating and if the warning signals of high failure rates are observed. Proper evaluation of failure data can, in fact, show such things as inadequacy of design, premature wear out, or lack of control in process.

SUMMARY:

Production environmental testing offers a means of producing components of proven environmental capabilities. In addition, the information collected in such testing can be of great value to both designer and those responsible for quality control. The total result is significant increase in the reliability of the device which is so tested.

FIGURE 1 TYPICAL LIFE CURVE

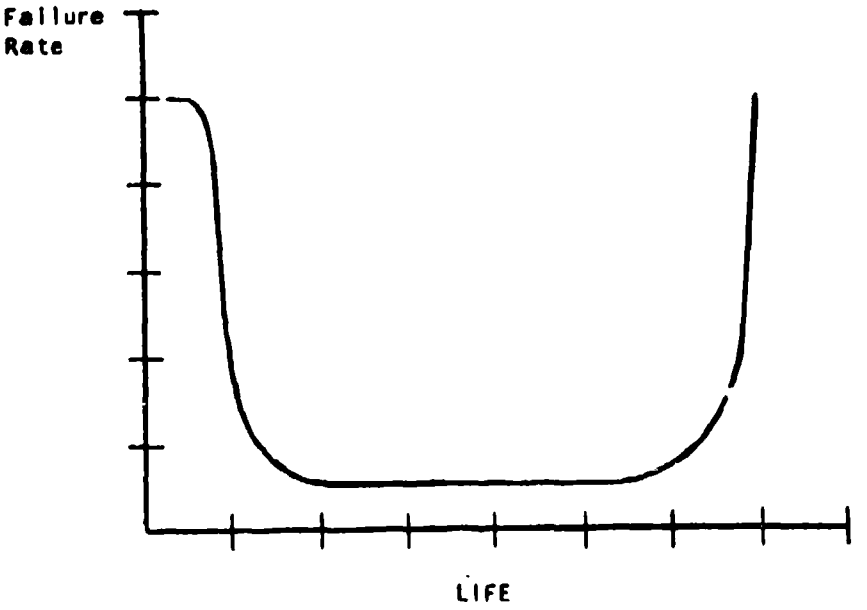
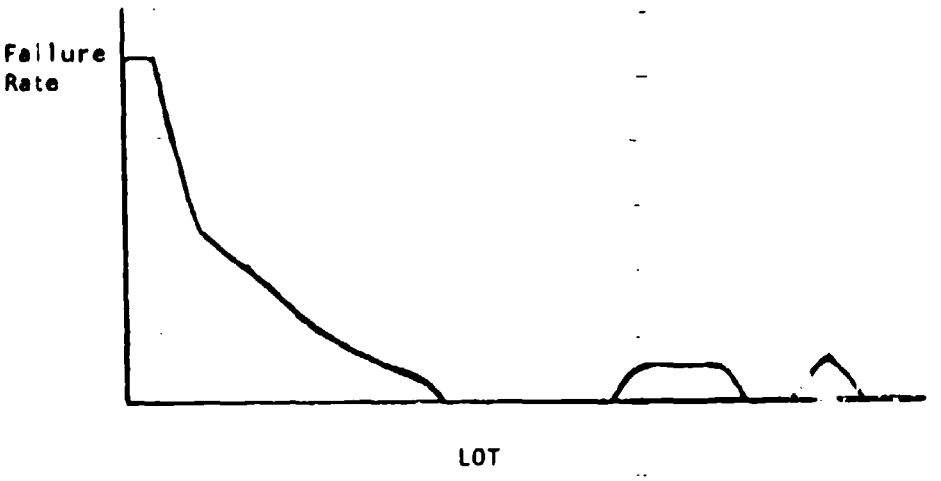


FIGURE 2 TYPICAL FAILURE EXPERIENCE ON SUCCESSIVE LOTS



THE VALUE OF P.E.T. AS A QUALITY CONTROL FUNCTION

By

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Production Environmental Testing is far from a new idea; for example, it wasn't many years ago that before a customer would plunk out cash for a new flivver he would insist upon being allowed to drive the car over the roughest road and up the steepest hill in town. Sometimes he would insist upon taking the car to a neighboring village whose favorite automobile test ground boasted a steeper hill or a rougher road. This Production Environmental Test the dealer rightfully feared, since he knew that if the tin lizzie rattled too much on the washboard road or refused to climb the hill in high gear, the customer would take his cash elsewhere.

In those golden days of the Model T, many cars wouldn't even make the hill in low gear and it was necessary to turn around and back up to make the top. Also, whoever heard of a Model T that didn't rattle right along. Thus, anybody who did not perform such a Production Environmental Test was considered an idiot by his friends and a sucker by the dealer. However, nowadays that the Automobile Designs and Production Techniques have been almost completely "debugged", the need to see if an automobile can charge up a hill prior to its procurement is unnecessary.

GENERAL DESCRIPTION OF THE P.E.T. PROGRAM

In the field of Missile Technology pertaining to component design and fabrication, sufficient fully developed and debugged components to completely outfit a missile are not available "off the shelf". For this reason, a Production Environmental Test Program was instituted by The Martin Company.

The Martin Company's Production Environmental Test (P.E.T.) Program, which is operated by an Engineering Group within Quality Control, consists of a 100% inspection, including functional and environmental tests, of the total production of a selected group of components. The primary purpose of The Martin Company's P.E.T. Program is to monitor Quality Control and Manufacturing Control of the component manufacturer.

Significantly, in running the P.E.T. Program, it has been found that design deficiencies become self evident. Information concerning these deficiencies may be sent to the Vendor immediately and, therefore,

design improvement does not need await the results of Field Tests. This ability of P.E.T. to detect design deficiencies, although it has not been considered the basic purpose of the Program, has wrought many useful design changes.

The components considered for inclusion in the P.E.T. Program were those which are considered to be of prime importance in terms of the success of the mission of the missile.

The criteria used for this selection of items and tests to be performed is:

1. Items selected must have potential modes of failure which could result in a serious loss of objective in the Flight Test Program.

2. There must be insufficient confidence that normal techniques such as in line inspection and bench testing can eliminate failures in these modes.

3. The P.E.T. test for the unit must significantly increase the probability of detection of deficiencies in the unit.

4. Previous test history on any item does not already give sufficient confidence that the item is adequately developed and the Production processes are under good control.

In the application of the above ground rules for the selection of the components to be included in the P.E.T. Program, Engineering judgment was exercised. For example, it is difficult to say exactly which component can or cannot by itself cause a catastrophic missile failure, if it fails to operate properly. This is particularly true in the gray area wherein a component operates out of specification by only a slight margin. The results of the selection, made according to these ground rules, is shown in Table I.

TABLE I

List of Components Presently Included in the P.E.T. Program

Quantity	Component Type
1	Position Gyro - Programmer Package
1	3-Axis Rate Gyro Package
2	Magnetic Amplifier Autopilot Package
1	Servo Magnetic Amplifier Package
4	Zener Diode Program Timer Package
3	Hydraulic Servo Actuators
1	Liquid Level Sensor
8	Relay Panel Assemblies

Quantity	Component Type
10	Telemetering Signal Conditioners
1	Telemetering Package
1	Command Control Receiver
3	End Instrument Power Supplies
2	Inverters (28 VDC to 115 V 400^{n}3P)
1	Plunger Switch
2	Relays
1	Hi-Press Relief Valve
1	3-Way Electrically Operated Pneumatic Valve
1	Power Supply
1	Rotary Frequency Converter
1	Hydraulic Regulating Unit
4	Tank Vent & Relief Valves
6	Tank Pressure Regulators
7	Pneumatic & Hydraulic Quick Disconnects
4	Fuel & Lox Shut-Off Valves
1	Trim Potentiometer Package
68	Total number of components in the present P.E.T. Program.

Percentage of Components In P.E.T. Program by General Categories

37% Mechanical

28% Electro-Mechanical

35% Electrical/Electronic

The type of components included in the three general categories listed above are as follows:

Mechanical

Valves, Regulators, Check Valves, Quick Disconnects

Electro-Mechanical

Hydraulic Actuators, Gyros, Relays, Switches, Inverters, Solenoid Valves

Electrical/Electronic

Autopilots, telemetering, power supplies

The only environment to which the selected components are subjected in the P.E.T. Program at present is vibration, with the exception that

cryogenic components are subject to cryogenic temperatures and vibration simultaneously. During the vibration testing, all components are functionally operated in the same manner that they are operated during missile flight.

The level of vibration used in the P.E.T. Program was obtained from basic contractual environmental test specifications. The levels of the vibration tests run in the P.E.T. Program vary from about 20% to 100% of the specification magnitude. In no cases were the specification magnitudes exceeded. Time durations of all tests were greatly reduced from specification requirements and all resonant search and dwell tests contained in the basic specifications were eliminated.

In the present P.E.T. Program the percentage of components being tested at various percentages of design levels is shown in Table II.

TABLE II

70% of the components are tested at 100% of design level.

7% of the components are tested between 50% and 100% of design level.

23% of the components are tested below 50% of design level.

At the present time, consideration is being given to expanding the P.E.T. Program to include other environments such as temperature, altitude, etc. In examining the deleterious effect of these other environments upon components, consideration will also be given as to the synergetic effect of these environments. It is not expected that combination testing or the inclusion of other environments will be employed as part of P.E.T. in the near future, or at least not until initial investigative tests can be evaluated.

OTHER ENVIRONMENTAL TESTING AS RELATED TO P.E.T.

Prior to acceptance of a particular component for inclusion in the R and D configuration of a flight vehicle, it is subjected to Evaluation Tests by Design Engineering. The purpose of these tests is to provide limited qualification for the component so the program may be activated in a minimum time span. Hence, only those environments that would have an immediate effect upon the successful flight of an R & D flight vehicle, such as vibration, high and low temperature, etc., are included. However, all testing that is done in the Engineering Component Evaluation Program is performed at the levels specified in Environmental Test Specification provided by the customer.

Prior to the fabrication of Operational Flight Vehicles, it is required that a full scale Qualification Program is accomplished. In this

program, the component will be subjected to all applicable environments as described in the contractual environmental specification.

The time lag between the completion of the Evaluation Testing and Qualification Testing is advantageous. The necessity of changing the component characteristics, design, or manufacturing techniques as uncovered by P.E.T. and R & D missile operations can be made prior to the commencement of an expensive Qualification Program. Often there is even sufficient time for complete evaluation of the "fix" to determine whether it has accomplished its purpose.

THE PHILOSOPHY OF P.E.T.

In the production of large complex devices such as missiles, which consists of many components, it would be ideal if the development of these components could be pursued in a logical step-by-step manner. A generalized description of such a step-by-step method is as follows:

1. Definition of the requirements.
2. Production and test of breadboard models.
3. Production of a prototype, which is subjected to environmental tests.
4. Re-design of the component, as dictated by the results of the prototype tests.
5. Production of several prototypes with production tooling and production techniques.
6. Full scale qualification testing of all these prototypes produced by production methods.
7. Re-design and retest of the production prototypes, as necessary.
8. Final production.

If all the components included in a missile design had gone through this process of evolution before installation in a missile, missile failures would be few and far between. However, we cannot afford such a luxury due to the compressed production schedules dictated by the Department of Defense, nor do we advocate the use of such a procedure. For, although admittedly it is ideal, we would never get the work done.

Therefore, for the most part, missile R & D production is pursued with components whose selections were based upon Engineering evaluation of preproduction prototypes. In taking this expeditious approach, some things are bound to "slip through the crack". It is the purpose of

P.E.T. to detect workmanship and manufacturing deficiencies which cannot be detected in a program operated on a compressed time scale wherein many steps of idealized component production must be eliminated. Specifically, the manners in which a P.E.T. Program can aid production are tabulated below:

1. By constant testing in a P.E.T. Program, deficiencies in Manufacturing procedures, piece part selection, assembly procedures, and Quality Control may be detected and eradicated.

2. Production may be monitored for any sudden increase in failure rate, which can be caused by carelessness, or loss of manufacturing control, or Quality Control, in the middle of production. With a P.E.T. Program, such a condition will be immediately self-evident and appropriate action may be taken immediately. Without a P.E.T. Program, such a condition might not be detected until field tests four or five months later. The partial elimination of resulting problems of retrofitting components in widely scattered missiles, make this perhaps one of the most advantageous aspects of the P.E.T. Program.

3. A P.E.T. Program will keep vendors on their toes. It functions as a relentless check of the vendors capability to produce quality components.

4. A P.E.T. Program will act as a Quality Control screen of component production, for occasional and inadvertent errors by the manufacturer. This property of P.E.T. is only valid, however, after the component exhibits a reasonable failure rate.

A P.E.T. Program will produce many valuable secondary effects, two of which are tabulated below:

1. A P.E.T. Program can provide a means through constant testing, of "de-bugging" troubles in designs.

2. In the initial stages of the program, the components whose design is hopeless can be eliminated. These are designs which somehow passed the original evaluation tests, but somehow the vendor just cannot produce workable components in quantity.

In pursuing a program in this manner, it should be expected that initially fairly high failure rates would exist and that a few designs would have to be eliminated. This does not mean that the original Engineering judgment, as expressed in the original selection of the original group of components, was poor. In fact, we have found that in the majority of cases, this Engineering judgment was excellent. The main reason of these initial failures is that the design is new and the vendor has had little experience in producing and testing this particular component.

INITIAL RESULTS OF P.E.T.

The initial results obtained in terms of component failures for the first three months of the operation of the P.E.T. Program are shown in Figure 1. This rather high initial rate, as previously stated, was to be expected. However, as usual, a hue and cry was raised that the test was at fault. In order to answer this question, as to test validity of testing done in the P.E.T. Program, a thorough investigation was made of all test laboratories.

IMPROVEMENT IN TESTING TECHNIQUES

The investigation of the test laboratories brought about by the high initial failure rate is a very intersting sidelight of the P.E.T. Program. Although this investigation brought to light some rather deplorable conditions, it did not invalidate the testing which had been accomplished. It was found that a very large percentage of the test laboratories had little or no control over contamination and showed a lack of understanding of the basic fundamentals of vibration testing. In short, good testing practices were being flagrantly violated.

To alleviate this condition, a system of laboratory evaluation was initiated and the P.E.T. requirements were "tightened up", particularly in the area dealing with vibration fixtures, contamination, and instrumentation. Laboratories that were found unacceptable were informed of their deficiencies and instructed as to the corrective action necessary. This vendor educational program for which P.E.T. was primarily responsible, although it does not have any direct bearing upon the improvement of the components, is one of the distinct advantages that were obtained from the P.E.T. Program. Testing done today is repeatable, dependable, and provides more information than was available in the initial stages of the Program.

POOR DESIGNS "WEEDED OUT"

Examination of Figure I indicates that there was a fair percentage of components that had failure rates above 60%. The items in this category were examined critically for the cause of the high failure rate. Included in this group, were four items that were cancelled due to inadequate design, during the first four months of the program. For two of these items, five each were built, and none could pass P.E.T. even after repeated reworks; for the third item, 51 were built and only 4 were able to pass P.E.T.; for the fourth item, 82 were built and only 25 were barely able to pass P.E.T. after several reworks and retests. The failures of these items occurred during the vibration portion of the P.E.T. Program; not during the pre-test functional and hence would not have been detected without P.E.T. Units that passed P.E.T. in the last category were installed in flight vehicles but were not function-

ally connected to the missile system. Telemetering records indicated that the four flights in which they were installed, the missile would have been destroyed had they been functionally active. The other three items were of such a nature that they could not have been installed in the missile system and yet remain inactive.

The components are a good example of the condition under which P.E.T. cannot be used as a Quality Control screening process. The failure rate of these components was so great in P.E.T. that no faith was placed in those few units which were able to pass a P.E.T. test. The flight test results proved this decision correct.

GENERAL IMPROVEMENT OF COMPONENT QUALITY

A general improvement of component quality is illustrated in Figures 1 and 2. Through the end of December 1959 in the P.E.T. Program, 10843 tests have been conducted with a total of 2,133 failures, or an average failure rate of 19.5%. It is not expected that this failure rate will significantly decrease throughout the P.E.T. Program. This is due to the fact that when the production of the component has been proven under sufficient control, it will be deleted from the P.E.T. Program. Hence, the P.E.T. Program will include only components whose failure rate is significant. To date, 20 components have been deleted from the P.E.T. Program because of this reason.

In identifying the improvement in component quality, it is first necessary to categorize failures into types. Table III lists the failure types as assigned to various categories.

TABLE III

Type Failures as Assigned to Various Categories

1. Manufacturing/Quality Control

    a. Improper Assembly
    b. Poor Finishes
    c. Poor Materials
    d. Incorrect Dimensions
    e. Improper Calibration Procedures
    f. General contamination in components
    g. Burrs not removed, etc.

2. Design

    a. Design includes only items for which physical changes in design were necessary to alleviate the problem.

3. Test Error

   a. Test Error is associated with failures in which the application of too much environment caused a failure.

4. Unknown

   a. This is applicable to random failures in which failure analysis indicated possible causes of the trouble but no definite correlation could be made. Also, those failures for which no explanation could be made.

   NOTE: For all the failures included in this report, failure analysis has been conducted.

It should be stated that it is difficult to segregate all failures into the various categories as listed. For example, an excellent design can stand more Manufacturing and Quality Control flaws than can be a marginal design. However, it is felt that the failure causes as presented are reasonably accurate.

The breakdown of the total failures to date are presented in Table IV.

TABLE IV

Tabulation of Cause of Failures for all Failures to Date

Cause of Failure	Percent
Design	47.9%
Manufacturing/Quality Control	41.9%
Test Error	7.3%
Unknown	2.9%

Figure 1 is a histogram of the history of the P.E.T. Program. The percentage of the component types that exhibit various failure rates are indicated. Examination of the figure shows that at the start of the Program, only 24% of the various components being tested had a failure rate of less than 5%, whereas now 57% of the components being tested have a failure rate of less than 5%. This percentage is actually much greater due to the 20 components that have been dropped from the P.E.T. Program since they continuously exhibited failure rates in this range. As a basis of comparison, the average failure rate is also indicated.

A trend is indicated that components are real good or real bad as

shown in figures for November and December; wherein the failure rate in the 5 to 10% range is significantly lower than the 0 to 5% range and the higher failure percentiles. In addition, examination of the failure rate of individual components indicates that when a component has been improved to the point its failure rate is below 5%, this failure rate will be maintained throughout that production run.

Figure 2 shows the failure rate plotted versus the length of time the P.E.T. Program has been operating. The increase in failure rate during April and May of 1959 coincides with the introduction of new missile lots which resulted in changes in component operating requirements and the addition of some new components. Thus, this increase in failure rate should be expected.

The final average failure rate reached at the end of 1959 of about 15% is actually lower due to the 20 components dropped from the P.E.T. Program which exhibited satisfactory performance.

Figure 3 illustrates in what portion of a Production Environmental Test components failed; i.e., 1. During the pre-functional test, 2. During the Environmental portion of the test, or 3. During the post-environmental functional test. This data is presented for all the components collectively.

The cross-hatched area, which includes the Environmental Test and the Post-Environmental Functional Test portions of the P.E.T. Program, represents the failures of components that probably would not have been detected without a P.E.T. test. This amounts to about 75% of the failures that occurred throughout the P.E.T. Program.

A large portion of the failures that occurred during the vibration portion of P.E.T. were of the intermittent type. That is, when the component was functioned under vibration, it failed to function within specification limits. Yet, when the vibration was removed, the component functioned satisfactorily. Relays that chattered under vibration are a good example of this condition.

PROBLEMS IDENTIFIED AND SOLVED DURING PRODUCTION ENVIRONMENTAL TEST

Listed in Table V are the number of components and the number of failures for these components for which the cause of failure has been identified and a proven solution identified. This action is a direct result of the Production Environmental Test Program.

TABLE V

Number of Problems in Component Design or Fabrication Procedures Discovered in the Production Environmental Test Program for which Proven Solutions have been Found:

Number of Component Types	Problems Identified	
	Manufacturing/Quality Control Problems	Design Problems
Mechanical Components 19 different components represented	15	14
Electro-Mechanical Components 13 different components represented	11	10
Electrical/Electronic Components 12 different components represented	16	19

Total number of components for which failure causes have been identified and corrected--44.

Total number of failure problems identified and corrected--85.

NOTE: When one vendor manufacturers more than one component, the same Manufacturing and Quality Control problems usually occurred on all components.

QUALITY IMPROVEMENT IN GROUPS OF LIKE COMPONENTS

Figures 4 through 6 describe the failure history in the P.E.T. Program for several sets of like components manufactured by different vendors.

Figure 4 represents the failure rate of similar mechanical components manufactured by a single vendor. This vendor had serious trouble with the designs and manufacturing procedures initially. These difficulties were great enough so that in the initial stages of the program, serious consideration was given to dropping this vendor from the program.

The failure rate of these units demonstrated to the vendor the need to completely revamp his manufacturing procedures and design. In making these changes, which were numerous, the vendor was able to use the P.E.T. Program to monitor the degree of success of the changes made while simultaneously allowing production to continue.

In addition to changing manufacturing procedures, the vendor made many changes to his physical plant. Probably the most effective in decreasing failures due to manufacturing causes was the improvement in Plant Facility in the Dust Free Assembly areas.

With this group of components, the P.E.T. Program produced perhaps the most spectacular results, particularly in view of the fact P.E.T. was conducted by the vendor in his own plant. The changes made in design, manufacturing procedures, and the physical plant were of his own volition.

The results of this action have been rewarding. The failure rate has decreased from a more or less constant 60% at the start of the program to the present 20%.

Figure 5 illustrates a group of fairly complex electro-mechanical components with which considerable design difficulty has been experienced throughout the program up to October. From then on no more failures have been experienced due to design. Numerous design changes were made and the rather violent changes in the failure rate curve indicates their success or lack thereof.

The success of the Program is evidenced by the failure rate in December wherein 65 components were tested with only two failures.

Figure 6 illustrates the failure history of a group of complex mechanical components for which the P.E.T. Program has not caused any significant change in failure rate.

Throughout the P.E.T. Program for these components, there have been innumerable changes made in Manufacturing Procedures, Quality Control techniques, and design. However, it seems as fast as one problem is solved, a new and different problem appears to take its place.

Although no overall general improvement has occurred in this component throughout the P.E.T. Program, at least P.E.T. has shown and continues to show where the difficulties with these components exist.

QUALITY IMPROVEMENT OF INDIVIDUAL COMPONENTS

The effect of P.E.T. on individual components is illustrated in figures 7 and 8. These figures show the failure rate, and cause of failure plotted vs Time for two different components. These components were selected to show two different typical situations:

1. A component which had fair design but control of manufacturing and Quality Control was lost long after production was started.

2. A component with which a great deal of design troubles were encountered.

Figure 7 shows a typical component with which considerable difficulty has been experienced throughout the P.E.T. Program. Initially, failures were due to design. This is to be expected with any new design. The design was reworked and only a few failures occurred afterwards which could be attributed to design deficiency. However, the next group of failures occurred with seemingly suddenness, i.e., no failures which were attributed to improper assembly techniques occurred until the material problem was resolved and no Manufacturing/Quality Control problems appeared until after the assembly problem was resolved.

Admittedly, it is possible that the initial failures masked the succeeding failures. However, this seems unlikely due to the nature of the various categories of failures. What seems most likely is that this vendor experienced a complete loss of Quality Control after eight months of production.

THE ABILITY TO DETECT A SUDDEN DECREASE IN COMPONENT QUALITY IN THE MIDDLE OF A PRODUCTION RUN IS PERHAPS ONE OF THE BIGGEST ADVANTAGES OF P.E.T.

Referring to the figures for December 1959 in which the greatest number of components per month were tested and the lowest failure rate experienced with this component occurred, it would seem that the manufacturing deficiencies with this component were slowly being resolved.

Figure 8 illustrates how P.E.T. aided the "DEBUGGING" of a design and simultaneously allow production to proceed. For this component, the design apparently is "out of the woods" as evidenced by the complete lack of design failures in November and December, and for December only one failure occurred out of 39 tests conducted which was due to test error. If this low failure rate continues, this component soon will be dropped from the P.E.T. Program. The dip in the failure rate curve in March cannot be explained.

DOES P.E.T. WEAR A COMPONENT OUT?

The argument most often lashed against P.E.T. is, "You are wearing the component out with P.E.T." "How do you expect a missile to fly with worn out components?"

Admittedly, this argument has some merit. Most certainly it is highly undesirable to fly a missile with worn out parts. Yet, simultaneously, it is foolhardy to assemble a missile with inferior components. It would be foolish to say that P.E.T. does not contribute to the "wearing out" process. However, when P.E.T. requirements were determined, consideration was given to prescribing a level that would not seriously

contribute to "wear out", and yet provide a useful tool for identification of problems and segregation of the usable from the non-usable components.

In vibration testing, it is difficult to specify what constitutes the complete wear out of the components. Only in cases wherein structural failure occurrs does an exact definition of "wear out" exist. In the case of non-destructive testing, the only way a comparison of the "wear out" caused by P.E.T. can be made to complete design life is if we consider a complete specification test as completely exhausting the design life of the component.

A reasonable way to make such a comparison is to compare the number of stress cycles used in a qualification test versus those in a P.E.T. test. The number of stress cycles is a function of the product of the applied acceleration and the time for which this acceleration is applied. The units of this comparison function are in "g" minutes.

The stress level imposed upon a component by a vibration test is a direct function of the "g" applied. Therefore, since the applied "g" in testing conducted in the P.E.T. Program never exceeds specification requirements, a comparison of the "g" minutes in both tests gives a good indication as to the degree of "wear out" in P.E.T.

Such a comparison has been made for all testing done in the P.E.T. Program. Results of this comparison show that the maximum amount of design life consumed by P.E.T. for any component is 4%.

Admittedly this method of comparison is not precise, but since the numbers do not turn out very low, it does give a strong indication that we should not expect "wear out" problems. Results have proven this true. We have only observed one type of component that exhibited "wear out" problems shortly after P.E.T. was completed. This component had a sub-standard bearing design which needed to be changed.

SUMMARY

A Production Environmental Test Program is very expensive. On an average, it has been found that the increase in cost of the individual component ranges from 10% to 15%. We feel that this increased cost is worthwhile. P.E.T. has demonstrated itself as a necessary augmentation to the R & D and early production phases of missile fabrication. Through the continued testing in P.E.T., we have learned a great deal about the components and their operating characteristics in a relatively short time.

We have been able to identify many modes of failure by this P.E.T. Program, and by establishing corrective action to process controls or by making design changes we have been able to eliminate these problems at an early time in the development cycle.

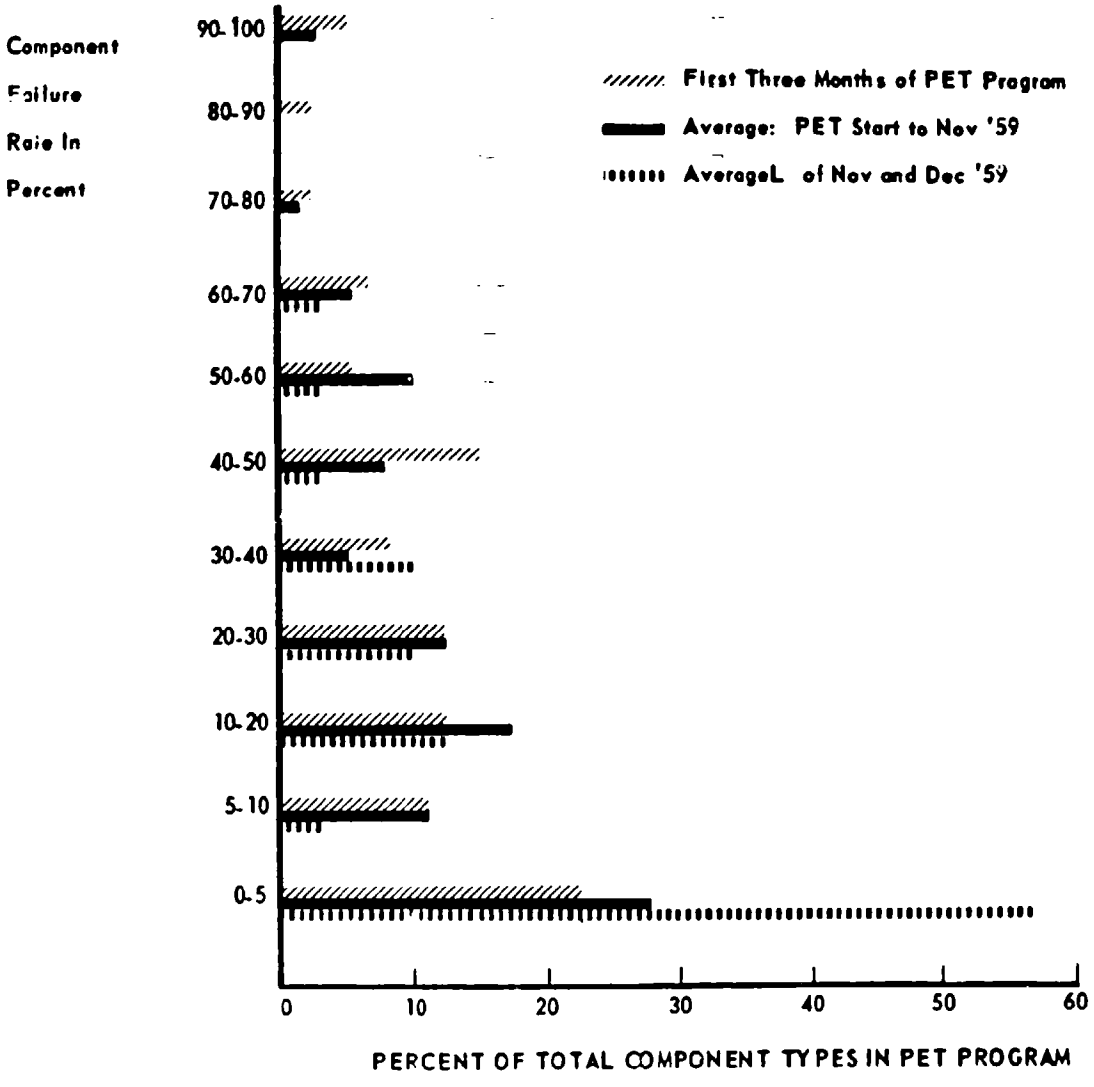


Fig. 1 Improvement in Component Performance, Nov 58 - Dec 59

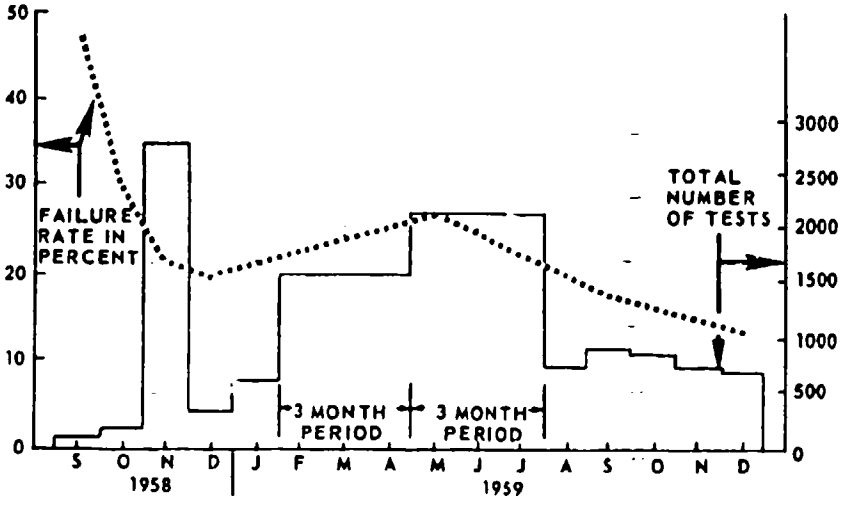


Fig. 2 Average Failure Rate and Number of Tests Run

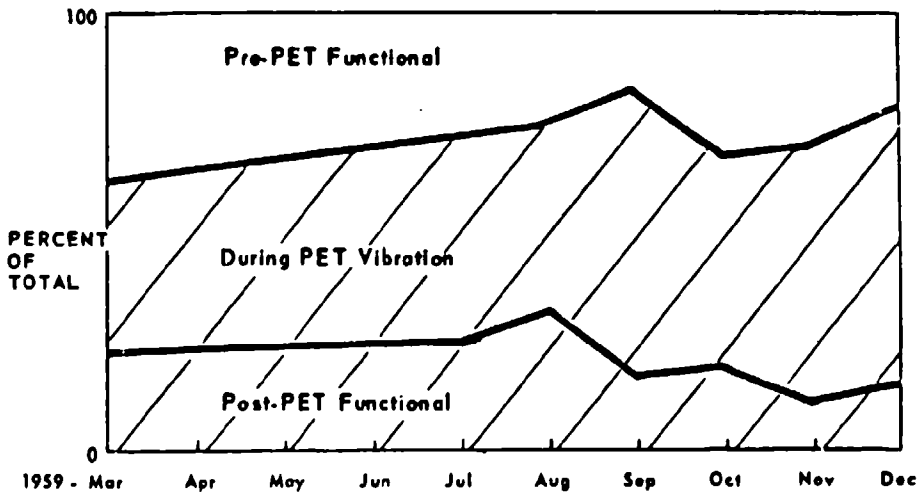


Fig. 3 Distribution of Failures During PET

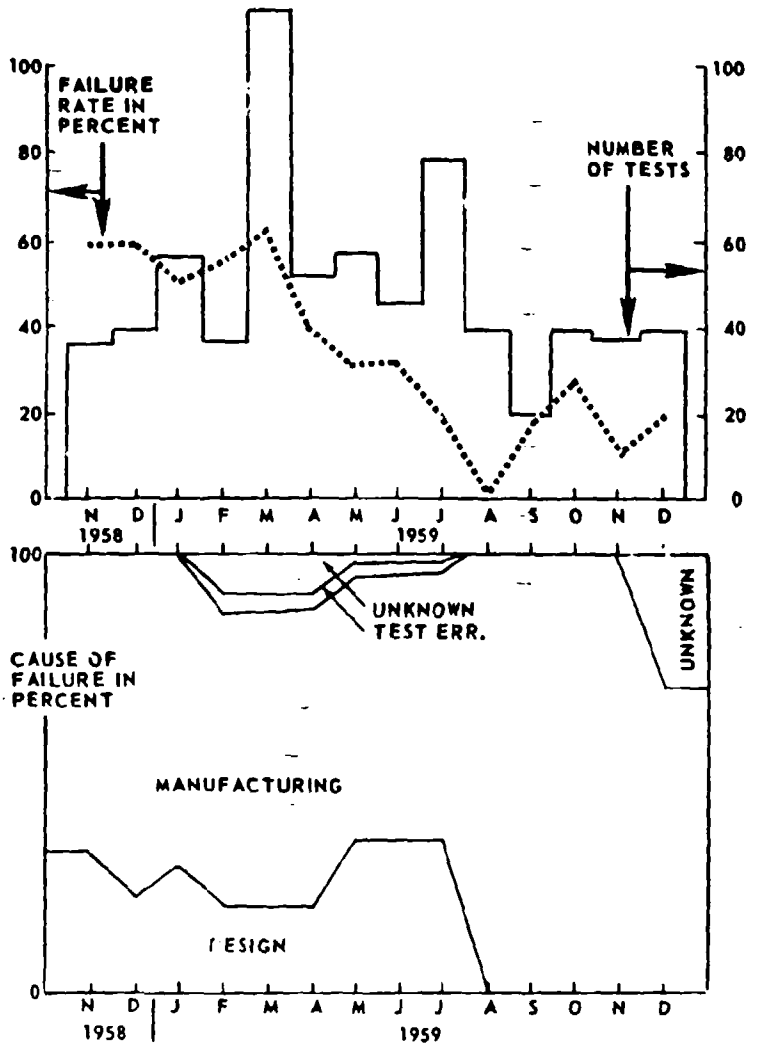


Fig. 4 Typical Mechanical Components, One Vendor

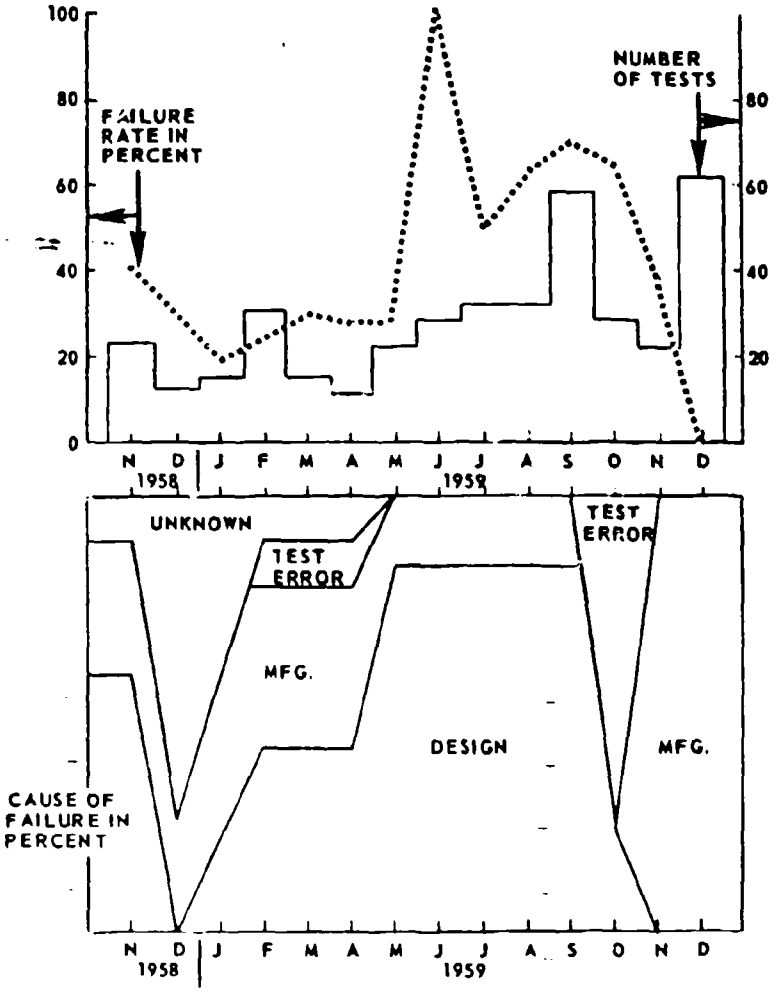


Fig. 5 Group of Electro-Mechanical Components Manufactured by One Vendor

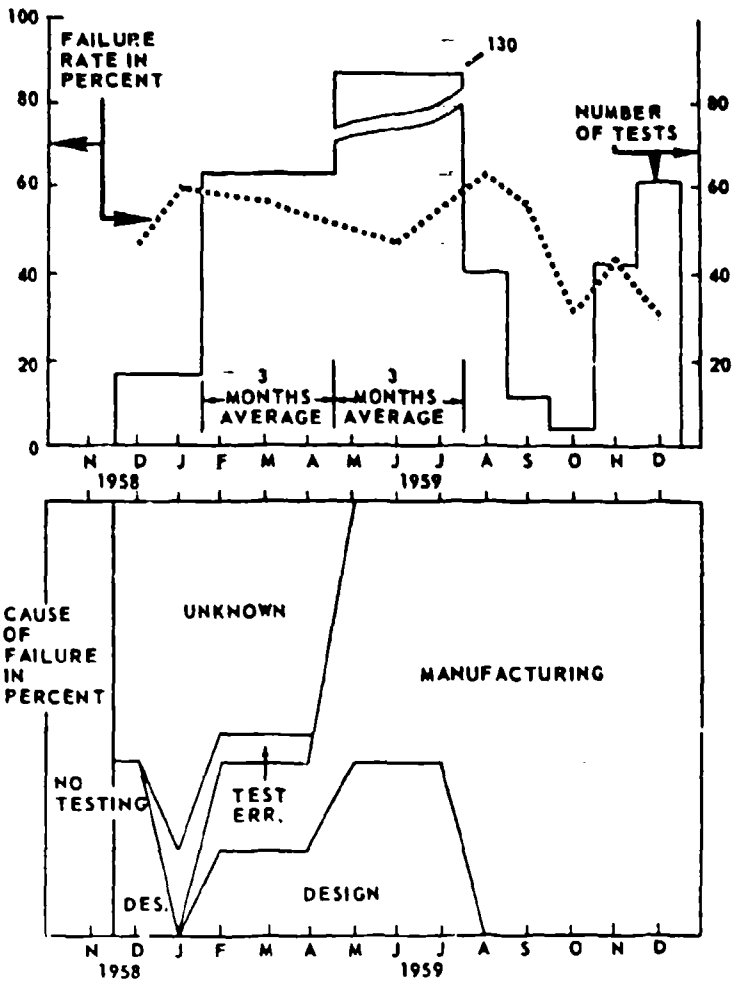


Fig. 6 Typical Mechanical Components, One Vendor

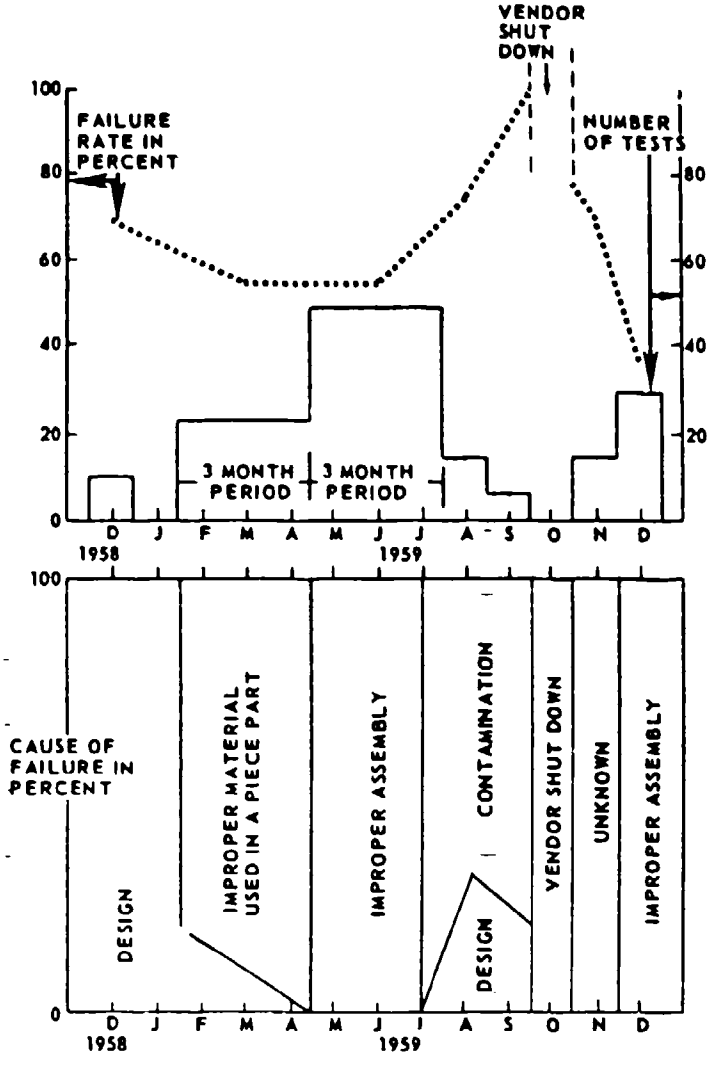


Fig. 7 Mechanical Component With Which Manufacturing and Quality Control Troubles Were Encountered.

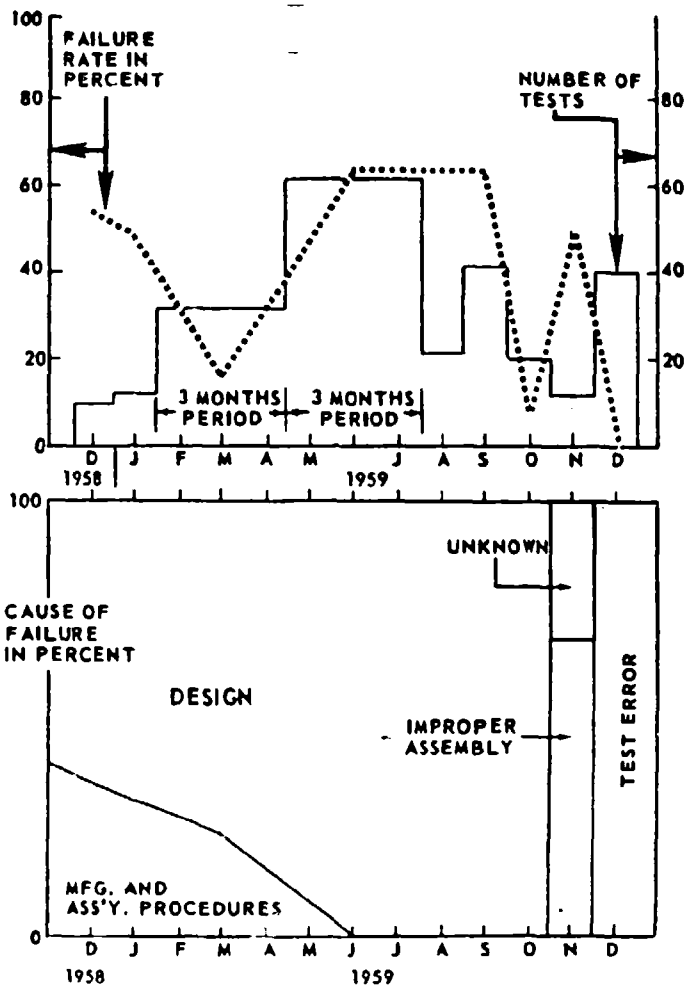


Fig. 8 Electro-Mechanical Component With Which Considerable Design Trouble Was Encountered

THE FALLACY OF PET AS A QUALITY CONTROL TECHNIQUE

BY: George A. Henderson - Army Rocket and Guided Missile Agency

Production Environmental Testing (PET) is used widely by the electronics industry as a quality control technique in an effort to "debug", or to screen bad parts and workmanship from good. The belief that the application of PET can increase the chance of success in missilery is a fallacy which will be demonstrated in this paper.

There seems to be considerable misunderstanding as to what is meant by PET. PET is the subjecting of 100% of manufactured hardware to some environmental test, such as vibration, shock, acceleration, temperature, etc., prior to flight testing or service use. It includes both R&D and production lot equipment at component or assembly level.

PET is perhaps the largest remaining controversy in the guided missile field, constituting expensive bottlenecks in some manufacturers plants. It is used in an attempt to assure quality by application of what proponents may feel is a panacea, rather than by application of proper process controls and suitable inspection.

It is the policy of the Army Ordnance Missile Command that no hardware which has been subjected to a vibration test will be used in any flight test, or otherwise delivered to the using troops. However, it is required that adequate quantities of samples be tested to failure (functional failure, not necessarily destruction) in each critical single and combined environment (within the state of the art). This includes both R&D and production lot equipment.

Army has had demonstrated some satisfactory levels of systems reliability without resorting to PET, simply by the application of sound development practices and time tested quality control techniques.

One is reminded of the story of the easterner who drove his automobile to the west coast and back again without use of credit cards or travellers cheques and without once having to identify himself or to sign his name. He used only time-tested cash. It appears necessary that testing to failure of adequate quantities of samples of hardware at all levels of assembly be "rediscovered" in order to achieve the necessary reliability in guided missile systems, rather than continue to depend on PET, which is at best no more than a "crutch".

The belief that PET can serve as a valid and useful means for detecting and correcting deficiencies, or for debugging, is based on the existance of "infant" mortality in inanimate equipment as there is in living things. This writer has examined much data collected from many sources, has reasoned with as much logic as he can muster, and has talked with many experienced people who also have considered the problem. He concludes that true infant mortality does not exist outside the realm of living things.

Consider the sea turtle which crawls from the ocean and lays her eggs in the sand along the beach. After a period of incubation, many small turtles are hatched and immediately begin to make their way to the sea. However, sea gulls pounce on them and kill many. Only a small percent ever reach the comparative safety of the sea. Of those that do, some are eaten by fish. Only a few survive to reach maturity and die from old age.

The above example illustrates true infant mortality. There are many such examples. In fact, all living things experience infant mortality due to natural enemies, disease, and pestilence. But what of inanimate objects such as vacuum tubes, resistors, capacitors, assemblies, and even complete systems? Are they preyed upon by other pieces of equipment? do assemblies eat components? are equipments subject to diseases which are more severe to young components than to older? The answer should be obvious. There is no similarity between inanimate objects and living things as related to infant mortality. Only in regards to chance and wearout is there is similarity.

Here it seems fitting to point out that much misunderstanding exists relative to chance and wearout. Far too much credit is given to failure due to chance when in reality nearly all such failures are due to wearout. In a field where there is much variability between individual components we would expect wearout to occur in such a random manner as to appear as though by chance. More will be said about this later in the paper.

Figure 1 shows the hypothetical model distribution upon which PET advocates base their belief that production equipment can be improved by debugging.

Perhaps the purest and most classical example of PET is the naval torpedo proof test program as reported by Dr. William R. Pabst, Jr., of the then Bureau of Ordnance, at the first of these reliability symposia (NOL-Corona, California, October 1954) in his excellent paper "Statistical Planning for Ordnance Proof Testing."

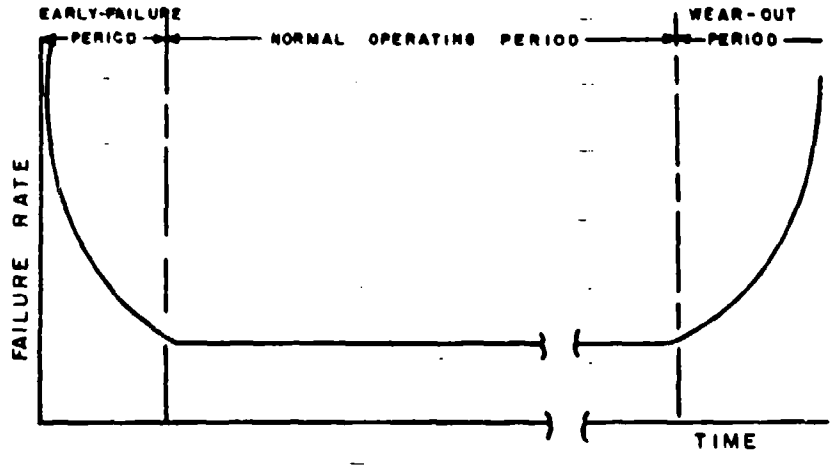


FIGURE 1. MODEL DISTRIBUTION UNDERLYING PET CONCEPT

Dr. Pabst's paper began:

"Torpedoes are in many respects like guided missiles. They are complex, automotive, and some possess intelligence and self-guidance. They differ in many ways, too, the most immediate differences being in numbers available, in the quantity of past experience, recoverability after test run, and possibly in cost. Whether torpedoes will differ from guided missiles in the development time to reach a state of high reliability may depend upon avoidance of some of the same mistakes. Because of these similarities and this desired difference, the recent planning of torpedo tests may guide, either by a warning or as a model, for those in the guided missile field.

"Within the last three years, the system for proof testing of torpedoes has been overhauled and placed on a more systematic, logical and statistical basis. Proof tests are those

final tests given torpedoes before they are released as serviceable torpedoes. These tests, actually run in the water, are considered to provide the necessary assurance that the torpedo will perform as needed in service use. In the past, however, because of the nature of torpedo performance and because of the failure to interpret test data properly, torpedo testing tended to provide a fallacious confidence in torpedo reliability, rather than the basis for improving it.

"The reason for the failure of proof tests to provide the necessary action leading toward reliability resulted from the fact that individual torpedoes were run and rerun until they passed the test, and then were accepted as satisfactory. It was a plausible yet erroneous picture that the faults of a torpedo were shown up on a proof run and corrected before the next. Thus it was also erroneous that individual torpedoes improved from these adjustments as additional runs were made. To an outsider the practice of repeating missile systems test after test seems dangerously similar.

"The old system, if it can be called a system, can be stated simply. If the torpedo passed the test, it was sent to the fleet as a 'passed and proved' torpedo. If the torpedo failed, it was analyzed for cause of failure, corrected or adjusted on the proof range or at the factory as necessary and rerun. If on the second trial it met standards, it was considered 'passed and proved'. If it failed, the sequence was repeated as many times as required for the torpedo to pass. Some torpedoes made more than twenty proof runs before they became 'passed and proved'. One Mark of torpedoes required on the average of 10.5 runs per torpedo over a series of years." Figure 2 shows the failure rate for one Mark of some 2600 torpedoes. The points have been connected in order to show any trend that might exist.

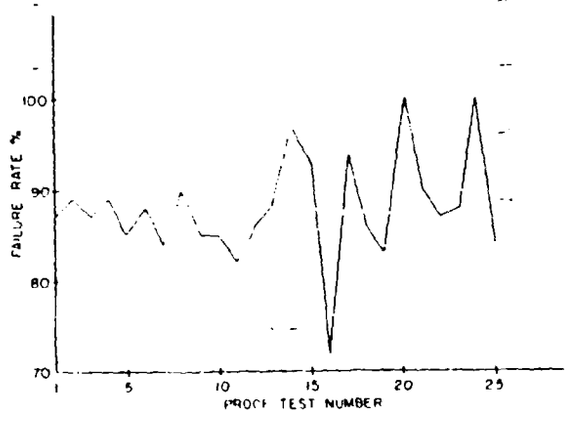


FIGURE 2 TORPEDO FAILURE RATE

Note the randomness of the curve. Definitely, no infant mortality is present.

Quoting further from the paper:

"Proof test runs over a series of years were analyzed. Of several thousand torpedoes, approximately twenty percent passed on the first run. Of the remainder tested on the second run, again approximately twenty percent passed. On the third, fourth and successive runs of the diminishing balance, approximately the same percentage with allowance for sampling variation continued. The result was about the same as if one started with many five sided dies and counted as satisfactory in succession those dies on which aces appeared. If torpedo performance actually improved after the successive adjustments and overhauls, the percentage score passing would have improved with each run. Contrary-wise if the test had separated out the bad torpedoes from the good, the percentage score would have decreased with each run. The consistently even score from run to run simply suggested that passing the test was a chance phenomena and that the adjustments and changes made in torpedoes from run to run were simply offsetting.

"Do not at this point be alarmed about the twenty percent score. This twenty percent measures as much the artificiality of the old technical proof specifications on the individual runs as it does the performance of the torpedoes themselves. As will be shown, the specifications based upon original hope needed to be tempered by experience.

"In view of the consistent percentage of torpedoes passing in the original proof test, it was a statistical prediction that "passed and proved" torpedoes would repeat about the same percentage if run again. Therefore, a special test was carried out in which five passed and proved torpedoes were tested five times each along with five prerange torpedoes. Prerange torpedoes are those that had not previously been water tested. These comparative tests were statistically designed so that all ten torpedoes were given the same treatment and all run on the same days approximately two weeks apart. In overall results, the prerange torpedoes scored seven satisfactory runs in the twenty-five trials in contrast to three satisfactory runs for the "passed and proved" torpedoes. It was probably accidental that the prerange torpedoes scored slightly better, for the difference did not meet tests of statistical significance. In specific characteristics of depth, deflection, and speed the two groups were very similar. The results of this test

confirmed the prediction that the single satisfactory runs of the 'passed and proved' torpedoes did not make them more reliable with respect to their future performance.

"These results also supported the contention that passing the proof run was largely a matter of chance. Improved reliability had to be sought in increasing this chance, that is, through increasing the proportion of satisfactory runs, thus through higher quality levels." End of quote.

A striking similarity exists between the torpedo proof tests and the application of PET to missile hardware. In the proof tests, no vain attempt had to be made to simulate environment, for these tests were run in water, the same as in use and the torpedoes were recovered; however, in the case of guided missiles, many attempts at simulation have been made, with varying degrees of sophistication.

The results of this above cited designed experiment clearly indicated that no early high failure rate existed, followed by a "long low stretch" of constant failures. It was demonstrated that passing such a test (as in PET) was but a chance phenomena.

Yesterday afternoon, R. D. Ginter of the Bureau of Weapons, in his paper, "Bullpup, A Round of Ammunition", said the following:

"BULLPUP specifications have always required that the missile meet a particular reliability goal. This goal has been continually increased during development, evaluation, and now production. All of these specifications recognized that continued testing of the missile during 'ready service' stowage would reduce the total missile reliability. The specifications allowed a ½% reduction in reliability after each test. That reliability would be reduced due to continued testing was proven during the Navy Technical Evaluation. A block of 30 missiles was subjected to repeated operational tests. None failed on the first or second tests. Failures began to appear on the third and subsequent tests. Testing missiles in an attempt to prove them ready was actually causing them to fail." Figure 3 shows the failure rate curve.

should be noted that the sample size varied from 30 missiles on the first test to 1 on the eighth. That part of the curve beyond test number 6 does not necessarily present a true picture. Had the sample been larger, it is reasonable to believe that the shape of the curve might be changed somewhat. However, it is interesting to compare this curve with that of Figure 9. The reason for the failure rate to fall-off to zero percent is due to there being virtually no samples remaining, as is the case in human mortality beyond age 100.

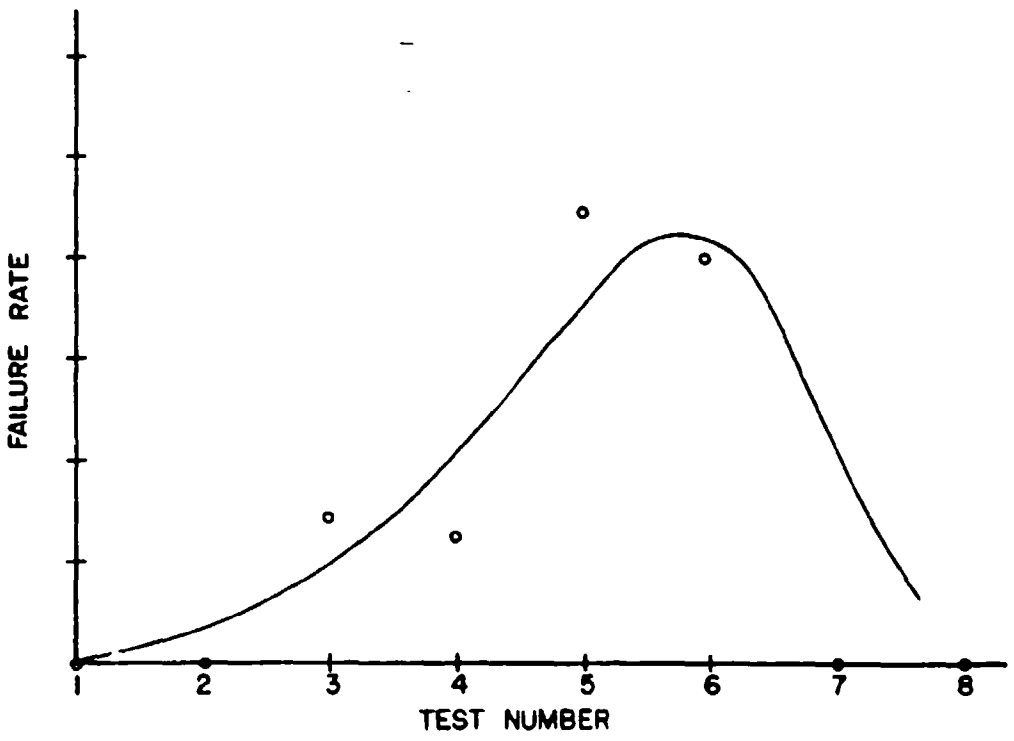


FIGURE 3. BULLPUP FAILURE RATE

This too, clearly indicates the absence of an early failure rate followed by the "long low stretch". In fact, just the opposite is demonstrated.

In December 1954, General Medaris, at that time Chief of Industrial Division, Office, Chief of Ordnance, directed that the Corporal PET program be stopped. Simultaneous with this decision, Firestone Tire and Rubber Company, the Corporal production contractor, published an analysis of 6 months PET results of 11 electronic assemblies. These tests consisted of subjecting all production of the 11 electronic assemblies to extended periods of vibration. If failures occurred, the equipment was repaired and retested in a manner similar to the torpedo proof test program. The results are shown in Figures 4, 5 and 6. (Sample sizes on first shake varied from 19 to 119, decreasing in number as subsequent shake tests were conducted).

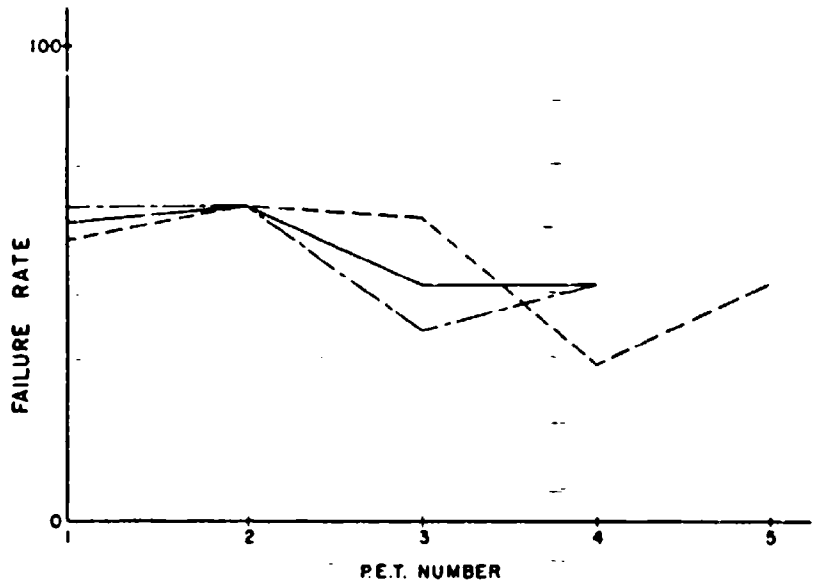


FIGURE 4. CORPORAL ASSEMBLY FAILURE RATE

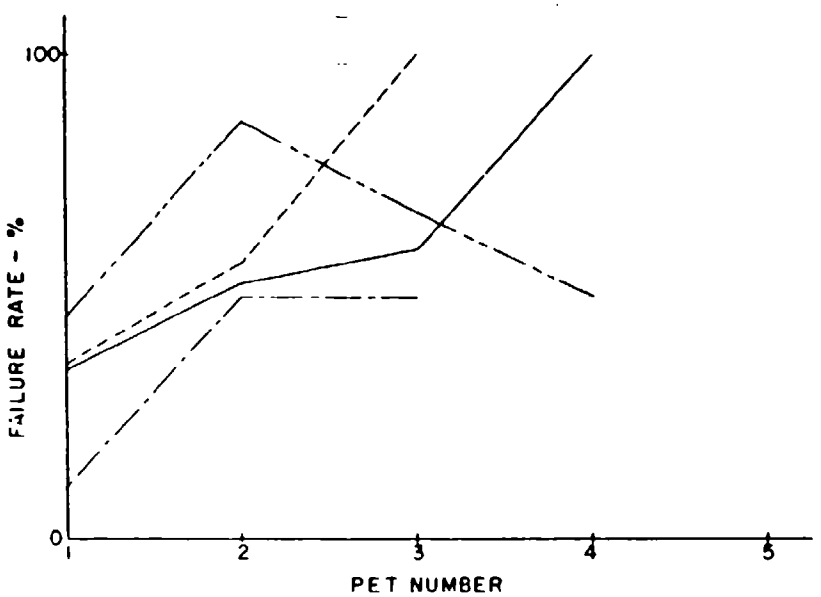


FIGURE 5. CORPORAL ASSEMBLY FAILURE RATE

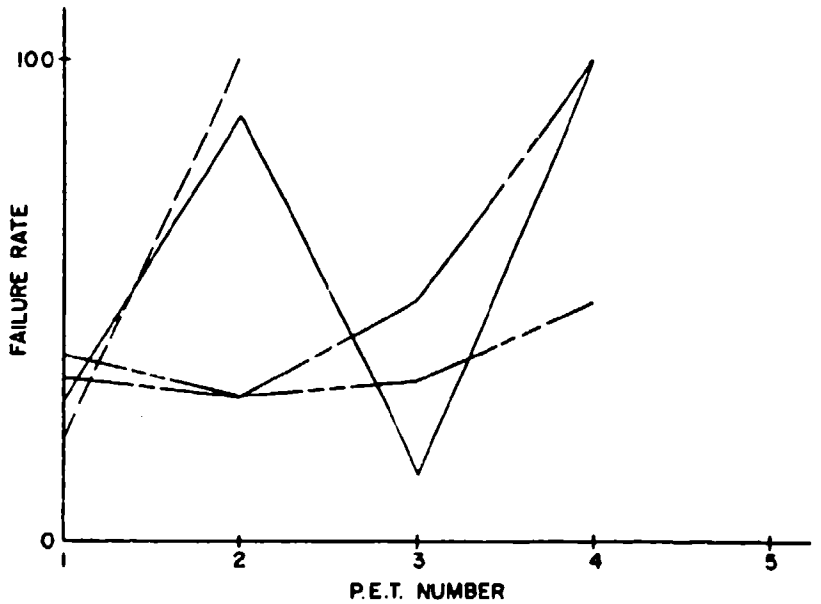


FIGURE 6. CORPORAL ASSEMBLY FAILURE RATE

It is seen that there is no "early" failure pattern exhibited, but rather a random one. This is further proof of Dr. Pabst's contention that passing such tests is merely a matter of chance.

A further study of Corporal PET was made by R. P. Henry, of Firestone, in a report dated 30 December 1954, "Analysis of Vibration Results". This analysis was of PET results on eight electronic "black boxes" chosen because they were thought to be "intrinsically weak". In this report it was said, "....to continue to shake packages as a routine production test to discover inherent weaknesses may perpetrate a system which introduces as many failures as it discovers."

The purpose of this analysis by Mr. Henry was stated as follows: "The analysis in this report attempts to assess this possibility [introducing as many failures as it discovers] with a simple but statistically rigorous test known as the contingency-type test making use of the chi-square distribution. It will answer the questions: (1) Are units failing at the same rate in second 'shake' as they are in the first? (2) Do those units which pass first 'shake' but were reshaken for some reason fail at the same rate as those which failed first shake and had to undergo additional testing?"

It was concluded: "The evidence from these eight packages all point in this direction. ....It is hypothesized that there is no real difference in shake failure rates from one shake to the next. Only in the case of 2 of the 8 assemblies tested is it possible to reject this idea; and, in these cases, the failure rates are actually worse. In spite of this, it is possible to pass a unit through vibration if enough tries are made. In fact, all units in the plant have passed a vibration test at one time or another. However, this analysis casts considerably doubt upon the ability of a unit to pass a subsequent vibration test (or flight) with any greater probability than the previous one, which of course, is no net improvement."

This is further proof that infant mortality is not present in inanimate objects. Can it be that infant mortality applies only to infants?

At the time the decision was made to stop the Corporal PET program, it is noteworthy that the R&D contractor (who had written the PET specifications) steadfastly maintained that the Corporal reliability would be degraded seriously if the PET were not continued. Figure 7 shows the reliability status of the Corporal during this period.

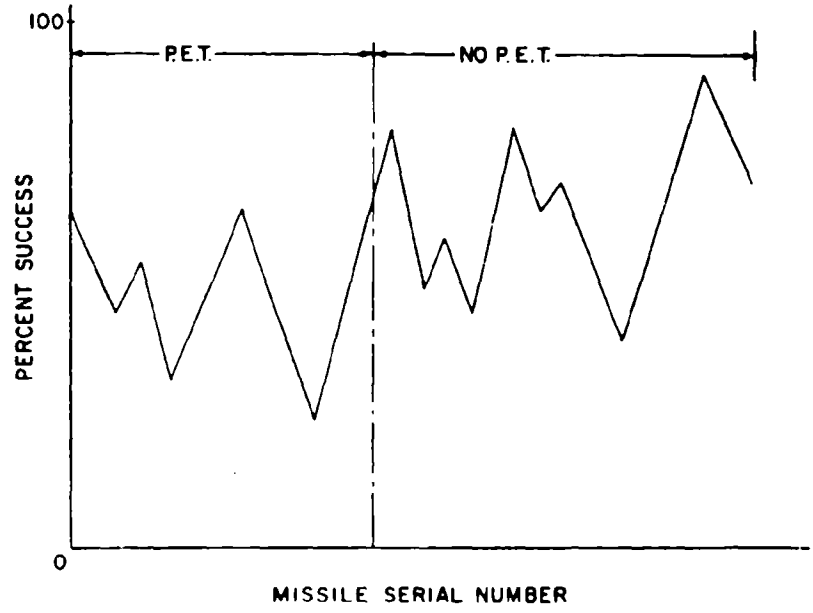


FIGURE 7 CORPORAL RELIABILITY CURVE

A twenty-round moving average (some irregularities in the curve have been smoothed out to simplify the diagram) of approximately 100 rounds of missiles with electronic hardware which was subjected to PET is shown in relation to approximately the same number of missiles having no hardware so mistreated.

It can be seen that there is no startling change in reliability status which can be related to PET. A gradual increase was to be expected due to normal system improvement caused by corrective actions resulting from field experience, combined with troop improvement in operational skills.

In another guided missile program in which 100% vibration testing is being conducted, the contractor lists the following items as the kind of failures or defects he is finding:

Loose nuts and bolts
Cold solder joints
Insulation wearing through from rubbing
Broken capacitor leads
Capacitor shorting
Microphonics on trimpots
Microphonic transistors
Intermittant relays
Broken wires
Broken mountings
Cracked transistors
Loose contacts
Microsyn gear retainer
Poor mechanical fit and looseness
Defective pot wipers
Snap ring failures

He concluded that these defects "would not have been discovered during normal manufacturing inspection." He also made the following "rediscovery": "Manufacturing failures appeared to be completely random."

I think we can assume safely, that if the contractor states that these failures and defects" would not have been discovered during normal manufacturing inspection", either his "normal" inspection is no good, or else these defects were not present at the time of inspection, and were therefore, the direct result of the PET. How else does insulation wear through from rubbing? surely not by sitting at rest undergoing normal inspection.

In his paper "Production Environmental Testing" (November 1957), Robert Lusser showed that the "Mortality curve" is shaped

by "force of mortality". This is shown in Figure 8. Note that the force of mortality must experience a decrease with time in order for the mortality to exhibit a like decrease.

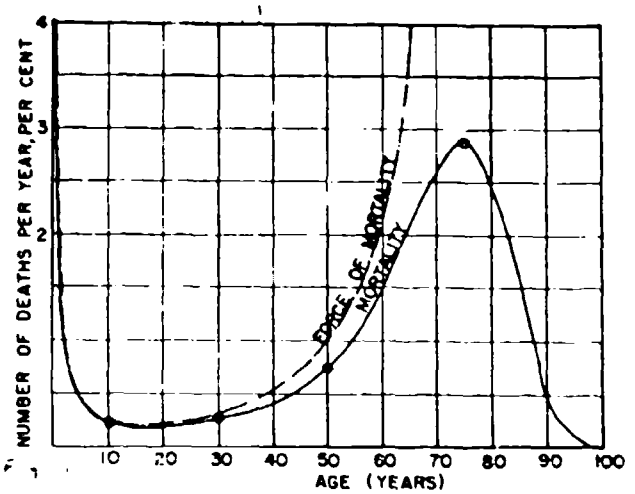


FIGURE 8. HUMAN MORTALITY DISTRIBUTION

This is the case with turtles, with all living creatures, and with human beings where the force of mortality decreases rapidly from time of birth until age 5 or 6, then is fairly constant until we reach age 45, thereafter rising steeply until no samples remain, all having failed mostly from wearout.

Consider now the case of the "force of mortality" in electronic equipment. Is there any similarity to human behavior? Is there any cause for a decrease in "force of mortality" during an early period of time in which equipment can be improved by "debugging"? The answer is an emphatic no.

In complex equipment, wear-out begins immediately in some parts, such that the overall force of mortality immediately begins to rise, however slight may be indicated, resulting in a gradual

increase of mortality. This is shown in Figure 9. Note the similiarity to the data presented by Ginter on "Bullpup", as was shown in Figure 3.

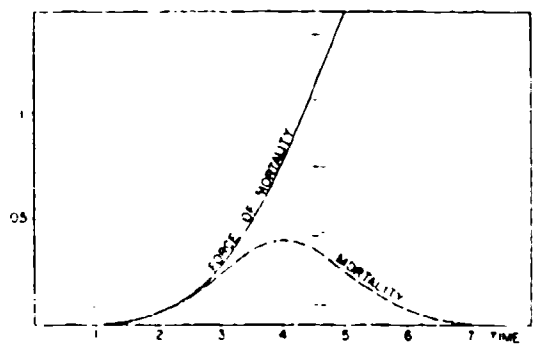


FIGURE 9. EQUIPMENT MORTALITY DISTRIBUTION

ARINC Research Corporation reported the results of a study made of incoming inspection and screening techniques of vacuum tubes utilized by three equipment manufacturers. This study, "Evaluation of Incoming Inspection and Selection Procedures for Electron Tubes", dated 4 April 1958, revealed some interesting things.

In the Foreword the following is written:

"The effectiveness of special incoming-inspection and selection procedures as 'screening agents' for reliability assurance is discussed. Three electron-tube inspection processes, generally representative of those being used by the equipment industry to weed out potential tube failures, are evaluated in detail. On the basis of these data, a general evaluation of electron-tube inspection procedures is formulated.

"Although the report is restricted to a discussion of inspection procedures related to electron tubes, it is

believed that the findings are applicable to many of the special procedures used to inspect and select other types of electronic parts and components...."

"Any one of several different methods could have been used to evaluate the incoming-inspection procedures described in this report. However, ARINC strongly believes that approaches other than those employed would have led to the same conclusions...."

From the Summary the following is extracted:

"The equipment industry has sought to complement the efforts toward basic tube improvement by establishing incoming-inspection processes designed to screen defective tubes from new lots as they were purchased.... The number of "defective" tubes rejected from each tube lot ran high -- as did the cost of acceptable tubes.

"Particularly because of the cost factor, it became desirable to evaluate the more typical incoming-inspection processes in order to single out those whose contribution to tube reliability was sufficient to merit consideration for adoption in military specifications.... four controlled tests were conducted to evaluate three different inspection processes.

"These tests revealed no significant improvement either in tube reliability or in equipment reliability as a result of the special tube-processing techniques investigated. The equipment manufacturers whose inspection tests were chosen for evaluation have eliminated these processes from their incoming-inspection procedures. Other equipment manufacturers who are aware of the findings have taken similar action."

The tests reported consisted of various combinations of visual - microscopic, vibration-noise, X-ray, polariscopic, and thermal shock. Generally, a batch of tubes was divided into two groups: a control group and a test group. The control group was installed in the equipment and operated until the removal rate (as a measure of reliability) was determined. At the same time, the test group was run through the equipment manufacturers screening-inspection process and were thus separated into 2 groups: those which passed the test, and those which failed.

The in turn, were also installed in the equipment and operated until the removal rate was determined. In all cases, no significant difference was found in the removal rates of the control group, the "good" tubes and the "bad" ones.

In the Proceedings of the IRE, August 1956, page 1073, the following is said under the topic, "Reliability Factors for Ground Equipment":

"It is now recognized that tube failures are most likely to occur during their early history, say, the first 50 or 100 hours. Like human beings, whose mortality is greatest during their childhood, if tubes get over this critical period, they are likely to have a normal life expectancy. To avoid these 'quickie' troubles it is becoming customary to 'burn in' tubes or to age them before they are accepted or are permitted to go into the equipment. After this period, failures seem to follow an exponential pattern; in a given time a given percentage of those still in service must be replaced."

Mr. C. R. Knight, Director, ARINC Research Corporation, responded with the following comment:

"This is not so much an error as reflection of the date of the material. This statement was believed to be true rather generally up through 1953. Growing masses of data since that time, however, have quite firmly established that in receiving type electron tubes this 'infant mortality' is no longer apparent and that the probability distribution of time to failure in receiving tubes is most frequently Gaussian. The unnecessary 'burning in' of tubes by equipment manufacturers and the attendant economic waste is a primary concern of military procurement agencies at this time."

Furthermore, D. S. Peck, Bell Telephone Laboratories, in his paper, "A Mesa Transistor Reliability Program" presented yesterday afternoon, noted that while undergoing life tests, "transistors experienced a constant failure rate".

D. B. Christian, Statistical Analysist, Bendix Products Division - Missiles, wrote the following in the abstract of his paper, "Examination of Reliability Theory and Practice" presented at this symposium yesterday morning: "The use of the infant mortality concept gives a fake impression that things will get better as faulty components are weeded out. But what assurance do we have that the replaced parts are better? The author has been told that testing de-bugs electrical systems so that more testing improves the product. This paper presents facts that failures are a function of time and the failure rate is essentially constant throughout the assembly test period. This does not indicate infant mortality."

Now, let's examine PET from the point of logic. In discussing this, I would like to take as example, wire wound resistors. I read in a reliability report published at a military installation 3 years ago a discussion of such an example. It was reasoned that wire wound resistors failed due to "nicks" in the wire which were produced during manufacture. It was assumed that the time to failure under use conditions was proportional to the size of the "nick" in the wire. It was concluded that by burning-in these resistors for a prescribed period of time, the resistors with defects (or nicks) would fail, thus, leaving the "good" resistors. The fallacy of this reasoning lies in the assumption that resistors either have "nicks" or do not have "nicks". The truth of the matter is, however, that nicks produced by a manufacturing process would be distributed from the largest (which might be visible to the naked eye), to the smallest (which might be detected only with a powerful microscope).

So, when does one stop the "burning-in" in order to separate bad from good? No matter what time is chosen arbitrarily, always there is the next smaller nick which will cause the resistor to fail in the next interval of time. That interval of time might well be the flight period under an actual engagement.

It must be concluded that screening techniques, so closely related to PET, are worthless unless parts screened actually are composed of a bimodal population, consisting of only "good" and "bad" parts with no inbetween.

I often use the example of eggs. Were I given a basket of eggs, some of which were very fresh, and the remainder very rotten, it would be possible to design a test whereby the good eggs could be separated from the bad with 100% certainty; but, if the eggs were randomly distributed from very good to very bad, it would be impossible to separate all of the good ones from the bad. For by what yardstick would one measure a good egg? or a bad one? There are many people in the world today who eat eggs which you and I would reject!

In the November 1955 issue of "Scientific American" there appeared an interesting article, "The Growth of Nerve Circuits", by R. W. Sperry, Hixon Professor of Psychobiology at the California Institute of Technology. In the article, the author discusses the effect on humans and animals of nerve injuries and the possibility of restoring normal nerve function through surgical means and by training and re-education.

The author tells how, sometimes, to prevent atrophy of the facial muscles when an injured facial nerve fails to regenerate, surgeons will connect the degenerated facial muscles to a nearby healthy nerve, such as the motor nerve of the shoulder muscle.

"Naturally, the primary concern of the patient in such cases is whether or not normal function can be restored. If the symptoms do not clear up spontaneously, can they be corrected by training and re-education? Not so long ago, the reply to such questions was a confident 'yes'. For most of the present century investigators and physicians were agreed that the central nervous system is plastic enough so that any muscle nerve might be reconnected to any other muscle nerve with good functional success."

"During the past 15 years, however, scientific and medical opinion have undergone a major shift, amounting to an almost complete about-face."

"The evidence for this [about-fact], which comes from new experiments and from exacting clinical observations, is so persuasive that it is difficult to understand how the opposite view could have prevailed so long. It appears that most of the earlier reports of the high functional plasticity of the nervous system will go down in the record as unfortunate examples of how an erroneous medical or scientific opinion, once implanted, can snowball until it biases experimental observations and crushes dissenting interpretations."

Can it be that the same is true of PET? that PET is another example of an erroneous scientific opinion, which, once implanted, has snowballed until it has biased experimental observations and crushed dissenting interpretations?

The management of a contractor which is producing hardware for the government is told by his technical personnel that a certain screening technique, vibration test, or PET, is separating good product from bad and is thus a useful quality control technique. The management accepts this as true, and in fact is happy in this belief that such a test is useful in improving his product and in providing assurance that the product he is delivering meets specifications and is good.

The fallacy arises from the fact that a production contractor is paid only for the hardware which he delivers from his loading dock. He therefore sees no need to evaluate realistically the results of the screening test or PET being used. He continues to ship hardware to the government which he sincerely believes is

better because of the test. What he doesn't know is that in all cases where PET results have been evaluated, it has been demonstrated that no product improvement has resulted. That is, the product which passed the PET screening was no better than that which was given no such test.

The argument was used by one contractor that PET provided the only source of failure data he had. He was conducting a mild test to failure on a 100% basis and was then delivering the used merchandise to the government!

The government must move to eliminate foolish, wasteful, and time consuming practices such as PET. It must insist that contractors determine appropriate environmental conditions, test to failure adequate samples of R&D (and later production) hardware in these environments, and demonstrate the existance of adequate safety margins. Furthermore, it must be willing to support these activities with adequate funds and proper schedules if it expects to receive reliable guided missile systems from its contractors.

THE ATLAS RELIABILITY TEST PROGRAM - INCREASED RELIABILITY RESULTING FROM COMBINED ENVIRONMENTAL TESTING

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A. INTRODUCTION

The high environmental severity levels in which today's complex missile systems must operate create a serious reliability problem. The record of missile flight failures during the early developmental stage stresses the magnitude of the problem. Major companies in the missile industry, fully aware of the stakes involved, are making an all-out effort to solve the reliability problem. However, since no single methodology has been developed that can be utilized to insure the reliability of each and every system, each company has approached the reliability problem from a different angle. This paper presents the reliability approach taken by Convair-Astronautics for the Atlas Missile system. In addition, the results achieved during the first four phases of the Atlas Reliability "Search for Critical Weakness" test program are presented.

The "Search for Critical Weakness" test program is based on the concept of early detection of component weaknesses in design, materials, and fabricating techniques so that corrective action can be implemented before operational failure occurs. In pursuing these objectives, the concentration of effort has been on the improvement of component reliability. Weaknesses were determined by exposing missileborne components to simulated flight conditions in the environmental laboratory, with the realistic features of combined environmental testing.

The reliability test program for the Atlas missile system is administered by the Reliability organization within Convair-Astronautics. In contrast to this, many other prime contractors delegate the responsibility for reliability tests to the manufacturers from whom components are being obtained. There are several advantages in having a group within the prime contractor's organization responsible for all reliability tests. Some of the advantages are: 1) close liaison is maintained with design groups, thus providing for a coordinated effort in determining adequate solutions for detected component weaknesses; 2) close liaison is maintained with the theoretical groups (Aerophysics, Thermodynamics, and Dynamics) for determining realistic environmental conditions; 3) close liaison is maintained with the flight evaluation groups for feed-back information from actual missile flights; 4) test requirements are standardized for all components, resulting in a valid comparative assessment of component reliability; 5) an independent evaluation is made of all items tested - thus, all biases are eliminated from test

results and isolated from the influence of the designer or the manufacturer. The general testing philosophy adopted for the "Search for Critical Weakness Program" is summarized as follows:

1. Component Types Tested

All missileborne components which fall within Convair Astronautics' responsibility and possibly have a critical effect upon an Atlas mission were selected for tests. Up to this time more than 300 component types have completed reliability tests. These components included electrical components such as battery packages, inverters, transponders; hydraulic, pneumatic and propulsion items such as staging valves, reservoirs, and accumulators; and electro-mechanical items such as servo valves, separation devices, programmers and destruct systems.

2. Sample Size

The number of specimens to be tested was determined by the total number of each component used per missile, and by its relative importance to the overall system. Short-life or one-shot type components such as primary batteries and explosive devices necessitated the selection of additional specimens. Program budgeting was established at the outset on the basis of five equivalent shipsets for Series A Atlas Missiles, three for Series B, three for Series C, five for Series D and six for Series E. This sample size has provided greater confidence in the test results and an indication of production and performance variability. Several instances have occurred where only one out of 10 or 20 specimens failed during the program. For example, one Hydraulic tank out of 10 tested, burst during Reliability tests. After revealing a structural weakness in the component, it was strengthened, leading to a more reliable unit (See Figure 1). The chances of revealing such a weakness would have been small if only one sample had been tested.

3. Selection of Test Specimens

It is essential that the test specimens are identical to flight articles and that the manufacturer is not aware which items are to be reliability tested. For these reasons the test specimens are selected at random from production stock.

4. Environmental Conditions

All equipment is exposed to simulated operational conditions in the environmental laboratory. In order to obtain information in the minimum time and to minimize the effects of fatigue, only the most adverse environments are selected for test conditions. In most cases these environments are sustained acceleration, high and low temperature, altitude and vibration. During Series A testing, these environments were applied singly. During all series thereafter, temperature, altitude and vibration were combined with the introduction of programmed radiant heat where

applicable. While experiencing these environments, the equipment was in an operating condition representing its time sequencing and end-use in flight.

5. Environmental Severity Levels

Although equipment may show adequate performance at the design level in qualification tests, this does not necessarily prove that it has attained the high reliability required for the missile system. Consequently, all specimens are tested at the design level of environmental intensity and then at two levels beyond this value. Testing beyond the design requirements is done to establish a margin of safety for each component type. This safety margin may then be used as a yardstick of equipment reliability for comparative purposes. Testing at more than one level also is important in the event that actual flight environmental severities differ from the expected, or in the event that a component is relocated. In this case, the test results permit us, without further testing, to establish a new safety margin and thus reassess reliability. Figure 2 illustrates a failure incurred by a helium staging valve during the third level of vibration intensity. Subsequent examination disclosed that the valve had been weakened by undercutting in the area of a sharp thread root. The weakness was easily corrected by eliminating the undercutting process, thus strengthening the valve considerably. This weakness would not have been revealed if tests had been conducted at only the design level requirements.

6. Test Results

When the final test results and any interim results are received by the Reliability Organization, they are reviewed in collaboration with the cognizant design group to provide an initial evaluation of the equipment's reliability. Follow-up action to eliminate any reliability problem is coordinated by the Reliability Organization. A written summary, known as a Reliability Test Evaluation, is prepared by the Reliability Organization and submitted, together with all associated reports, to the cognizant design group.

The Reliability Organization meanwhile, conducts the necessary statistical analyses required for a final reliability evaluation. These include: a) an investigation of variability in performance data as a function of the environmental severities; b) a study of the relationship between safety margin and equipment reliability; and, c) an evaluation of comparative reliability. After the final analysis, component performance is classified under one of the three following categories: 1) satisfactory, 2) out-of-tolerance failure, and, 3) catastrophic failure. Within these three classifications, each component is further classified according to the severity level at which it failed and the number of failures. This listing of components then served as an indication of the relative reliability of each component listed, from the most reliable to the least reliable.

B. TYPICAL FAILURES

One factor leading to the revelation of many weaknesses was the application of combined environments while the specimens were operating. Several structural type weaknesses were revealed such as faulty welds, castings, flanges and brackets. Leakage around the various types of seals was prevalent at low temperature-vibration. Diaphragm damage and aluminum strength created a problem at high temperature-vibration. Arc-over led to one serious failure at combined temperature-vibration-altitude. Electronic equipment, in general, was weak with respect to broken leads, solder joints, vacuum tubes, and wiring interference problems. Electrolyte leaked from all battery canisters. Rotating equipment was particularly susceptible to sustained acceleration testing. Three such weaknesses appeared during the test program: 1) the inverter armature slipped on its shaft severing the output leads; 2) the Asusa transponder fan blades were damaged, and, 3) the servo amplifier package cam slipped on its shaft. All of these failures occurred with the axis of rotation in line with the acceleration force.

Workmanship discrepancies led to a number of failures. For example, (Figure 3) during vibration testing of a fuel fill and drain valve, the position switch cover assembly came loose. Examination of the assembly showed that 20 out of 22 cover screws were missing. Inspection was alerted to this oversight and a special check of similar valves in stock was made.

In another case, a pneumatic relief valve was examined by x-ray to investigate the reason for erratic performance. It was noted that a spring retainer had been inserted backwards, permitting the spring to drift off center. (See Figure 4)

In some instances a series of failures occurred which were sufficiently alike to fall into a distinct class. One case of a typical class of failures was detected when several coil springs mounted in rise-off and staging disconnect valves failed during the test program. Analysis of the test specimens showed that the coil springs would bow during compression and while operating under simulated environmental conditions would rub against their housing. This action led to three serious weaknesses: 1) in a staging disconnect the rubbing action of the coil spring scraped metal fragments off the housing, causing contamination, (See Figure 5) in addition to a fractured spring. This discrepancy was corrected by introducing a hard metal sleeve in the housing and changing the coil spring design; 2) in a ground rise-off valve the bowed spring exerted a side load on its housing, causing the poppet to seize in an open position. (See Figure 6) Such a failure, if occurring during actual operating conditions, would have resulted in loss of tank pressurization. This was corrected by adding a spring guide and a hard metal sleeve. Another example of a bowed spring exerting a side load is shown in the x-ray photograph (See Figure 7), of a large fuel staging valve; 3) the spring on a hydraulic relief valve (See Figure 8), bowed, scoring the cylinder wall, poppet and spring. This led to erratic poppet performance. It was corrected by introducing a telescoping spring guide as shown in the photograph. The failure of any one of these components during actual operating conditions would have precluded the fulfillment of the intend-

ed mission -- a high price to pay for a relatively inexpensive spring.

Another class of failures was attributed to "stress raisers" in the fatigue areas of the specimens. These failures usually fell into the classification of insufficient blend radii where geometrical discontinuities exist or where sharp corners act as focal points for stress concentration. The result is that many excellent system designs are negated by a critical component failure that may have been avoided by merely having a radius instead of a square corner. The servo valve receptacle cap shown in Figure 9 is a classic example of how a fatigue crack not only starts at a sharp corner but often will propogate from one fault to another. Figure 2 shows a staging disconnect in which there was no provision for a relief cut at the end of the threaded portion; the sharp end thread became the focal point for fatigue. In addition, the inner diameter of the threaded portion was severely undercut. In Figure 10 the failure of a telemetering transducer probe illustrates the effect of a geometrical discontinuity without a blend radius with a comparatively large sphere at the end of the slender necked down area.

Having revealed such critical weaknesses through realistic testing, the Reliability Organization was able to institute corrective action. Further studies were made in the Reliability Diagnostic Laboratory using the X-ray fluoroscopy facility coupled with high speed motion pictures. Designers, manufacturers, and inspectors were alerted to the critical conditions that exist in their respective areas. This is done most effectively by the use of Reliability Bulletins. These documents are released on a wide distribution basis for such items as the two classes of failures discussed above.

C. CONCLUSIONS

Corrective action for those weaknesses revealed during the program, has varied from intensified inspection techniques and improved materials to complete redesign or change in vendors. During the first three phases of the program, an average of 63% of the component types tested were redesigned to correct the type of weakness revealed during the test. The factors responsible for detecting such a large number of weaknesses and obtaining subsequent high reliability may be attributed to the following:

1. Central control was maintained over all testing by Reliability as an independent organization.

2. Realistic combined environmental conditions were applied.

3. Tests were conducted over a range of environmental intensities, establishing safety margins.

4. A number of each component type were tested providing performance and production variation data.

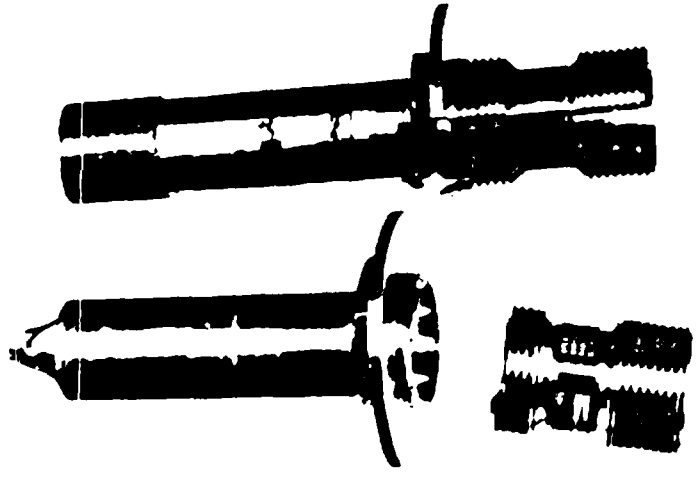
Carrying out this same general testing philosophy since the early phases of the program has enabled Convair-Astronautics to realize the continual improvement of the Atlas Missile components.

SUSTAINER HYDRAULIC TANK
FRACTURE AT SHARP CORNER



Figure 1

STAGING COUPLING ASSEMBLY
SHARP THREAD ROOT AND SEVERE UNDERCUT LED TO FATIQUE FAILURE



1-350

Figure 2

FUEL FILL AND DRAIN VALVE
SHOWING FAILURE CAUSED BY MISSING SCREWS

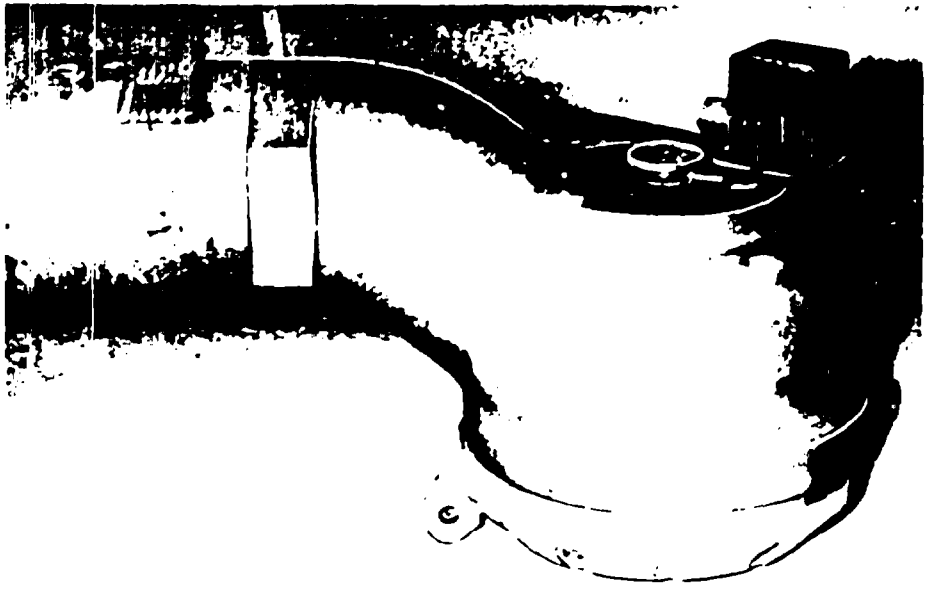


Figure 3

X-RAY OF PNEUMATIC RELIEF VALVE

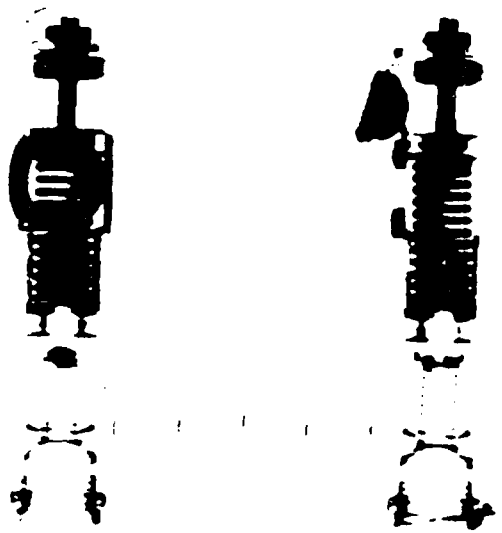


Figure 4

HELIUM STAGING VALVE
BROKEN SPRING & CONTAMINATION

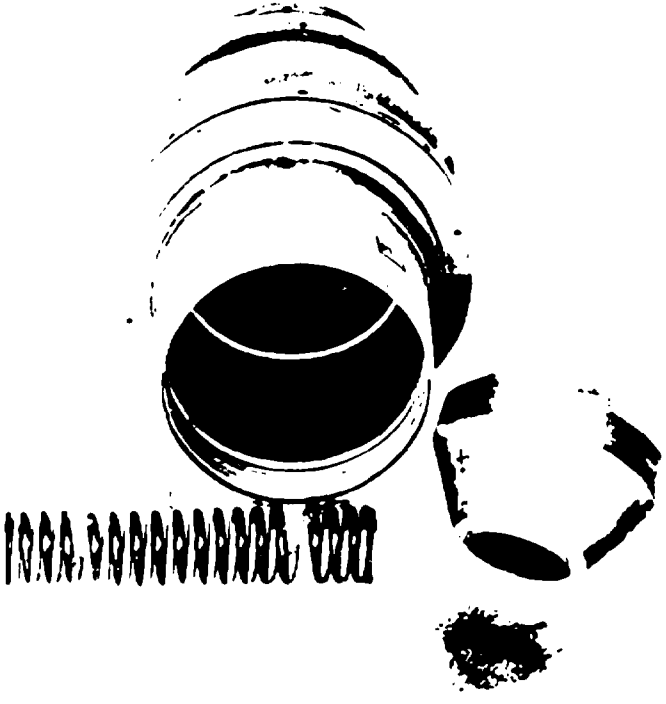


Figure 5

HELIUM RISE-OFF DISCONNECT
GALLED SURFACES AND X-RAY OF BOWED SPRING

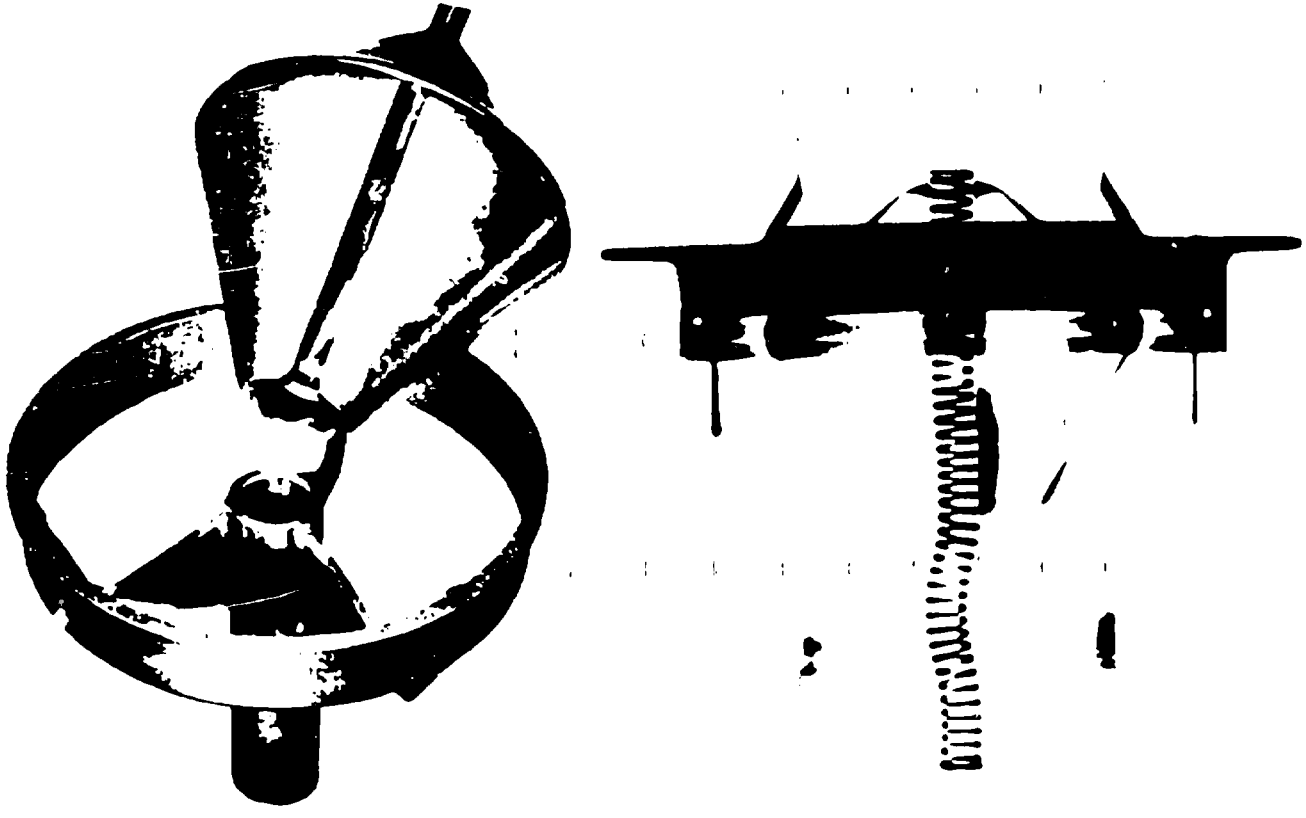


Figure 6

FUEL DISCONNECT VALVE

X-RAY SHOWING BOWED SPRING

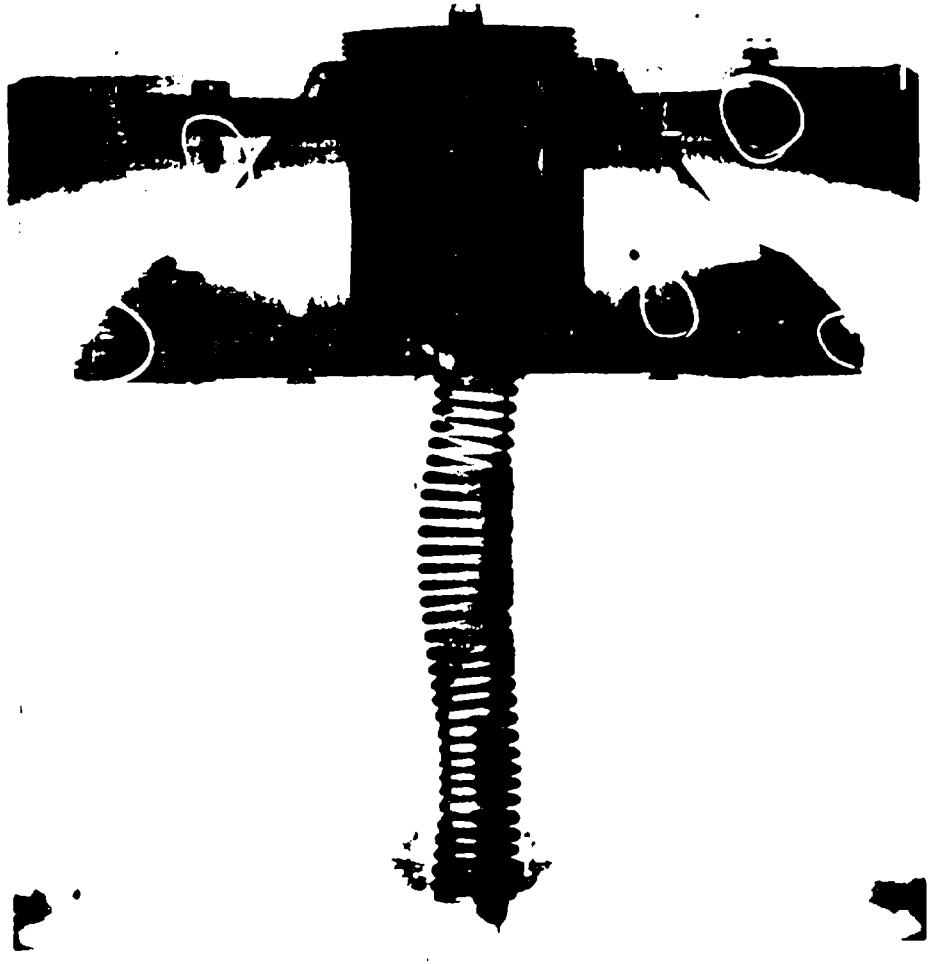


Figure 7

HYDRAULIC RELIEF VALVE WITH AND WITHOUT SPRING GUIDE

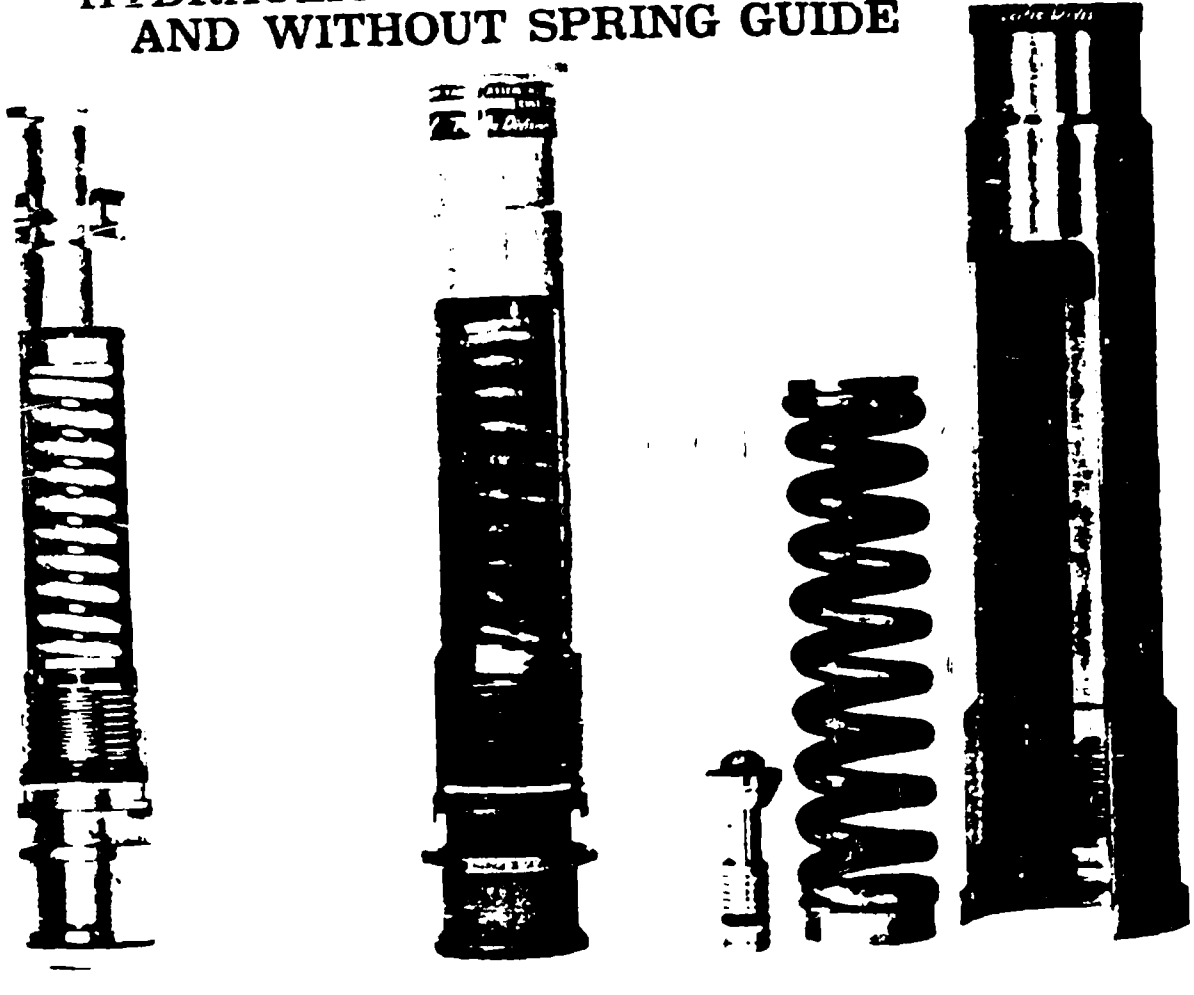


Figure 8

HYDRAULIC SERVO VALVE CASE
FATIGUE CRACK AT SHARP CORNER



Figure 9

TELEMETER TRANSDUCER PROBE
LACK OF BLEND RADIUS RESULTED IN FRACTURE

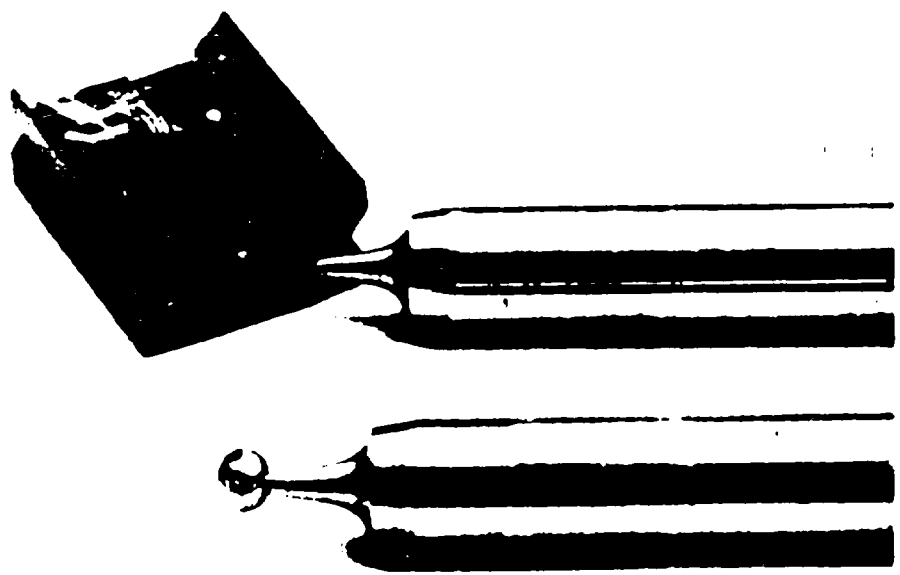


Figure 10

AFBMD SPONSORED COMBINED ENVIRONMENTAL TESTING OF FLUID COMPONENTS

Sherwin Lewis
Liquid Rocket Engines Department, Space Technology Laboratories, Inc.

Ballistic missiles using tanked propellants, which require pressurization, pumping and controlled flow, need valves, regulators, and switches. Reliability requirements for these components were beyond the state of the art at the outset of the ICBM development programs. Recognizing this, the Air Force Ballistic Missile Division initiated a Valve Improvement Program under the technical direction of Space Technology Laboratories, Inc. The objectives of this program were, first; making a better and more complete evaluation of existing valve and switching hardware, and second; to provide guidance and coordination in the development of new components which would meet the stringent requirements of ballistic missiles.

Primary consideration in meeting the first objective of better testing and evaluating equipment for existing valves was directed toward developing techniques and methods for subjecting these components to combined environmental conditions. Some attempt had been made at establishing acceptance and qualification tests at both the prime contractor and the valve vendors' establishments which simulated some of the characteristics of the potential environment. But, in most of these cases, the urgency inherent in the delivery schedules resulted in waivers and relaxed environmental demonstration so that the flow of hardware could proceed. These methods produced little real information as to the location of the basic design weaknesses of these components and contributed relatively little to the improvement of the product. For reasons of this type, the AFBMD program was established on the basis that, whenever possible, evaluation of valve, regulator and switch components would be made under full flow conditions with actual missile fluids and subjected to a combination of missile environments including vibration, acceleration, high and low ambient temperatures, altitude and humidity.

To fulfill the second objective of the program, requests for bids to develop new components were sent out to the valve industry and seven contracts resulted from approximately 100 proposals received and evaluated. Part of the effort contracted from three of the seven, Aerojet-General, AiResearch, and the Missile Division of North American Aviation, Inc. was to undertake the development of combined environmental devices.

The first combined environmental testing in the AFBMD program was done by the Propulsion Laboratory of the Wright Air Development Center acting jointly with the Aeronautical Accessories Laboratory of that same Center. This work involved the use of a large centrifuge table available at the Aeronautical Accessories Laboratory. Following the

transfer of the rocket development responsibilities from the Wright Air Development Center to the Air Force Flight Test Center at Edwards, California, the latter has developed a valve testing laboratory which will soon be complemented by a combined environmental centrifuge capable of handling the largest present day missile fluid system components. In addition to these efforts, two commercial laboratories also have joined the effort to establish suitable combined environmental apparatus.

A description of the approaches taken by each of these organizations will aid in an understanding of the accomplishments already achieved and the potential which remains in the science of properly evaluating valve and switch components.

At the Aeronautical Accessories Laboratory, a Calidyne Model 44 shaker with a force output of four hundred fifty (450) pounds was mounted between two (2) massive steel centrifuge discs, twelve (12) feet in diameter. (Figures 1, 2, 3) The large mass of the discs minimized the effects of vibration reactive forces. The vibrator was modified as follows:

> Retaining plates were made to support the shaker casting, wooden spacers were installed to support the field winding, additional flexures were fabricated, and a positioning indicator and positioning devices were devised.

As a result of these modifications, the output of the vibrator was not adversely affected by accelerations as high as forty-five (45) g. The concepts evolved at WADC were made available to private companies for use in combined environmental apparatus. Wright Air Development Center conclusively proved that combined environmental testing was possible and practical.

Aerojet-General Corporation chose to build an apparatus in which the rotating boom was mounted on a shaker. Aerojet further decided to tackle the problem of designing a versatile machine to control the orientation of the vectors of acceleration and vibration so that vibration could be imposed either parallel or perpendicular to the acceleration. The major portion of the design effort was concentrated on the development of a rocker assembly to convert the vertical vibration vector to a horizontal vector. The rotating assembly was secured to an electrodynamic shaker by means of a pre-loaded thrust bearing assembly. (Figures 4, 5, 6) Work by this contractor was stopped by fund limitations; however, at the time of suspension sufficient progress had been made to establish the feasibility of the approach. A comparison of the centrifuge-on-shaker approach with the opposite more conventional approach of placing the shaker on a centrifuge, reveals the following advantages of the former:

1. The system is more compact. Realistic dimensions would have been a forty (40) inch chamber diameter and forty (40) inches over-all height as measured from the shaker table.

2. The installation is cheaper, if a shaker of the proper size is available. This advantage is largely due to the smaller size of the system and to the simpler plumbing and instrumentation.

3. Slip-rings are not required to supply power to the shaker.

4. The shaker is readily freed for other tests.

5. Altitude and acceleration transients are easily produced to simulate missile gyrations. The evacuating equipment can be closely coupled and the centrifuge portion of the system has low inertia.

6. Fewer slip-rings and swivel connections are required because the heating, cooling and evacuating equipment is stationary.

Conversely, the disadvantages are:

1. Pronounced acceleration gradient across the specimen because of the relatively small centrifuge radius. Variations are as great as ± thirty (30) per cent for bulky specimens.

2. The system is limited to vibration testing of specimens weighing less than five (5) pounds.

3. The ratio of total vibrating mass to specimen mass is relatively large. The extraneous masses are those of the lower bearings, lower shaft and rocker arms.

4. Larger vibrators are required.

A third approach was taken by the second AFBMD valve contractor, AiResearch Manufacturing Division of The Garrett Corporation. AiResearch also decided that for the relatively small component being developed, and with the availability of a large company owned shaker, the optimum configuration was centrifuge-on-shaker. (Figure 7) To keep the effort within financial bounds, AiResearch decided to build a device limited to imposing vibratory excitation perpendicular to acceleration. It was reasoned that this would be useful for the development testing and for a portion of the qualification testing and that eventually commercial laboratories would supply the remaining vector relationships. The device built by AiResearch works as follows:

> Sinusoidal vibration with frequencies up to two thousand (2000) cps, applied by the shaker, is transmitted to a cart. The cart and counterweight travel in an annular track at the end of a ten (10) inch radius arm centrifuge on the top of the shaker head. (Figure 8) The valve is mounted on this cart. There are

ball bearings beneath the center of the cart and a set of outboard bearings on top of each end of the cart. The center bearings run on the lower track surface while the outboard bearings run on the upper track surface. The vibratory forces are transmitted from these surfaces. The bearings are internally pre-loaded with a force greater than the vibratory forces to prevent brinneling. The shaker is required to shake the track, cart, the unit being tested, the counterweight, and the insulated pressure vessel which surrounds the test article. A hollow shaft driven by an electric motor drives the radius arm from above and serves as a conduit for the thirty (30) channel leads and plumbing for the vacuum system. High pressure helium, as well as the regulator and heat exchanger for conditioning the fluid, is stored on the rotating components prior to test.

The third AFBMD contractor undertaking the development of a combined environmental apparatus was the Missile Division of North American Aviation, Inc. Like the other two contractors, NAA had a total fixture weight of less than five (5) pounds and desired to utilize available equipment without impairing individual capabilities; however, the end result was strikingly dissimilar. The NAA decision was to place a conventional M-B C6C shaker with a rated force output of two hundred (200) pounds and an upper frequency limit of five thousand (5000) cps on a Genesco Model C-159, ninety-two (92) inch diameter centrifuge with a rated capacity of two thousand (2000) g pounds and a maximum static load capacity of one hundred (100) pounds. (Figure 9) As a result of analytical studies and static tests, the centrifuge beam was stiffened. Two vibration exciters with a properly designed whiffletree were used to counteract loads on the centrifuge bearings making possible the use of weights more than eight (8) times the rated capacity of the accelerator. Difficulties with swivels were worked out; a special air cylinder to locate the moving element in the centrifugal force was devised; and slip-rings were debugged. High and low temperatures were obtained on the centrifuge by impinging gas on the test valve. For gross loads on the shaker of about eight (8) pounds this device works very satisfactorily. Because of the nature of the component, simultaneous vacuum was not required.

To provide additional test and evaluation capability in addition to the in-house capability of WADC and AFFTC, the Air Force, early in 1959, invited bids to procure environmental test services. Five proposals were received from test laboratories and two laboratories, Stellardyne Laboratories and Wyle Laboratories, were chosen by the Air Force Ballistic Missile Division to evaluate current components under a call contract with technical direction from Space Technology Laboratories, Inc.

Stellardyne Laboratories has built a combined environmental apparatus consisting of a ten (10) foot centrifuge arm fabricated from steel tubing with a Savage V1000 vibrator especially adapted to centrifuge

applications by a unique method of alignment retention of the moving element. (Figure 10) Stellardyne also has had to work out the varied problems of compensating the weight of the moving element during radial vibration, slip-ring selection, rotary joints, imposing temperature, and recording instrumentation. Stellardyne is now currently testing ballistic missile components to Air Force requirements.

Probably the most complete combined environmental apparatus in the AFBMD program was built by Wyle Laboratories. (Figure 11) This incorporates a nine (9) foot radius centrifuge mounting, carrying an M-B C25H vibration exciter with sinusoidal and random capability. The centrifuge arm consists of two (2), sixteen (16) inch I-beams with suitable structural ties, mounted on a hollow shaft through tapered roller bearings. The combined environmental system provides simultaneously:

A. Vibration to 3500 pounds force, 2000 cps.

B. Acceleration to 20 g.

C. Altitude programmed to 250,000 feet.

D. Temperature programmed from -300°F to +500°F.

E. Humidity to 100 per cent.

F. Liquid Oxygen, gaseous oxygen, fuel, hydraulic fluid, and helium flow as required.

The machine incorporates the following innovations:

1. Tension rods from the shaker trunnions to the center member dynamically isolate the shaker from the beam horizontally, and a cantilevered leaf spring takes the vertical load.

2. A special auxiliary flexure was devised to maintain coil centering in the M-B C25H shaker.

3. A special environmental chamber was devised to fit on the shaker; this chamber incorporates an air spring to provide centering of the shaker table during horizontal vibration conditions.

4. The slip-ring assembly includes twenty (20) shielded instrumentation rings and fifty (50) rings rated from ten (10) to one hundred (100) amperes.

5. The system includes a concentric tubing swivel assembly. A vacuum can be maintained in the four (4) inch outer swivel tube while cryogenic fluid is carried by the one (1) inch inner swivel tube.

6. In conjunction with this system, the helium system can be

programmed as to temperature (-150°F to +500°F and flow rate (0 to 2 pps) and altitude can be programmed.

The combined environmental apparatus of the AiResearch Division of The Garrett Corporation has not yet made its debut; and as noted above, the efforts of Aerojet-General were dropped because of financial limitations. The early WADC effort was primarily directed to working out difficulties of the combined environmental apparatus proper. Although combined environmental testing of propulsion system solenoid valves was accomplished and interesting behavior was noted, it was not established that the combined environment of acceleration, vibration and temperature was more significant than the simple combination of vibration and temperature.

Results obtained to date have come mainly from the efforts of NAA, Stellardyne, and Wyle Laboratories.

The programs of combined environmental testing are all in their early stages, and the results do not yet show a definite pattern. Some examples of the varied results are given below:

At one extreme of the spectrum of testing results is a missile propellant tank pressure regulator. The valve went completely unstable during the test and finally ceased to regulate. Subsequent inspection showed that the poppet valve in the shut-off assembly had worn severely and was the primary cause of the malfunction. The specimen had been subjected to a preconditioning humidity and icing cycle at 14 ± 4°F. The specimen was then subjected to a centrifugal acceleration of ten (10) g applied in the Z axis, and random vibration at a level of ninetenn (19) g RMS was applied in the Y axis. Once these conditions were established, a temperature-altitude-flow program simulated missile conditions by varying the inlet flow temperature from +100°F to -100°F to +450°F along a specified curve, and the ambient pressure was varied from 14.7 psia to ballistic missile altitude. This was a very severe test and the regulator failed. Needless to say it is desirable that ballistic missile regulators pass such tests, but at the present time the ballistic missile program cannot afford to eliminate regulators that do not pass such a test. In discussing this regulator the prime contractor project engineer stated that laboratory test results are considered only an index of comparison and that flight is the only valid basis of evaluation.

At the other extreme of the test result spectrum, Stellardyne Laboratories tested a ballistic missile accumulator relief valve and a low flow engine regulator under conditions of eight (8) g acceleration and twenty-five (25) g vibration. Generally, there was no apparent effect.

Between the extremes of "accelerated failure" and "no apparent effect", there is an area that requires close scrutiny.

North American Aviation, Inc., Missile Division conducted combined environmental testing during the development of the solenoid valve in the AFBMD New Valve Design and Development Program. During this testing it was discovered that under conditions of acceleration in line with the solenoid slug and vibration perpendicular to the acceleration, the solenoid valve leaked excessively. Single environmental vibration testing at high g levels produced a similar effect. However, it was necessary to impose an artificially high vibration level that had no correlation to missile flight conditions. Combined environmental testing has direct correlation.

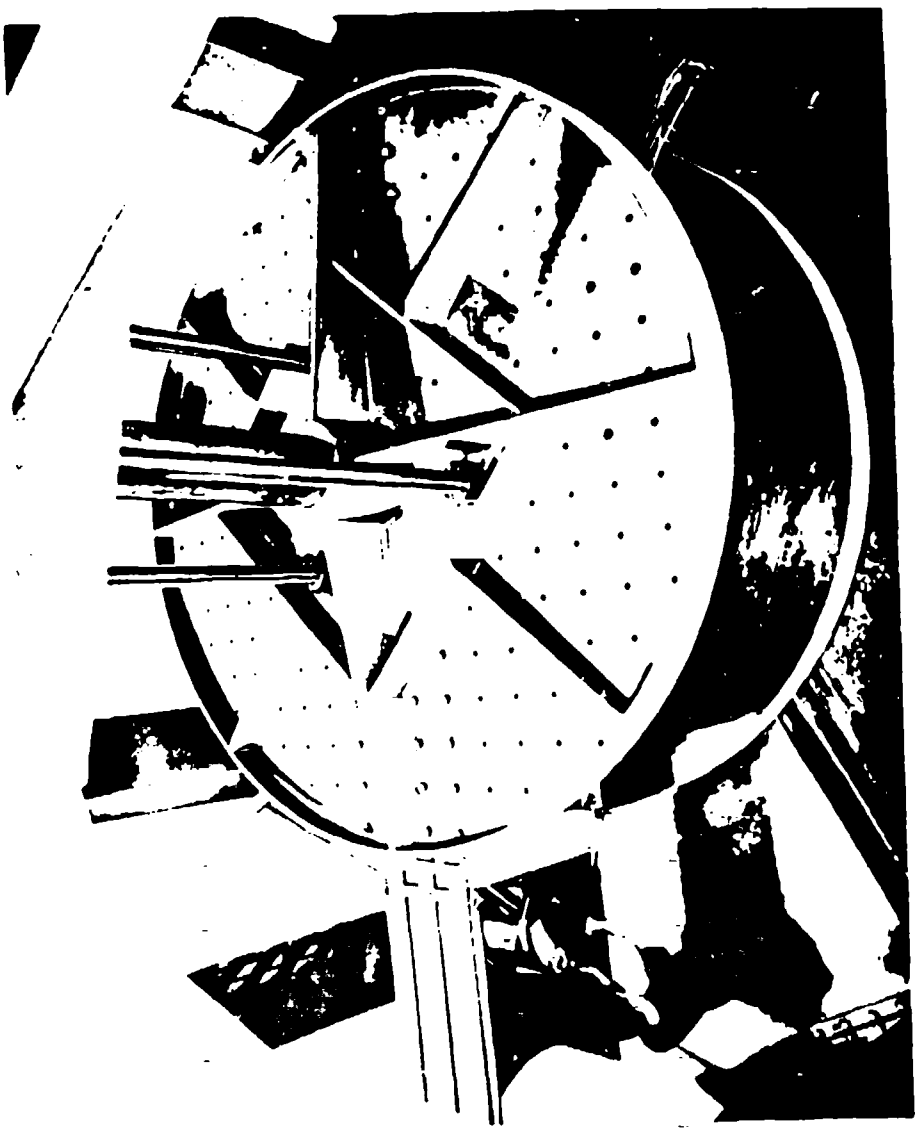
Another malfunction occurred during the qualification testing of the Frebank Company pressure switch, another component developed in the AFBMD New Valve Design and Development Program. In the initial phases of the qualification testing, these pressure switches were subjected to dual environments of vibration and temperature. The pressure switches were subjected to twenty-five (25) g vibration scans from twenty (20) to two thousand (2000) cycles per second while immersed in temperature control boxes at -300°F and +300°F. These components showed no tendency to chatter or malfunction. However, during combined environmental testing a switch failed. Investigations showed that the failure was the result of a fabrication problem in which the high heat of soldering had caused the electrical elements to lose their temper and distort the plastic case. The intensive testing of scrambled temperature, attitude and vector combinations rapidly brought about a failure that would have been attributed to random causes on a missile.

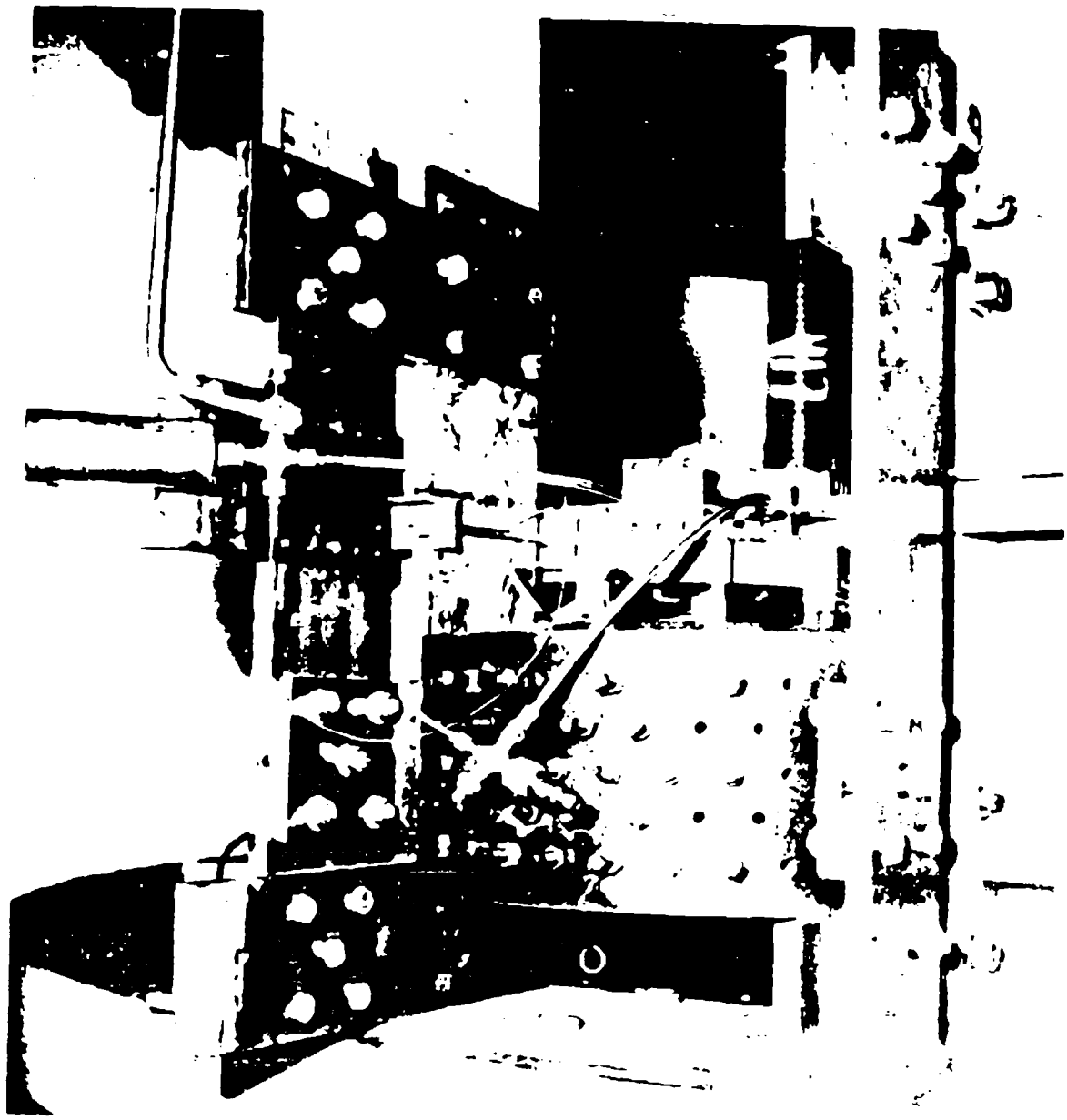
Results of combined environmental testing are only beginning to become available from the AFBMD programs.

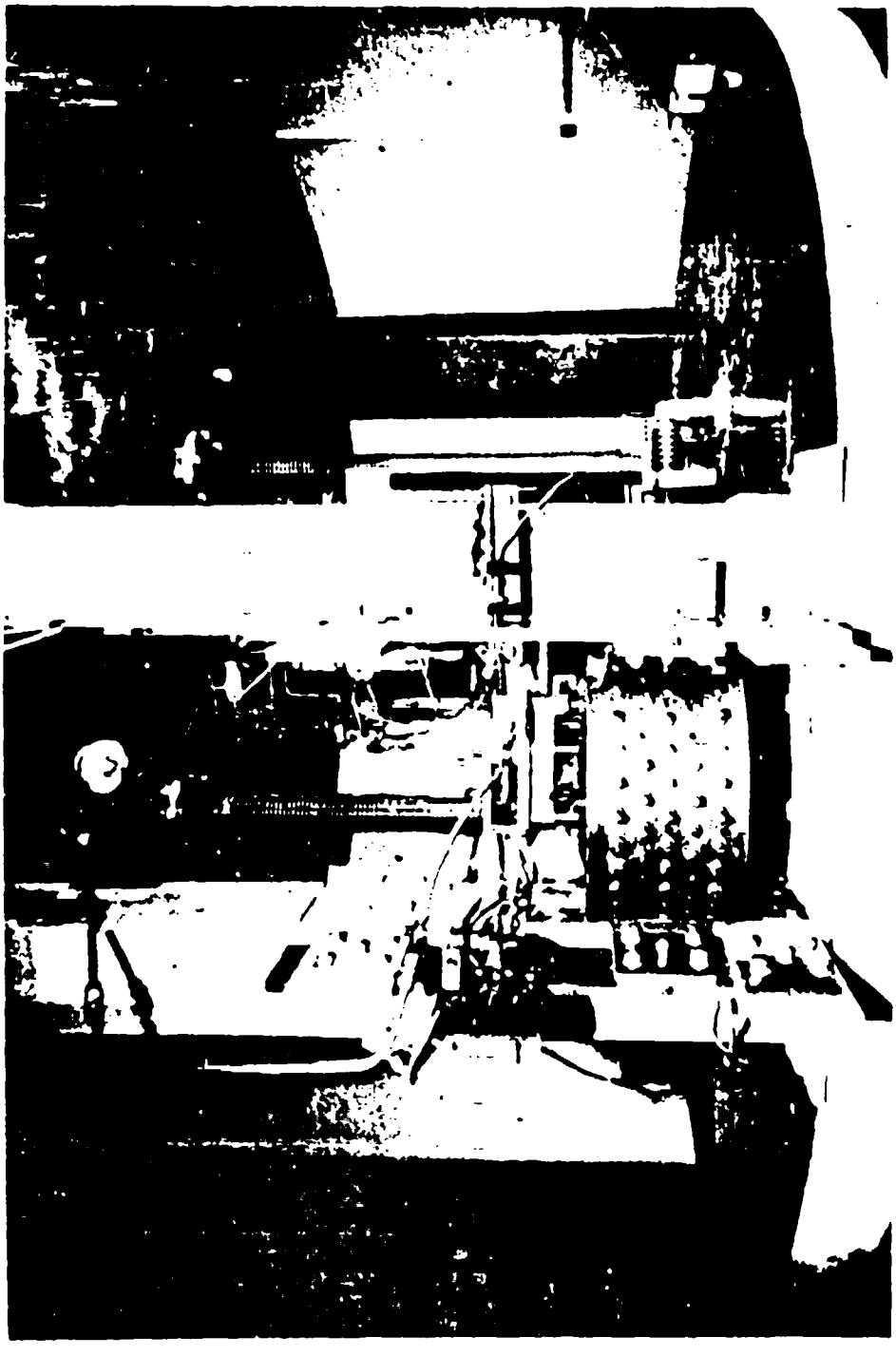
Combined environmental testing is currently proceeding in both the New Valve Design and Development Program and in the evaluation of current ballistic missile hardware. Each test adds another bit of data for the evaluation of this mode of testing for increasing the reliability of ballistic missile components. In the meantime, consider three bits of data: one, a complex ballistic missile propellant tank regulator that failed under combined environmental testing; two, the failure of a pressure switch that had completed intensive single environmental testing to such a degree that all engineers associated with it were positive that it would pass; and three, a prime contractor that considers laboratory testing insufficient evidence to determine flight worthiness. Each instance indicates present testing methods are insufficient.

The significance of combined environmental testing is that it will judge a component by a much more rigorous standard than the wisest of engineers uses when evaluating the results of single environmental testing. If the design meets this rigorous test, the prime contractor can have a new confidence in the inherent reliability of the component.

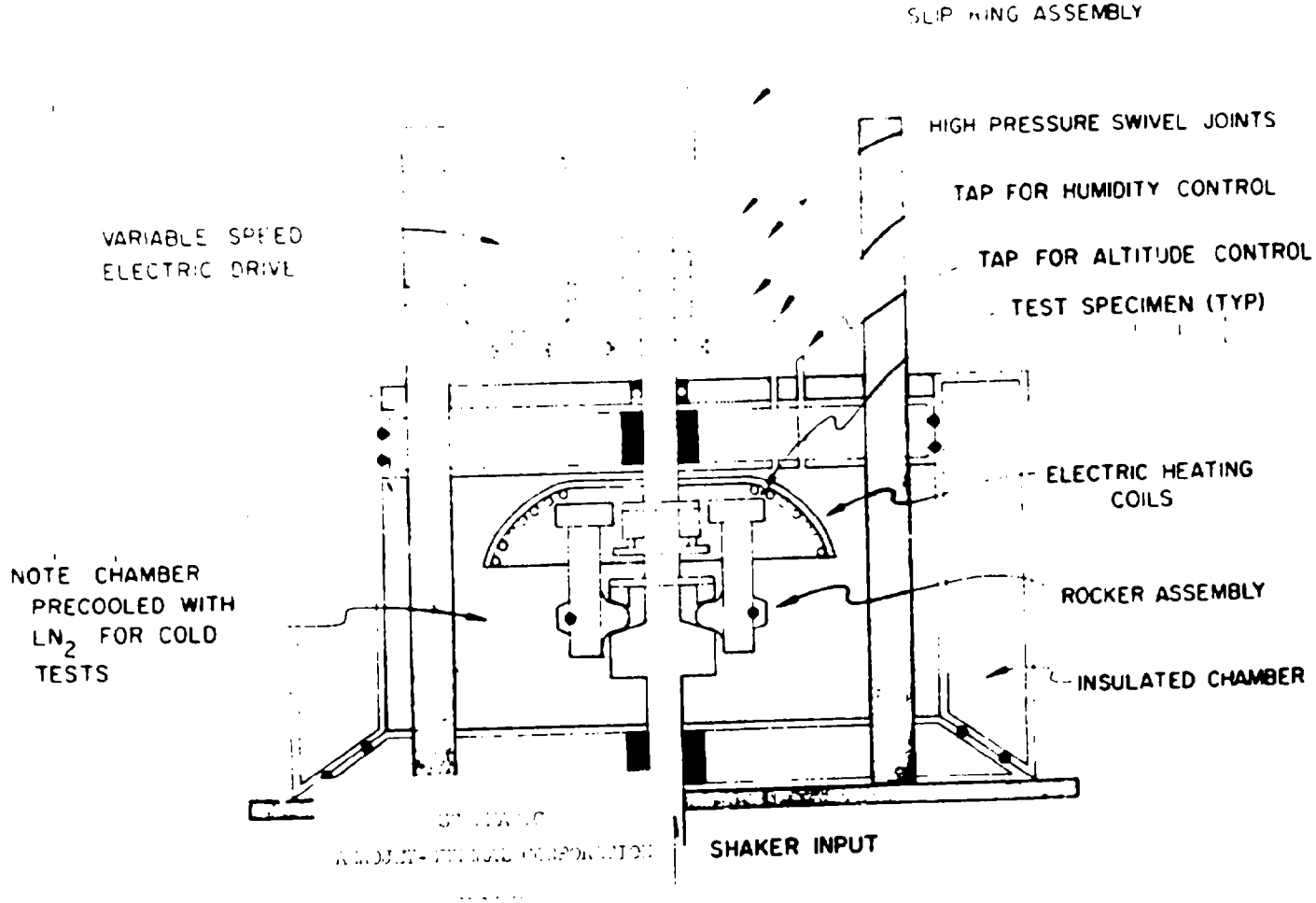
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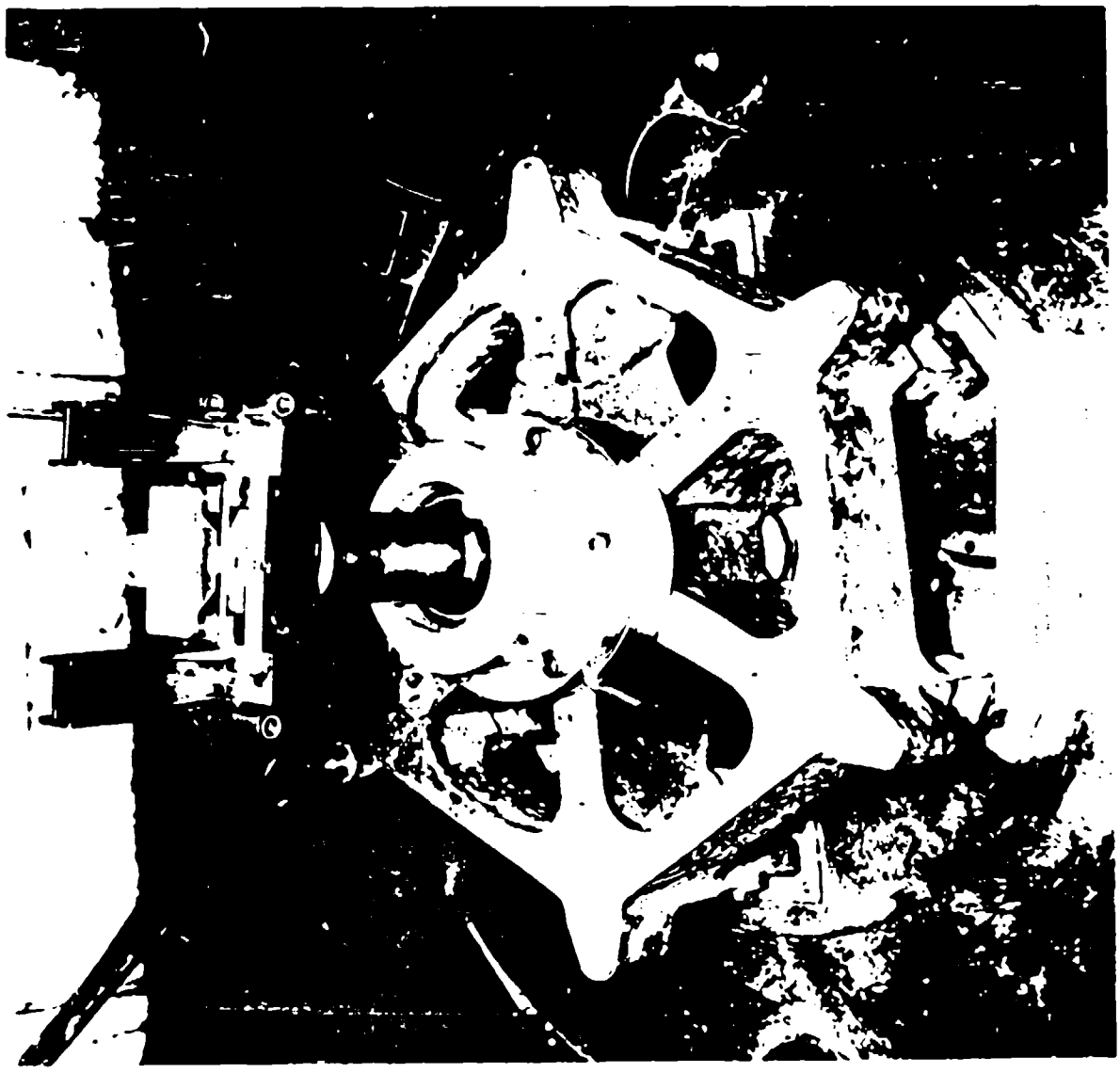


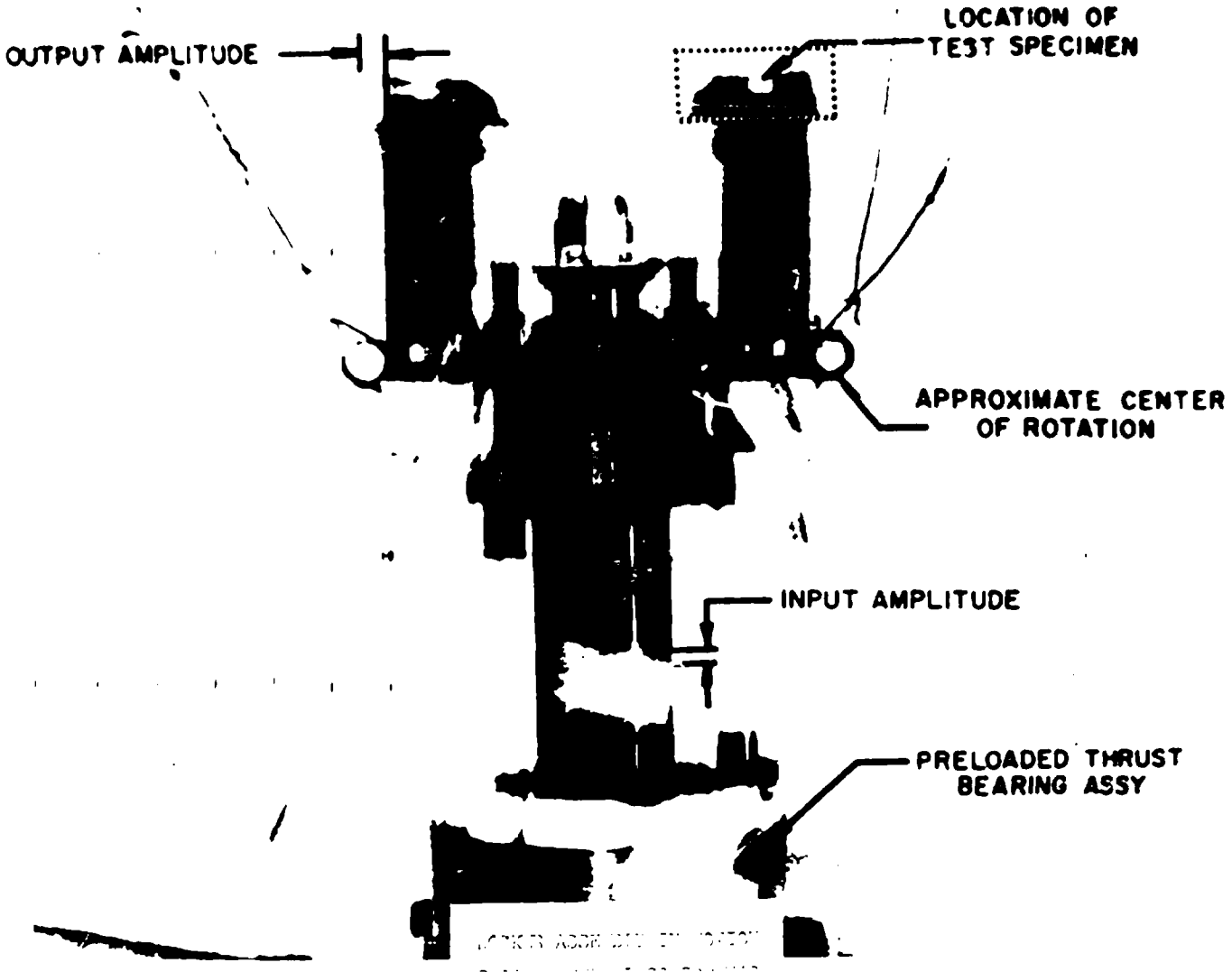




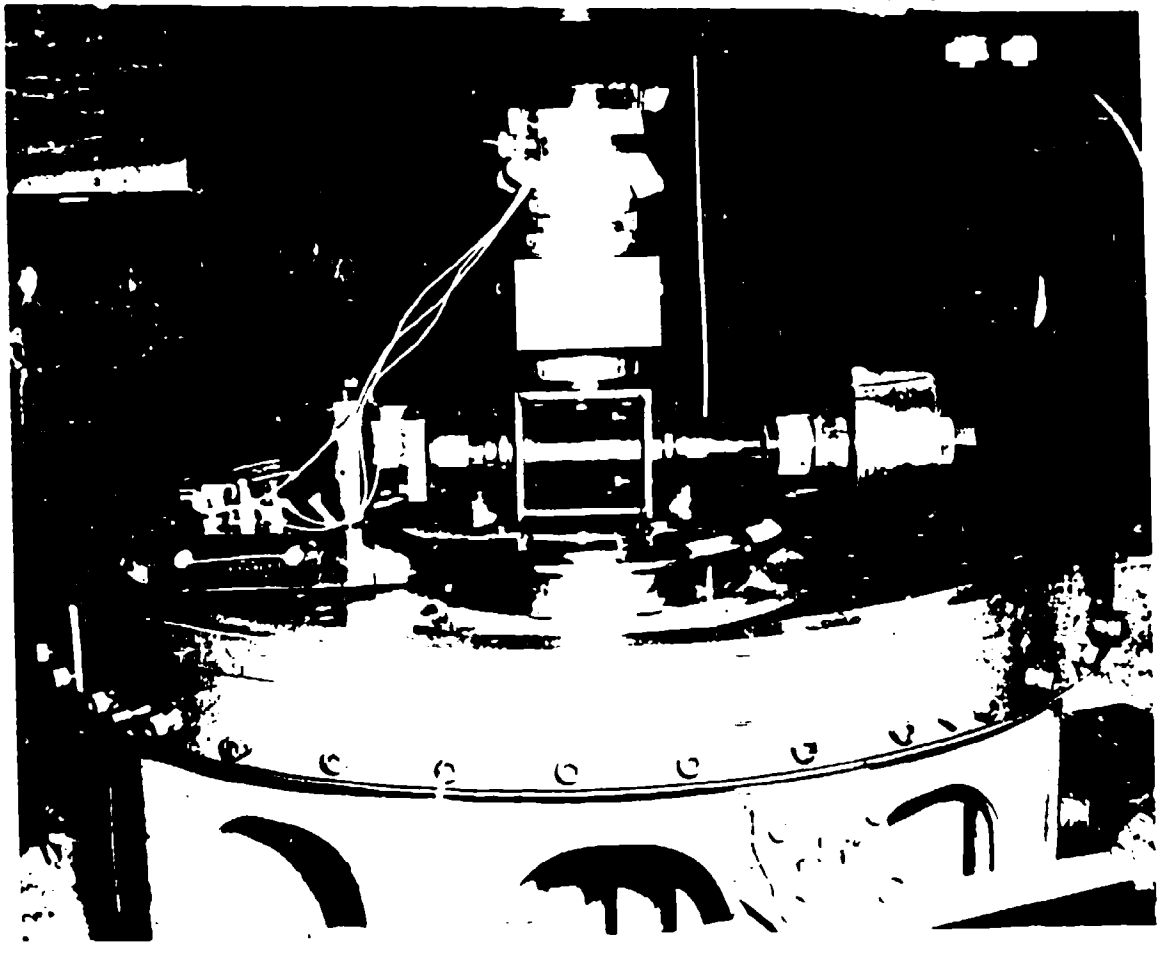
COMBINED-ENVIRONMENTS TESTER

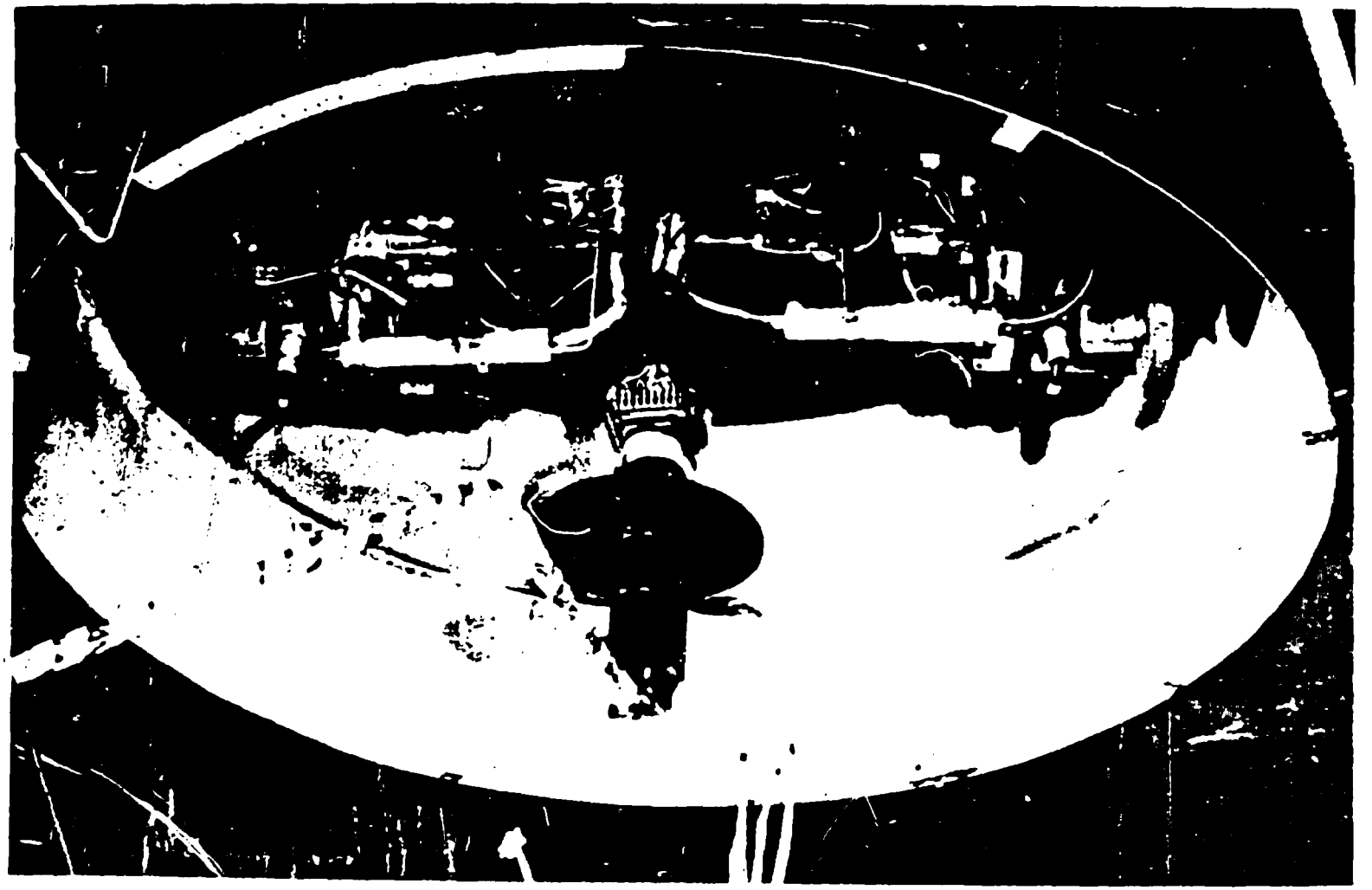


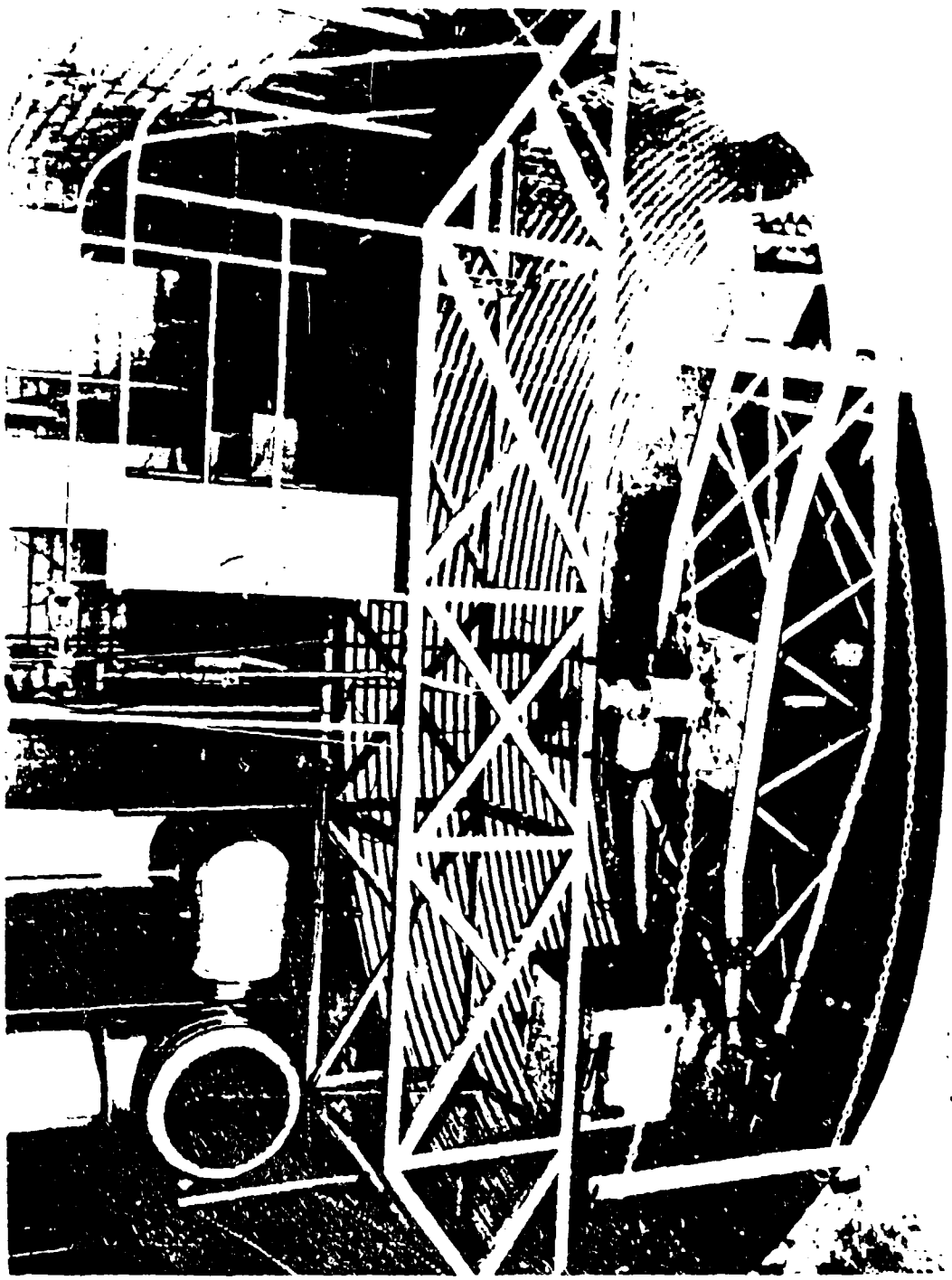


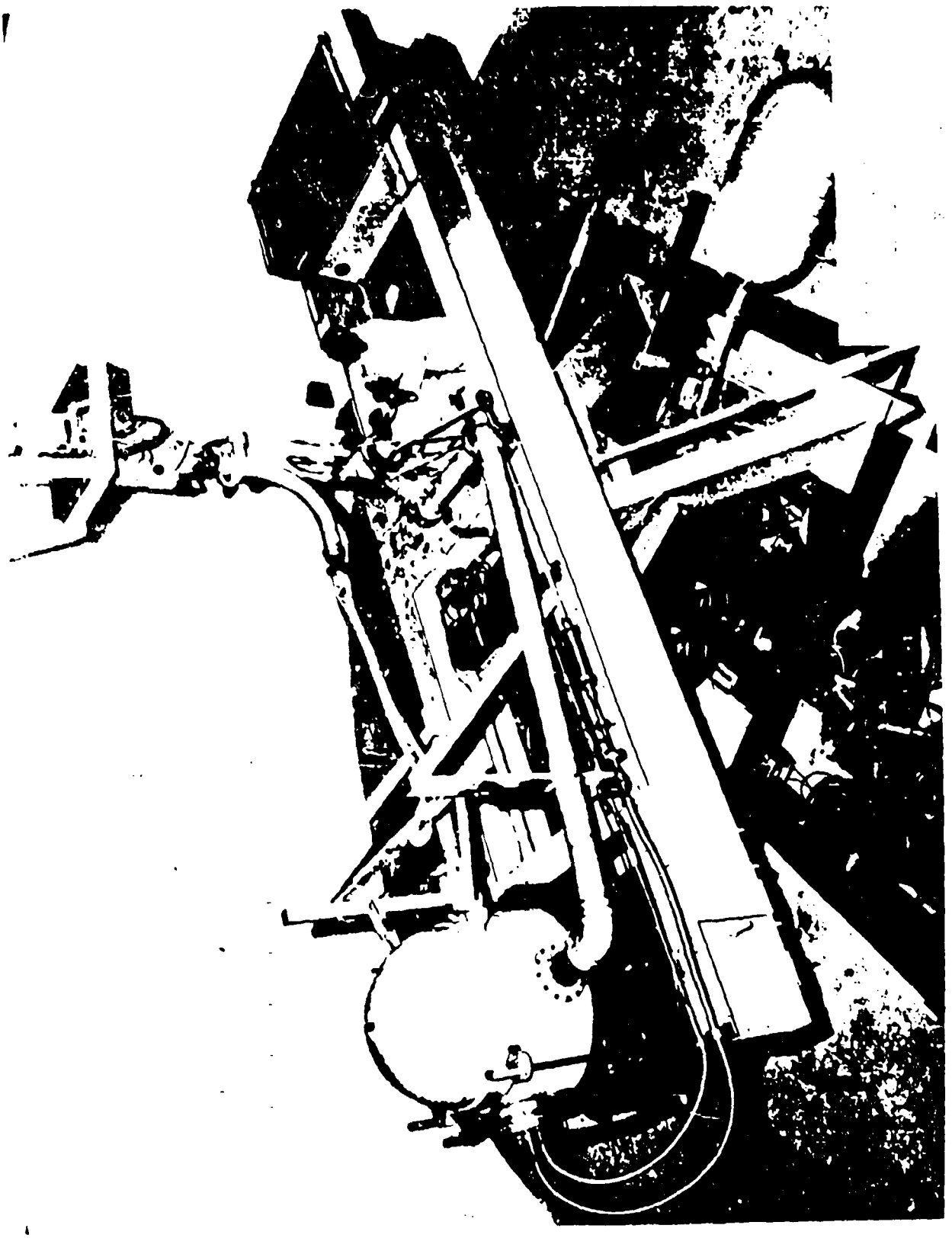

OUTPUT AMPLITUDE
LOCATION OF
TEST SPECIMEN
APPROXIMATE CENTER
OF ROTATION
INPUT AMPLITUDE
PRELOADED THRUST
BEARING ASSY











RELIABILITY THROUGH ENVIRONMENTAL TESTS

T. L. Commons
Bendix Mishawaka Division
Mishawaka, Indiana

INTRODUCTION

Environmental testing today is done under a wide range of programs, given various names and classifications and performed in varying degrees of severity. At Bendix-Missiles, we have four categories or classifications of tests for evaluating our product: Design Margin Evaluation, Design Evaluation, Quality Assurance, and Production Test. There are, undoubtedly, numerous other classifications and names given by other manufacturers for environmental tests which may or may not have the same definition as the tests performed at Bendix-Missiles. However, all the names, classifications, and severity of tests have only one ultimate purpose--reliability.

The Engineering Department at Bendix has an evaluation laboratory which evaluates and qualifies small piece parts such as capacitors, resistors, etc., but this paper deals only with those tests which are performed by the Quality and Reliability Department, henceforth called simply "Quality" Department, either alone or in conjunction with the Engineering Department. This does not mean that Quality is out of the picture in regards to piece parts. On the contrary, Quality is very much concerned with the parts evaluated and the results obtained. However, test procedures are written, tests performed, results analyzed, and conclusions drawn entirely by the evaluation lab. In the case of the other tests performed on the larger items, such as gyros, inverters, modules, systems and missiles, Quality and Engineering together determine what tests are to be performed and the Quality Department is then responsible for writing the test plans and test procedures, performing the tests, and writing the reports. During the entire testing phase, numerous conferences are held with Engineering to clear up problems that arise, or to change the test plans as a result of some previous test. Figure 1 is a block diagram of the Quality organization within Bendix-Missiles.

I might explain the difference between "piece part," "component," and "subassembly" as they are used by Bendix. The major difference between piece part and component is the dollar value. The term "piece part" is applied to all items costing less than an arbitrary figure of $50.00. A "component," besides being expensive, may also be considered as consisting of a group of piece parts made

up into an assembled or a potted unit. A "sub-assembly" usually refers to a mechanical sub-system on the same level of complexity as a component. An example of each of these would be as follows: piece parts - resistors, capacitors, tubes; components - magnetrons, klystrons, inverters, gyros; sub-assemblies - fuel pump, hydraulic pump, actuators, servos.

RELIABILITY EFFORT

Reliability is an essential organization at Bendix-Missiles and their activities are varied. The Reliability Group at Bendix is in the Quality Department and reports directly to the Quality Manager as indicated in Figure 1. Reliability is responsible for an extensive failure reporting system which covers the sub-contractor, in-plant, and field operations. The group also provides engineering investigation and follow-up, statistical and mathematical assistance in setting up and analyzing tests and test results, statistical and mathematical analysis of failure data, and, also, conducts quality examinations and Quality Assurance Tests.

As part of the engineering follow-up, individuals in the group are responsible for monitoring various activities within the plant. One of these activities is the Environmental Test Laboratory where all Design Margin Evaluation (DME), Design Evaluation Tests (DET), and Quality Assurance Test (QAT) Programs are conducted. On all test programs, we in Reliability provide Engineering with historical failure data as well as engineering and mathematical assistance in analyzing failures that have occurred under test. We also assist in evaluating the changes that have been initiated as a result of the failures. An example of this type of assistance occurred during a DET program. Two crystal diodes had failed during test. One of the test engineers on the program recalled that they had had some failures on these diodes on the production floor. A request was made to Reliability to investigate the failure history of this diode. The investigation proved that the diode had a failure history at one time but that steps had already been taken by Reliability to cure this problem, which was due to mishandling by assembly and test personnel. Later reports indicated that the failure rate had definitely declined.

Another instance occurred when a plug shorted out. One of the follow-up engineers remembered that a similar failure had occurred a couple of months previously. It was assumed by the test personnel at the time that the plug was mis-wired since the short existed between a live pin and a spare pin and the plug was discarded. However, the junction on the unit to which the spare pin is mated is wired to ground for other test purposes. When the second failure occurred, both plugs were depotted by Reliability and it was discovered that the

plugs were wired with bare wires and that one of the wires had shorted against a spare pin. It was also discovered that the automatic test equipment used for testing the plugs had not been wired to detect shorts that existed between used and unused pins. Corrective measures were taken immediately.

The failures mentioned here were not peculiar to the environmental test being performed since similar failures occurred elsewhere. But these two examples do point out some of the assistance provided by the Reliability Group. Some of the failures that were detected as a result of the test program will be shown later along with some of the test setups and environmental equipment used.

Reliability has also provided extensive assistance in evaluating the accuracy, stability, and reliability of some automatic test equipment. The analysis section of the Reliability Group devised the test sequence and specified the data to be recorded. The data was analyzed, results derived, and recommendations made regarding maintenance and adjustment schedules. A complete description of this test is given in another paper. * Another test statistically controlled by Reliability was an interchangeability test. This was performed by exchanging parts and units from several different missiles in a statistically controlled sequence and determining the effects on missile performance.

TEST PROGRAM

At this time, I would like to discuss the philosophy and purpose which Bendix-Missiles has in performing these various tests. Figure 2 indicates the "ideal" sequence which we attempt to follow in carrying out this entire test program. As illustrated in this diagram, Design Margin Evaluation Tests (DME) are usually performed on one or more of the first engineering models produced. The environments to which these units are then subjected determine the ultimate capabilities of the missile design. The tests as performed are necessarily detrimental to the test specimens since to determine the ultimate capabilities means invariably testing to destruction. However, we feel that this is a very necessary expenditure and a profitable venture in the long run. The changes necessary to correct flaws of design or construction discovered during these tests are put into the pre-production or production prototype models.

As indicated in Figure 2, it is at this stage of the test program that the Design Evaluation Tests (DET) are begun. Although the same tests are conducted in both DET and DME, the severity level of the environment is considerably decreased in the DET. The purpose of DET is to determine if the missile, module or component will meet the requirements as called out in the design specifications. This means testing to the limit of the specification requirement and

no further, and also tests which are not necessarily destructive in nature. After a sufficient amount of rework, the test items are frequently used for special engineering flight tests or additional marginal testing. If any design changes are deemed necessary as a result of the DET program, these changes are then put into the early production models.

The next phase of the test program is a joint phase with both Quality Assurance Tests (QAT) and Production Tests being performed at the same time. Production Test is the normal routine method of providing the customer with the assurance that he is receiving a product that is functionally correct. Production Testing consists of operating the units under static environmental conditions by applying electrical and mechanical power and varying the input parameters in a predetermined sequence to ascertain if the unit responds correctly. Other than the few words just mentioned, I do not intend to spend any more time on Production Test, but will go on to the final subject as indicated in Figure 2, Quality Assurance Testing. Where Production Tests are simplified acceptance tests based upon minimum acceptance criteria, QAT are tests taken directly from the DET test program, and DET test procedures are used. Production Tests are performed on every major unit and every missile as well as some sub-assemblies, components and parts while QAT is performed on a sample basis on these items.

There is one major difference between DET and QAT. Each missile and each module which is used for DET receives the entire sequence of tests. In other words, each unit is tested to the entire design specification. In QAT, each sample of missiles and modules is subjected to only a few of the tests at a time, but over a series of several samples, all of the tests performed in DET will have been performed under QAT.

On the component and sub-assembly level, each sample in QAT will receive only those tests which are judged to be the most critical to the construction and design of these parts, and these tests will remain the same on all samples unless a design change reflects a change in the sensitivity of the unit to the environment to which it is being subjected. Piece parts are in a slightly different situation from the categories of units just presented in that each lot of piece parts received is sampled and each sample is tested to the environments judged to be the most critical for that type of part.

Reliability in conjunction with the Test Engineering Group conducts the entire QAT program. Test Engineering is responsible for the larger items such as missiles, modules, assemblies and systems, with Reliability providing mathematical and engineering follow-up assistance. Reliability is responsible for

conducting the test program on small piece parts, components, and sub-assemblies with the assistance of Test Engineering and Evaluation Engineering.

To illustrate in more detail how the QAT program operates and to what extent the tests are performed, Figure 3 gives what might be considered an operating schedule which could be used on six (6) items. These items could be missiles, modules, or assemblies and would not necessarily be limited to six. The number of items tested would depend on two things: the capabilities of your testing laboratory unless you contracted your testing out to someone else, and the number of items you are producing over a given interval.

You will notice that Figure 3 lists only 12 codes. There could be many more in which case you would change your testing schedule accordingly. Code number 12 is used to provide sufficient time and funds in your program for any possible rework that may be necessary as a result of the tests performed and for the necessary Production Tests after rework. Because QAT is not designed to be detrimental and the number of tests performed on any one item is limited, the units are normally considered acceptable by the customer after production retest operation. In this instance, the number of tests being performed on any one unit has been limited to four.

There is no real need to adhere to a firm schedule or test sequence such as presented above. Occasions may arise when a unit type develops a series of troubles during the program and a close periodic check is made over a period of time where the same test is repeated on succeeding QAT units until you are sure that the trouble has been adequately corrected. Also, the customer may have some complaints from the operations out in the field, or in our case the fleet, and the customer desires that you prove out some units in the QAT program under the conditions which have shown up a problem area.

As mentioned previously, the QAT program conducted on missiles, modules, and other major items is performed under the cognizance of the Test Engineering Group. This group is responsible for writing the test plans and test procedures and for making known to Engineering and Quality any failures that develop as a result of the tests conducted. To inform the various organizations of these failures, two forms are used. (1) A TALOS Discrepancy Report known as a Test Tag, Form 494. This is the normal discrepancy reporting test tag used throughout the plant and is the reporting form for which the Reliability Group is responsible. (2) A two page report form referred to as a Corrective Action Report (CAR). Figure 6 shows the Test Tag, Form 494, and Figures 7 and 8 show the two-page document used by Test Engineering.

Reliability immediately receives a copy of page 1 of the CAR as well as the Test T. g. If the failure is such that comments and analysis are required from Engineering, Engineering then fills out page 2 and returns it to the cognizant test engineer with a copy also being sent to the Reliability Group. From past failure data and engineering knowledge, Reliability determines if the recommended action is sufficient and if the comments made are appropriate. When the tests are completed, a complete report is made to the customer, indicating the test performed, discrepancies found and action taken. When all the action to be taken is completed, a supplemental report is issued to the customer and the entire cycle starts over again.

In regards to the QAT program being conducted at the present time by the Reliability Group on piece parts, components, and sub-assemblies, this operation is performed both at Bendix-Missiles and at our subcontractors. Figure 4 describes this program. The subcontractors are responsible for about 90% of the testing effort on the piece part program and the Missile Plant accounts for the other 10%. On the other hand, Bendix-Missiles conducts and performs all the testing on the components and sub-assembly QAT program. Figure 4 is just an indication of the over-all flow of piece parts and test results and is given to show the participation by the various organizations in the test program. Figure 5 goes into more detail on the present QAT operation on piece parts which was my main interest at the time this paper was written.

QAT is a relatively recent idea at Bendix-Missiles and was inaugurated only a little more than a year ago. As in most cases, we started small and planned to build up to a full scale QAT program after we had learned more about what we were intending to do and to accomplish. For this reason, you might say we have had three different QAT programs on piece parts. For discussion purposes let us refer to them as the "introductory," "intermediate," and "standard." This is not to preclude further modifications of the approach used, but simply to define the programs which have been considered and used to date (reference Figure 5).

The "introductory" program was intended primarily as a learning process for the Reliability Group Planning and Test engineers. In this program we tried to establish our ground rules, our objectives and our methods. Engineering judgment was tested and refined. Specifications were reviewed, test methods studied, and various blind alleys and impracticalities rejected. All testing was performed at Bendix-Missiles using the facilities of the Environmental Test Lab. Although a tentative test plan was prepared and approved before testing started, detailed test plans and procedures were not prepared in advance. A Reliability Engineer assigned to the project coordinated all testing, procured parts and equipment, monitored operations, and made decisions on the spot. The logs and test reports

prepared for this program formed the basis for further study and development. Although this was a low budget program and sample sizes were comparatively small, results were useful in taking action on poor quality hardware. Fortunately, from the QAT viewpoint, about midway through this program a serious part quality problem was found in production testing. This problem would, in all likelihood, have been detected and eliminated by a complete QAT program if one had been in operation at the time. The savings in cost and time which QAT could have effected were quite helpful in showing top management the need for QAT.

As soon as possible after the "introductory" program got underway, preliminary planning for the "intermediate" program was started. Time and funds available were again somewhat limited, although considerably greater than for the introductory program. A "General Test Plan for QAT Program" was prepared and approved by the Navy. This plan established the basic concept and approach to be followed. A second "Test Plans for Piece Parts QAT" was then prepared to define in some detail the tests to be performed on various classes and types of parts, components, and sub-assemblies. Test Requirement Sheets were included for each type of item; these sheets defined the environments and operating conditions to be imposed during test. As a rough rule of thumb, we attempted to restrict the tests to the four to six most critical tests in the DET sequence. In all cases, loads and environments were held to the level imposed by the procurement specification. These sheets were prepared by Reliability Engineers assigned to the project, and were discussed and coordinated with the Test Engineering and Evaluation Engineering Departments.

Testing was conducted both at Bendix-Missiles in the Environmental Test Lab, and at the plants of major subcontractors in the program. Special purchase orders were written to authorize and fund the subcontractor effort. Each subcontractor was required to determine a sequence of testing parts to ensure the most effective use of funds and to minimize the amount of production rework necessitated by the discovery of bad quality. In other words, each subcontractor was asked to review his own records and exercise his own judgment to ensure testing the most critical items first. This schedule and the detailed test procedures written by the various subcontractors were reviewed and approved by the Bendix-Missiles Reliability Group before testing started. Test results were sent to Reliability at Bendix-Missiles for information and follow-up.

When a failure or failures occurred which had a definite effect on production and the test program, the Reliability Group was immediately notified and suitable action was taken to alleviate the problem. On such occasions, the subcontractor was asked to take the necessary steps in his plant and also to contact his vendor

to correct the existing situation. At the same time, other subcontractors using the same part and same manufacturer were notified and requested to check their stock.

The "standard" program modified the basic rules of the "intermediate" program in that the majority of testing and preparation of detailed paper work was made the responsibility of the subcontractors. The "Standard Quality Requirements for Purchased Material," the basic quality spec for all subcontracted material, requires each subcontractor to establish and operate a piece parts QAT program as part of his normal operations on TALOS contracts. The responsibility for planning and documenting the test program under this program rests with the subcontractor. To maintain control, this specification requires each bidder on a subcontract to include a description of his proposed QAT program with his proposal. In this proposed QAT program he describes his approach, concept, capability, equipment requirements, and program cost estimate for review and approval by Bendix-Missiles. After a contract is awarded, the subcontractor has a definite deadline, before delivery of the first unit, to start testing. Detailed test plans and procedures are prepared by the subcontractor and approved by Bendix-Missiles Reliability before this testing can start. The responsibility for taking action, both internally and with parts vendors, rests with the subcontractor and is carefully monitored by Reliability. Various test reports and status reports are required for control.

A considerable amount of paper work was required to start the program and even more is required to keep it going, but with the funds available and time limit involved to get the program into operation, it was thought necessary to use the subcontractors' existing test laboratories rather than build a new lab or expand our own. This program, however, has been effective, and will increase in effectiveness with time and increased experience. In the long run, however, this method is probably the most expensive and not the most effective for a piece part QAT program. Even though the over-all missile program may require several thousands of parts, when this amount is divided up among eight or nine subcontractors over a period of one year, the amount of parts coming in per month at any one place is small. The test sample in most cases has to be made up from several shipments in order to get a sample size of any significance. By this time, the program is well underway and if a problem does develop which requires any sort of retrofit action, the expense and production schedules are greatly affected.

There are two alternate solutions to a situation such as this where the prime contractor, and in some instances the customer, requires an extensive QAT program on piece parts and the contract is divided up into many sections. The

first method that could be followed is to have the part vendor responsible for initiating and carrying out the QAT program on the piece parts. This type of program might be impractical since each prime contractor has a different environmental requirement and to impose all the requirements on any one part would probably be prohibitive from the cost standpoint alone.

The second method which I believe to be the most effective and, over a long range program, the most economical, is to set up a central inspection and testing center, as illustrated in Figure 9, controlled by the prime contractor but set up to operate as a separate agency. This center would be responsible for inspecting and testing all electrical piece parts used in the program, and would also have the responsibility for taking action with the various part vendors. The center would serve somewhat the same function that the Reliability Group QAT effort does at the present time at Bendix-Missiles. This method would ensure prompt action on test results that are derived from better statistical test samples.

Since this central agency would be concerned only with the quality of the piece part, the prime contractor through his failure reporting system could feed back information received in his own plant plus that information received from his subcontractors and from his customer in the field. This system could provide close control over the continuing quality of the piece parts and could also provide a direct control by the prime contractor who utilizes his own Preferred Parts List. Such control could be more effective than controlling subcontractors' purchases by means of this Preferred Parts List.

This second plan, as presented here, is only general in nature. The details of how such a plan would function and all possible pitfalls have not been worked out. I believe, however, that such a plan could be worked out which would benefit both the prime contractor with lower production costs and the customer with increased reliability.

Before closing, I should like to make some remarks concerning the test equipment used to conduct these various programs. In many cases, a strong argument is put forth that basic engineering test programs, such as our DME programs, should have the majority of funds allocated for equipment procurement, and the production test programs, such as our QAT, should use this same equipment after the original test program is completed. This is not only a false argument but a dangerous one. Our experience has shown us the necessity for providing high-grade test equipment for all of the programs described in this paper. Early test programs will frequently wear out test equipment to the point where accuracy is degraded or extensive and costly maintenance is required.

Differences in unit design between the original engineering model and the production model, such as the ones made as a result of the findings of the DME and DET programs, may render the original equipment inadequate unless extensively modified or even "hay-wired" to do the job. Although temporary hook-ups and arrangements may be permissible during early engineering tests--and this is debatable--the demands for repeated use in production tests and QAT programs make permanent installations necessary. Unless these equipment needs are considered from the start, the perennial conflict between production delivery costs and chedules on the one hand and QAT requirements on the other may result in the QAT requirements coming off second best. The idea of using "left-overs" and "hand-me-downs" for QAT should never be tolerated.

A complete test program, including an extensive Quality Assurance Test Program, is essential if the military is going to require a high reliability figure in a program as complex as the missile program is today. People have to be made to realize that such an extensive testing program in the missile industry is essential in producing a reliable product. I do not know the situation at other industries, but I do know that at Bendix-Missiles the test program outlined here is a necessary rather than a luxury program.

*Reference paper written by R. H. Hollis, "Missile Test Equipment Reliability Study," presented at the Sixth Joint Military-Industry Guided Missile Reliability Symposium, February 1960.

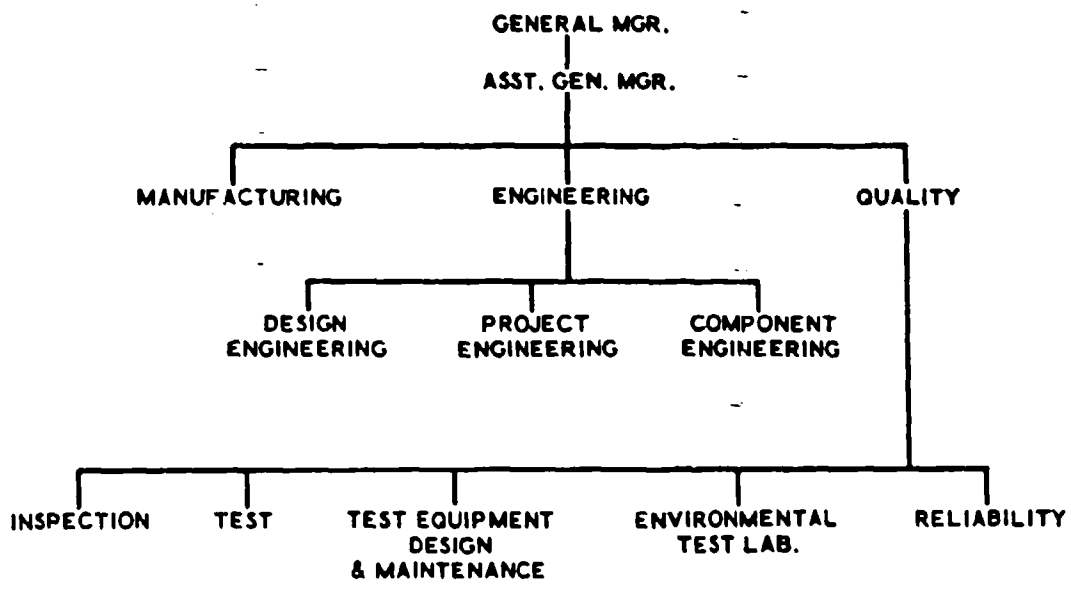


FIGURE 1 - ORGANIZATION CHART

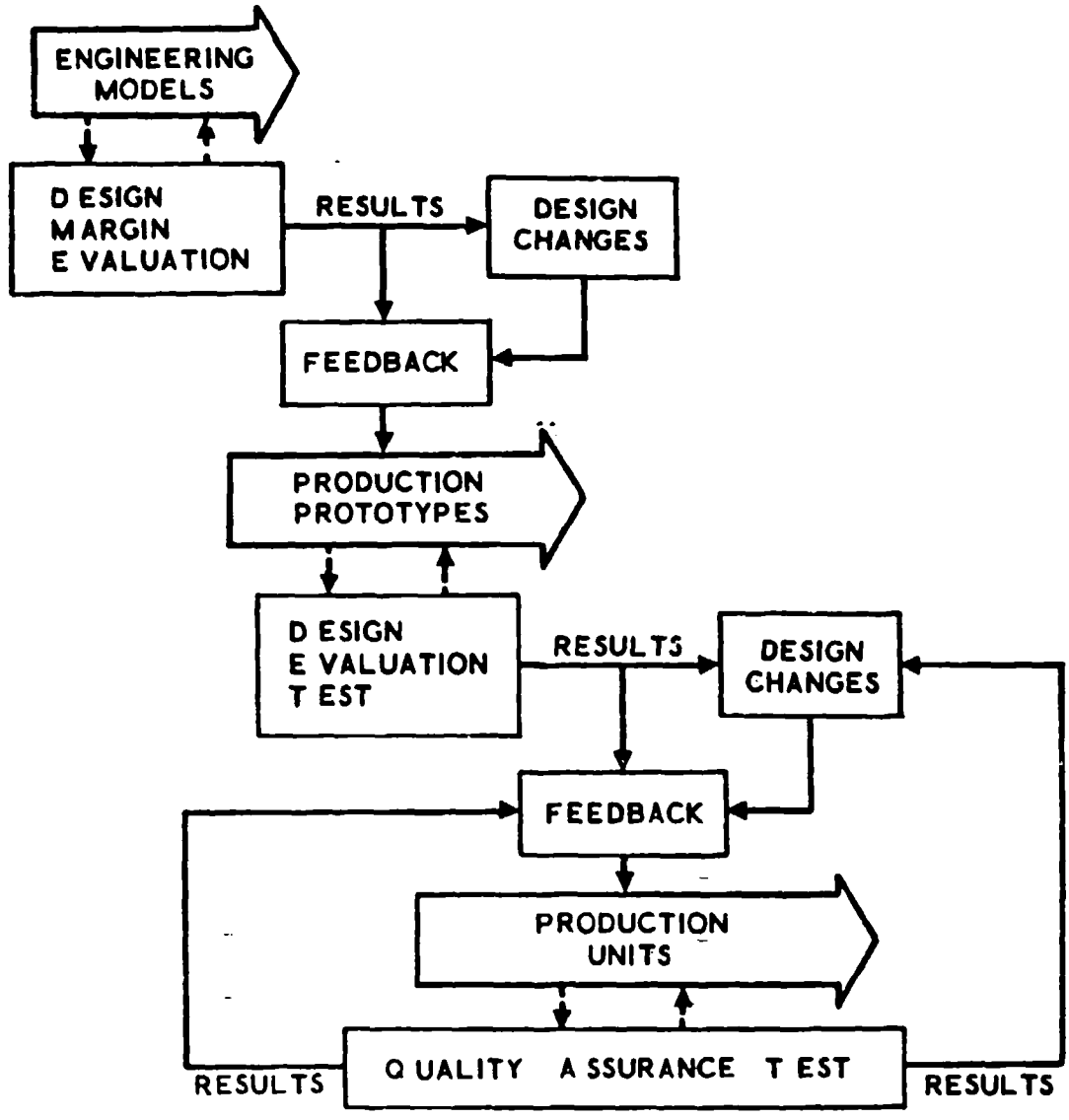


FIGURE 2 - ENVIRONMENTAL TEST FLOW CHART

UNIT NO.	TEST SCHEDULE	CODE
1	1 3 5 9 12	1. SHOCK 2. STORAGE VIBRATION
2	2 6 7 10 12	3. STOWAGE VIBRATION 4. ACCELERATION
3	4 8 10 11 12	5. HUMIDITY 6. HIGH AND LOW TEMPERATURE
4	3 6 8 11 12	7. TEMPERATURE CYCLING 8. RADIO INTERFERENCE
5	1 5 6 4 12	9. DEGREE OF ENCLOSURE 10. SALT SPRAY
6	7 10 9 2 12	11. ALTITUDE - VIBRATION 12. REWORK AND RETEST

FIGURE 3 - QUALITY ASSURANCE TEST SCHEDULE

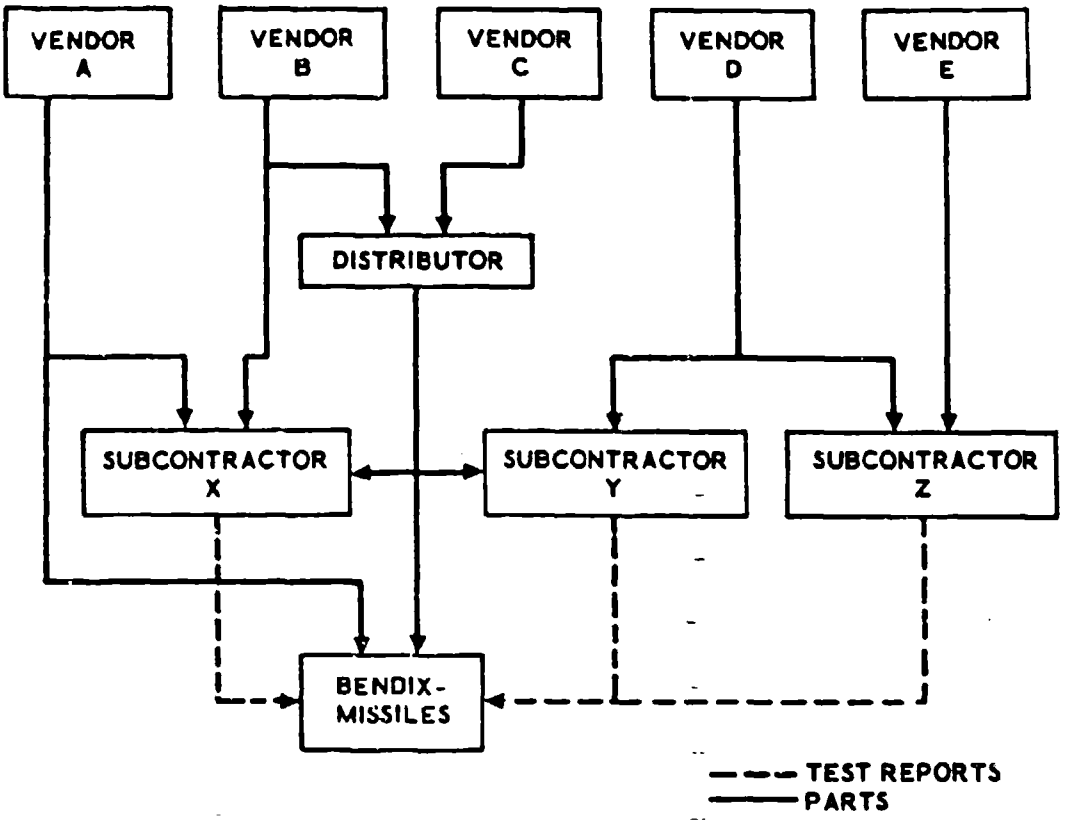


FIGURE 4 - PRESENT PIECE PARTS QA1 PROGRAM

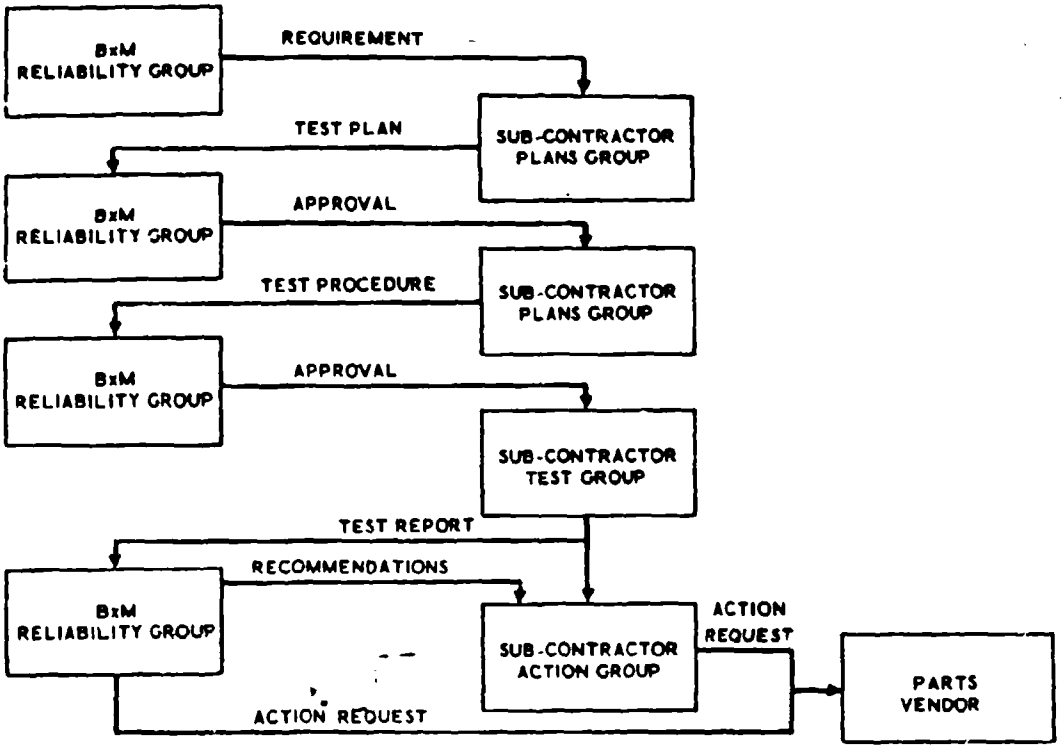
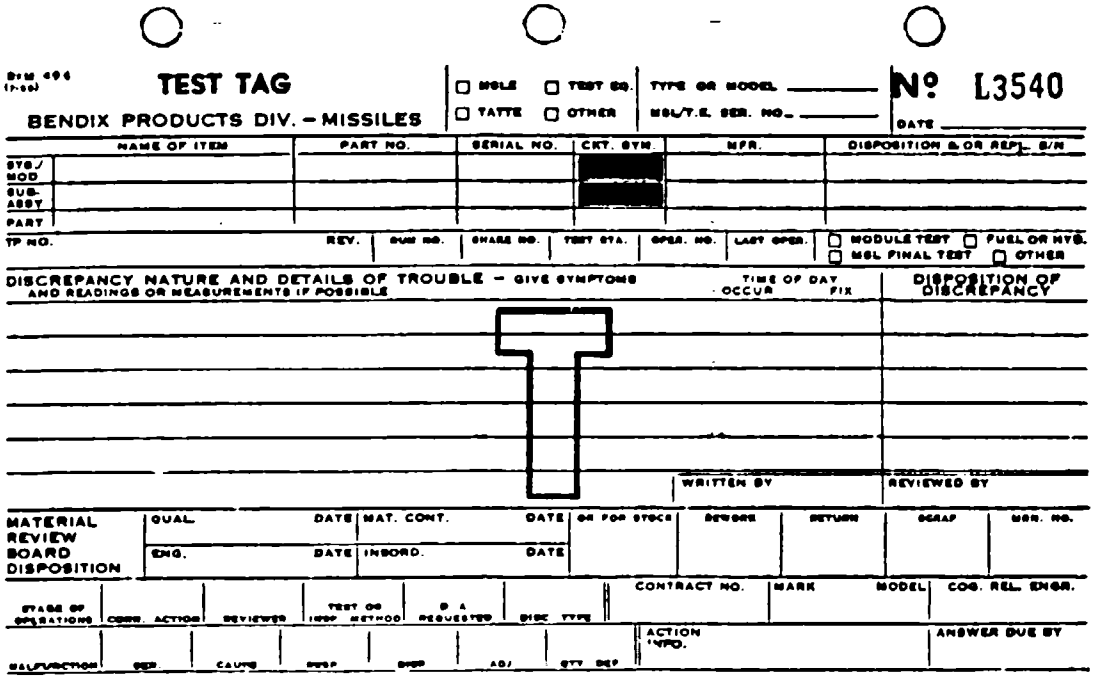


FIGURE 5 - PRESENT PIECE PART TEST PROGRAM



BENDIX PRODUCTS DIV. – MISSILES

TEST TAG

☐ MOLE ☐ TEST EQ. ☐ TATTE ☐ OTHER

TYPE OR MODEL _____ MSL/T.E. SER. NO. _____

Nº L3540

DATE _____

	NAME OF ITEM	PART NO.	SERIAL NO.	CKT. SYM.	MFR.	DISPOSITION & OR REPL. S/N
SYS./MOD						
SUB-ASSY						
PART						

TP NO. | REV. | DWG NO. | SHARE NO. | TEST STA. | OPER. NO. | LAST OPER. | ☐ MODULE TEST ☐ FUEL OR HYD. ☐ MSL FINAL TEST ☐ OTHER

DISCREPANCY NATURE AND DETAILS OF TROUBLE – GIVE SYMPTOMS AND READINGS OR MEASUREMENTS IF POSSIBLE | TIME OF DAY OCCUR | FIX | DISPOSITION OF DISCREPANCY

WRITTEN BY | REVIEWED BY

MATERIAL REVIEW BOARD DISPOSITION	QUAL.	DATE	MAT. CONT.	DATE	OK FOR STOCK	REWORK	RETURN	SCRAP	MDR. NO.
	ENG.	DATE	INBOARD.	DATE					

STAGE OF OPERATIONS	CODE	ACTION	REVIEWED	TEST OR INSP METHOD	D. A. REQUESTED	DISC. TYPE	CONTRACT NO.	MARK	MODEL	COG. REL. ENGR.

MALFUNCTION	SER.	CAUSE	PROP.	DISP.	ADJ.	QTY REP.	ACTION TAKEN	ANSWER DUE BY

FIGURE 6 - TEST TAG

MISSILE NO.	QUALITY ASSURANCE TEST		TDR #	CAR #
SYSTEM, PACKAGE, ETC.		S/N	MFR. TYPE	
SUB ASSEMBLY		S/N	MFR.	
PART NAME		CIRCUIT SYMBOL	VENDOR	
PART NUMBER		DATE CODE	S/N	

HOW DETECTED: VISUAL CHECK ____ CONTINUITY CHECK ____ MAT # ____ CALIBRATION ____
TROUBLE SHOOTING ____ DESIGN EVALUATION TEST ____ OTHER ____

NATURE OF DISCREPANCY (SYMPTOMS). ____

DESCRIPTION OF TROUBLE AND PROBABLE CAUSE (APPLIES TO PART). ____

PROPOSED IMMEDIATE CORRECTIVE ACTION. ____

WRITTEN BY ____ DATE ____ ETL ENGINEER OR CREW CHIEF ____ DATE ____

APPROVAL TO CONTINUE TEST: TEST ENGINEERING ____ GOVT. INSP. ____

IMMEDIATE CORRECTIVE ACTION TAKEN AND DISPOSITION OF PART. ____

____ BY ____ DATE ____

TEST ENGINEERING: IS ENGINEERING INVESTIGATION REQUESTED? YES NO (EXPLAIN BELOW).
WHAT EFFECT WOULD THE FAILURE HAVE ON OPERATION, INTERCHANGEABILITY, LIFE, PERFORMANCE, OR USABILITY?

____ BY ____ DATE ____

B&M RELIABILITY DEPT. USE ONLY	SERIOUSNESS	CAUSE	RESPONSIBILITY	ACTION TDR	FCA REQUESTED	REC'D BY	DATE

FIGURE 7 - CORRECTIVE ACTION REPORT

B&M ENGINEERING DEPARTMENT
THIS PORTION OF THIS REPORT IS TO BE FILLED IN BY B&M ENGINEERING DEPARTMENT ON ALL DESIGN EVALUATION CORRECTIVE ACTION REPORTS. PLEASE RETURN THIS REPORT TO THE SPECIAL MISSILE TEST GROUP, TEST ENGINEERING.

TDR # _____ CAR # _____ ENGINEERING CORRECTIVE ACTION REQUIRED YES__ NO__

EXPLANATION _____

PERMANENT CORRECTIVE ACTION AND DATE. RETROFIT REQUIRED? YES__NO__

BY _____ DEPT. _____ DATE _____

TEST ENGINEERING. WHAT EFFECT DOES THE CORRECTIVE ACTION HAVE ON THE VALIDITY OF PREVIOUS TESTS? ARE NEW TESTS NECESSARY?

BY _____ DATE _____

NIO COMMENTS. _____

NIO APPROVAL _____ DATE _____

FIGURE 8 - ENGINEERING CORRECTIVE ACTION FOLLOW-UP

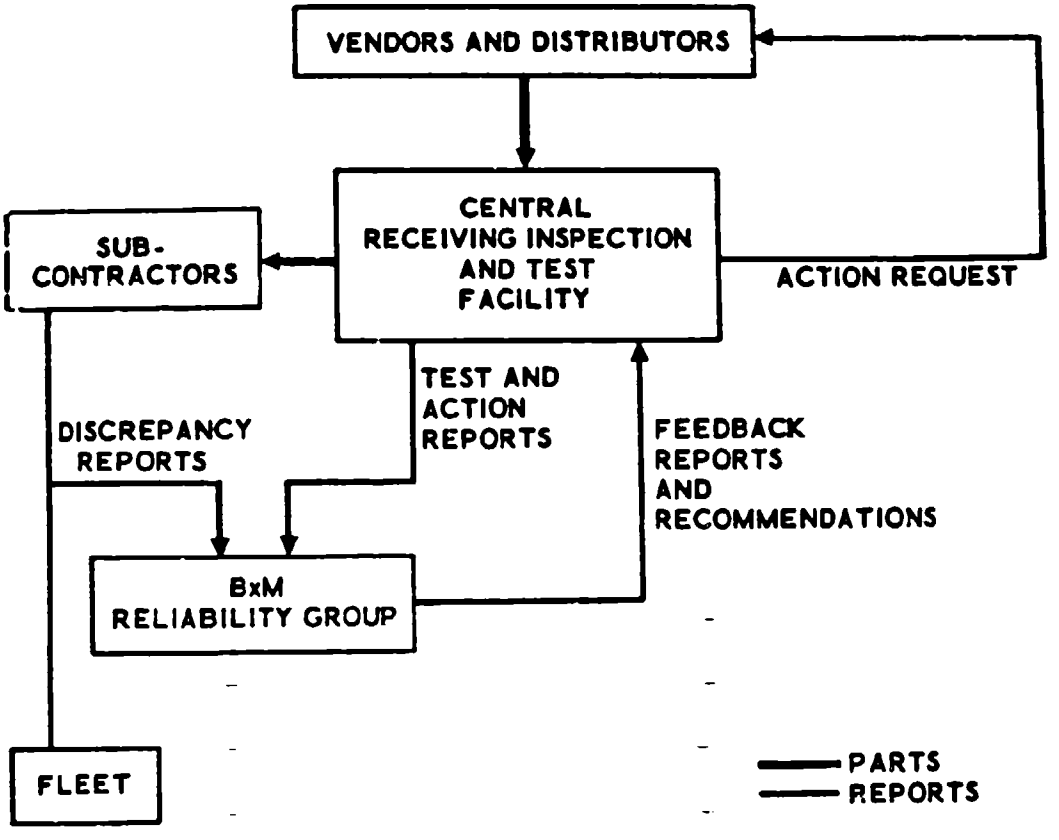


FIGURE 9 - QAT PROGRAM USING CENTRALIZED TEST

EMPLOYMENT OF LAUNCH SITE TEST EQUIPMENT FOR MAXIMUM SYSTEM RELIABILITY

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INTRODUCTION

This paper presents methods for resolving some of the problems encountered by the systems designer in the early development stages of a missile ground support system. The emphasis is on the employment of ground test and control equipment at launch site. The work summarized in this paper was done in connection with a subsystem of the Atlas, but it should be generally applicable to other ICBM and IRBM systems as well.

MAINTENANCE REQUIREMENTS OF BALLISTIC MISSILES

The configuration and mode of employment of a missile ground support system will depend on the maintenance requirements of the particular missile in question, which in turn depend on the operational requirements of the weapon. The time elapsing between the placing of the missile on the launch pad and its firing or replacement by another missile may amount to a matter of years. Even in the case of a major subsystem of the weapon, the required period for uninterrupted on-line operation will usually be measured in weeks or months.

During this lengthy period the missile must be maintained at such a level that it has a satisfactorily high probability of being launched successfully after very short warning. This goal must be met over a period of years without ever exercising the equipment fully, and over a period of months (or in some cases even years) without removing the missile from the launch pad or disassembling it.

Since it is likely that any complex weapon will suffer decrements in reliability after standing in an inert state for long periods of time, it becomes apparent that one vital ground support function will be to provide for the periodic testing and checkout at the launch site of those circuits and components in the missile which are subject to

deterioration with disuse. In addition, the operational requirement of a very low probability of malfunction at the beginning of a countdown may make it advisable to have continuous monitoring of some functions which are performed by particularly unreliable components, or are subject to a high rate of turn-on stress failure.

"MISSION PROFILE" OF LAUNCH SITE GROUND SUPPORT EQUIPMENT

The mission profile of the ballistic missile is both simple and difficult to accommodate. While in the maximum readiness state, the missile must be instantly ready to enter the final countdown phase with no pre-existing or incipient malfunctions extant. And, depending on the particular weapon system under consideration, it may be required to maintain this state of readiness for many hours at a time. Future missile systems will undoubtedly require even higher proportions of maximum readiness times than do present-day, perhaps eventually amounting to all the on-line time of the missile.

The desirability of performing as many maintenance and monitoring functions as possible at the launch site while the missile is fully assembled in alert status is self-evident from the mission profile just described. Only where the failure rate of a particular functional component is very low, or when a function cannot be checked in the assembled state, or when the amount of support equipment required to check a function makes launch site testing impractical will a required test not be performed at the pad.

Evidently, it will be necessary for some of the launch site ground support equipment to fulfill the same mission profile as the missile itself. Primarily, this will be the equipment which performs some essential function in the countdown. A failure of this equipment is equivalent to a failure in the missile itself in its effect on the mission capability, and immediately puts the whole system down. The continuous monitoring equipment (if any) will also have the same mission profile as the missile, even though it may not enter the countdown procedure directly. Other launch site support equipment, while essential in meeting the availability requirements of the weapon, is not used in the firing sequence. The latter equipment will have an intermittent profile, being required only at intervals.

We can distinguish between two types of intermittently used equipment: that which is used at periodic intervals to test the condition

of the missile or to perform some servicing function; and that which is called upon at random intervals to facilitate the repair or replacement of a failed missile or component thereof. Failure of the first, or non-critical type of intermittently used equipment, is not ordinarily a very serious matter, for minor deviations in checkout or routine servicing schedules are unlikely to significantly affect the probability that the weapon is in a state of readiness. In the case of the second, or critical type of intermittently used equipment, chargeable missile downtime is incurred if the missile should fail while the ground support equipment is inoperable, in which case there would be a delay in repair or replacement of the failed component of the missile.

It seems apparent that, other things being equal, it is highly desirable from a reliability standpoint to design as much of the ground support equipment as possible of the intermittent use type, and to minimize the number and complexity of equipments whose mission profile (and therefore essentiality) is the same as that of the missile itself. As a consequence, monitoring functions should, where the reliability of the particular missile component or subassembly permits, be performed during periodic checks and excluded from the firing sequence.

DETERMINATION OF OPERATING MODES

As indicated in the previous section, the mission profile of much of the launch site GSE is predetermined by the nature of its functions. Much missile handling and repair equipment is of the intermittent type, while certain electrical and positioning gear is integral to the firing sequence and is therefore automatically endowed with a continuous type availability requirement.

In the in-between area is a great deal of necessary test and checkout equipment. The designer here has the option of specifying whether the particular test is essential to completion of the countdown, or whether it can be assumed that the function in question, having checked out satisfactorily at the previous periodic examination, is stil OK. In addition, the systems designer must decide whether a function should be monitored continuously by the GSE or only periodically to insure a satisfactorily high probability of successful launch. The present section attempts to develop a mathematical model which will assist the systems designer in arriving at these decisions.

At the outset we recognize that the support requirements of the "maximum readiness" missile (if indeed, there are any other kind of on-line missiles in future military systems) are the most stringent from the standpoint of launch site ground equipment required, and these needs will in all probability govern the design of this support equipment. Furthermore, the support equipment provided must maximize not only the probability that the missile is ready to begin the countdown, but also that it will complete it successfully.

If we regard the weapon as being composed of a series of separate functional components or subassemblies, it becomes feasible to analyze each subassembly in turn to determine the manner and frequency with which it should be checked at launch site so as to maximize the probability of the system functioning through the countdown without failure. In performing this analysis, it is desirable to distinguish between "primary" units (or subassemblies) of the weapon, and "secondary" units. Primary units include all airborne subassemblies, plus those ground support units which perform some essential function in the countdown and consequently have the same mission profile (call it a "continuous critical" profile) as the missile proper. In general, all primary components of the system will need to be checked out from time to time (either at launch site or in the maintenance area) to insure that the system is operating satisfactorily.

There are in general four possible modes of on-line testing which can be assigned to any primary subassembly of the system:

Mode 1. The subassembly is checked out periodically, but not during the countdown.

Mode 2. The subassembly is checked out periodically, with a mandatory check during the countdown.

Mode 3. The subassembly is monitored continuously.

Adoption of the first check mode for a subassembly means that the status of ground suppo t checkout equipment will have little effect on the probability of the subassembly being alert (i.e., ready to start the countdown), or of successfully completing the countdown once started. Mode 2 implies reliance on test equipment during countdown, while Mode 3 implies full-time dependence on the checkout gear.

Of course periodic maintenance area testing as well as launch site checkout is necessary to the maintenance of the system. However, for the purpose of analyzing the alternative test modes described on the preceding page, it is necessary to consider only those tests which can be performed at the launch site.

The probability of a given subassembly being alert at any given time while on line depends on:

1. its failure rate in the environment encountered;
2. the time elapsed since the last checkout;
3. the magnitude of turn-on and other stresses experienced during checkout; and
4. the mean time required to replace the subassembly (or higher assembly or subsystem of which it is a part), or the mean time to repair the subassembly in place.

Repair time and replacement time can be lumped together as "mean time to return to service," or mean turnaround time. The estimate of mean turnaround time should include the possiblity that the repair or replacement operation may have to be repeated one or more times for a single failure if the first repair is unsuccessful, or if the replacement subassembly also turns out to be faulty.

Assuming that a given functional component or subassembly is alert when the countdown begins, the probability that it will still be operating at launch is a function of the turn-on stress, and the checkout and countdown stresses experienced, if any

We define:

A_i = the probability that the circuits and/or functions checked at the launch site are in working order, given operating mode i.

L_i = the probability that the circuits and/or functions checked during launch site testing survive the countdown without malfunction, given operating mode i.

B	=	probability that the subassembly will survive turn-on stress.
C	=	probability that the subassembly will survive checkout stress.
D	=	probability that the subassembly will survive countdown stress.
$\bar{r}$	=	mean time to return to service, or remove and replace time, for the subassembly or higher assembly of which it is a part.
s	=	launch site checkout interval for the subassembly.
λ	=	random failure rate during "OFF" condition of circuits and/or functions of the subassembly checked at launch site.
μ	=	random failure rate of the subassembly in the "ON" condition.

The following assumptions are made in the subsequent analysis:

1. Failures are random in time, i.e., independent of time. This condition is met by the exponential distribution of time-to-failure, $e^{-\lambda t}$, where λ is the failure rate and t the time.

2. The countdown may occur at any random point in time with equal probability.

3. The time required to perform a periodic launch-site checkout is negligible in comparison with the time between checkouts.

Mode 1 -- Periodic Checkout Only

Let A_1 symbolize the probability that a given functional subassembly of the missile is alert (as regards those functions which can be checked at launch site) at any random point in time when operated in Mode 1; and let L_1 be the probability that the subassembly is not only alert at the beginning of countdown, but will finish the countdown without a failure of any of the functions checked at launch site.

There are apparently two kinds of cycles, each of a different length, which may be encountered by the missile subassembly under analysis. Cycle Type I, of length s (the interval between checkouts) is that cycle in which no failures occur. Cycle Type II, of length (s + r) occurs when a malfunction in the system is detected during checkout and includes the time r necessary to get the missile back on the air. Figure 2 following, illustrates the situation graphically.

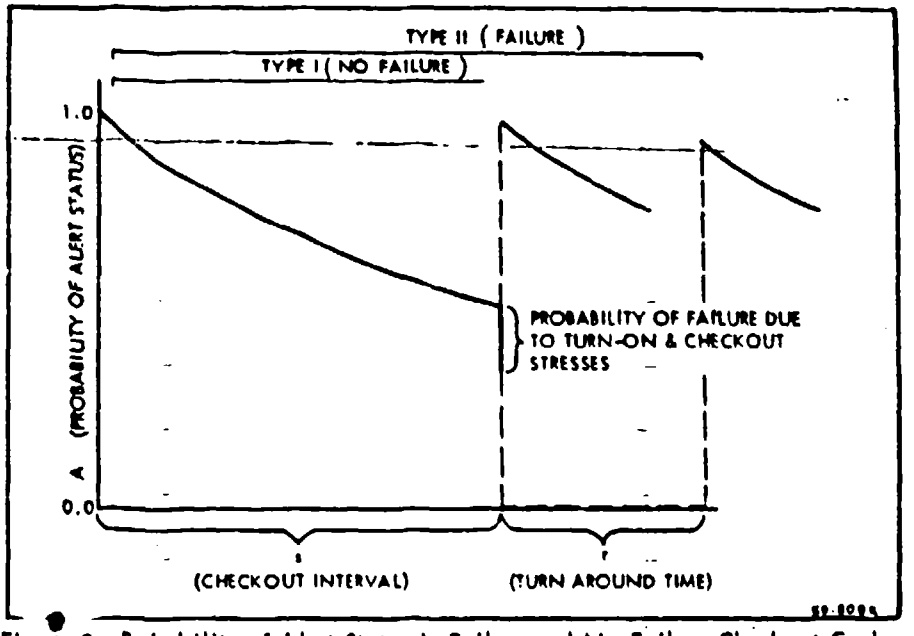


Figure 2. Probability of Alert Status in Failure and No-Failure Checkout Cycles

The probability A_1 that the subsystem, having checked out satisfactorily at the beginning of the cycle, is still on alert status declines with time in accordance with the exponential function $e^{-\lambda s}$. At the end of the checkout interval it receives a stress from the checkout procedure itself, which further (and abruptly) diminishes the probability of its being operable. At this point the checkout reveals either that the tests were passed successfully and a new cycle begun or that the equipment has failed the checkout. In the latter case, an interval of downtime r commences which lasts until the missile is "on the air" again.

It is convenient to recognize two varieties of Type II (failure) cycles:

1. That cycle where the failure occurs in the waiting period (call this Type IIA).

2. That cycle where the failure is induced by the checkout itself (call this Type IIB).

The probability that the weapon is on alert status at any random point in time is given by:

$$A_1 = \frac{\text{(Good time in all cycles)}}{\text{(Total time in all cycles)}}$$

But:

$$\left(\begin{array}{c}\text{Good time in a}\\ \text{given cycle}\end{array}\right) = \left(\begin{array}{c}\text{Length of}\\ \text{cycle}\end{array}\right) \cdot \left(\begin{array}{c}\text{Fraction of}\\ \text{time good}\end{array}\right)$$

From which:

$$\left(\begin{array}{c}\text{Good time in}\\ \text{all cycles}\end{array}\right) = \sum_{\text{All cycles}} \left(\begin{array}{c}\text{Length of}\\ \text{cycle}\end{array}\right) \cdot \left(\begin{array}{c}\text{Fraction of}\\ \text{time good}\end{array}\right) \cdot \left(\begin{array}{c}\text{Probability}\\ \text{that cycle}\\ \text{occurs}\end{array}\right)$$

while:

$$\left(\begin{array}{c}\text{Total time in}\\ \text{all cycles}\end{array}\right) = \sum_{\text{All cycles}} \left(\begin{array}{c}\text{Length of}\\ \text{cycle}\end{array}\right) \cdot \left(\begin{array}{c}\text{Probability}\\ \text{of occurrence}\end{array}\right)$$

The table below translates this logic into the symbology of the problem at hand.

TYPE CYCLE	LENGTH OF CYCLE	FRACTION OF TIME GOOD	PROBABILITY OF OCCURRENCE
I (No failure)	s	1.0	$e^{-\lambda s} BC$
IIA (Failed in waiting period)	$s + \bar{r}$	$\frac{v}{s + \bar{r}}$	$(1 - e^{-\lambda s})$
IIB (Failed at checkout)	$s + \bar{r}$	$\frac{s}{s + \bar{r}}$	$e^{-\lambda s}(1-BC)$

The parameter v is the mean amount of good time expected when a failure occurs during the checkout interval. This is not exactly $\frac{s}{2}$, (although $\frac{s}{2}$ is sometimes a reasonable estimate) because under the exponential distribution the probability of failure is greater at the beginning of the interval than toward the end. Instead,

$$v = \frac{1}{\lambda} - \frac{s e^{-\lambda s}}{1 - e^{-\lambda s}}$$

The probability (A_1) that all the circuits and/or functions in a sub-assembly checked at the launch site are on alert status is computed in accordance with the rationale set out as:*

$$A_1 = \frac{1 - e^{-\lambda s}}{\lambda s + \lambda \bar{r}\,(1 - BCe^{-\lambda s})} \qquad (1)$$

*See Appendix I for complete derivation.

The probability that the subassembly operating in Mode 1 survives the countdown itself is a function of the turn-on stress, and also the countdown stress if this is a factor. The over-all probability of a successful launch under Mode 1 testing is given by:

$$L_1 = A_1 BD \tag{2}$$

Mode 2 -- Periodic Checkout, Plus Check During Countdown

The probability of a subassembly being alert at countdown is exactly the same under Mode 2 operation as under Mode 1. In addition, however, it is also necessary for the checkout equipment itself to be alert. The probability that a given functional componenet of a subassembly and the test equipment necessary to check it are both alert is:

$$A_2 = A_1 A'_2 \tag{3}$$

A prime is appended to variable and parameters which refer to the checkout equipment, so that A'_2 is equal to the probability that the checkout gear associated with the primary unit or subassembly under analysis will be on the alert at countdown.

It is reasonable to assume that when a checkout of an airborne subassembly or other primary unit is performed, this check will also serve to test the checkout equipment. If this is the case, the checkout interval s will be the same as for the primary unit being checked. Computation of the probability of the launch site checkout equipment being alert is then analogous to the computation for the primary unit itself, and is given by:

$$A'_2 = \frac{1 - e^{-\lambda' s}}{\lambda' s + \lambda' \bar{r}'(1 - B'C' e^{-\lambda' s})} \tag{4}$$

In this case, $\bar{r}'$ is the mean time required for the successful replacement or repair in place of the checkout equipment, λ' is the failure rate of the checkout equipment, and B'C' is the probability that the checkout gear will survive the turn-on and checkout stresses.

The probability of successful launch using Mode 2 testing is given by:

$$L_2 = (A_1 BCD)\ (A'_2 B'C' D') \tag{5}$$

Mode 4 -- Continuous Monitoring

Under the continuous monitoring mode there is no doubt about the condition of the circuits being monitored. The probability of alert (A_4) for a particular subassembly is then equal to the total time on-pad (h), minus the downtime experienced due to the primary unit itself (d) and its associated checkout equipment (d'). *

$$A_4 = \frac{h - d - d'}{h} = \frac{1}{1 + \mu \bar{r} + \mu' \bar{r}'} \qquad (6)$$

where

μ = the failure rate of the primary unit in the "ON" condition.

μ' = the failure rate of the monitoring equipment (for the primary unit) in the "ON" condition.

$\bar{r}$ = the mean replacement or repair time of the subassembly or higher assembly of which it is a part.

$\bar{r}'$ = the mean replacement or repair time of the associated monitoring equipment.

Unfortunately, it is nearly impossible to assign a dollar penalty to firing delays in the combat situation. Delay in commencing a countdown because of an inoperative monitoring unit might result in the destruction of the missile on the pad, or the loss of a major city, or in no measurable disadvantage at all. Similarly, the launching of a missile containing a malfunction might result in the survival of a critical target which otherwise would have been destroyed. Or, if there were no time to repair the missile anyway, the matter of whether or not it were launched would be of no consequence. Further research into this problem might result in a practical method for evaluating these possibilities, but for the present the problem seems insurmountable.

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*See Appendix II for derivation

Being unable to quantify the ideal optimizing criterion, the researcher is forced to seek compromises. One possibility is to determine the probability of successful launch after x hours delay in the countdown, for a number of values of x. Equations (2), (5), and (7) give these probabilities for ($x = 0$). The systems designer will then be in a position to evaluate (or to have evaluated for him) each mode of operation for several values of x weighting each subjectively according to the operational specifications of the weapon system being designed.

The equations specifying the probability of successful launch with x hours delay are not difficult to write. In addition to the parameters already introduced they depend on:

1. The number of malfunctions occurring during the countdown; and

2. The probability that all malfunctions can be corrected in less than x hours.

Unfortunately (or perhaps not) considerations of brevity prohibit the reproduction of these equations in this paper.

OPTIMUM LAUNCH SITE CHECKOUT INTERVAL

Before the relative merits of the four different test modes for a given primary component of the system can be satisfactorily evaluated, the optimum launch site test period s must be determined for those modes calling for periodic checkout.

The purpose of periodic checks at the launch site is to make sure the missile is in alert status, that is, ready to begin countdown if called upon to do so. The probability of a given missile subassembly being on alert was given as (Mode 1 operation):

$$A_1 = \frac{1 - e^{-\lambda s}}{\lambda s + \lambda \bar{r} (1 - BCe^{-\lambda s})} , \qquad (1)$$

The optimum value of s can be obtained by employing a slightly different rationale to obtain a simpler expression, which can be differentiated and set equal to zero to obtain the value of s which maximizes A_1. This approximation for the optimum value of s is:

$$\hat{s} \approx \sqrt{\frac{2\bar{r}(1 - BC)}{\lambda}} \qquad (8)$$

* Solution suggested by Alan S. Manne, See Appendix III.

The approximation holds with remarkable accuracy for the usual ranges of λ, $\bar{r}$, B and C.

For Mode 2 the approximation of Equation (8) is less accurate because it fails to take into account the necessity for the checkout equipment to be on that alert also. However, if A_1 (the probability of the missile subassembly being alert) is substantially smaller than A'_2 (the proability of the checkout equipment being alert) and A'_2 is fairly close to 1.0, Equation (8) will give an acceptably accurate approximation of the optimum checkout interval $\hat{\theta}$ for Mode 2 operation also.

Figure 3 following shows the optimum launch site checkout interval as a function of the three basic parameters; mean time to return to service (or turnaround time), stress, and failure rate. As might be expected, the lower the failure rate the greater the optimum interval between checkouts. Reducing the failure rate per hour to one-tenth its former value will result in an increase in the optimum checkout interval of slightly more than three times if the other factors are held constant.

Also as expected, the shorter the turnaround time, the shorter the checkout interval -- in fact, the optimum checkout interval is exactly as sensitive to changes in turnaround time as to changes in failure rate, but in the opposite direction.

The length of the optimum checkout interval is directly proportional to the probability of <u>not</u> surviving the turn-on and checkout stress, or (1-BC). The greater the turn-on and checkout stress, the less attractive checkouts become and the greater the optimum checkout interval. The sensitivity remains the same as for turnaround time, except that the values which the probability (1-BC) is permitted to take on are limited to the range 0.0 to 1.0.

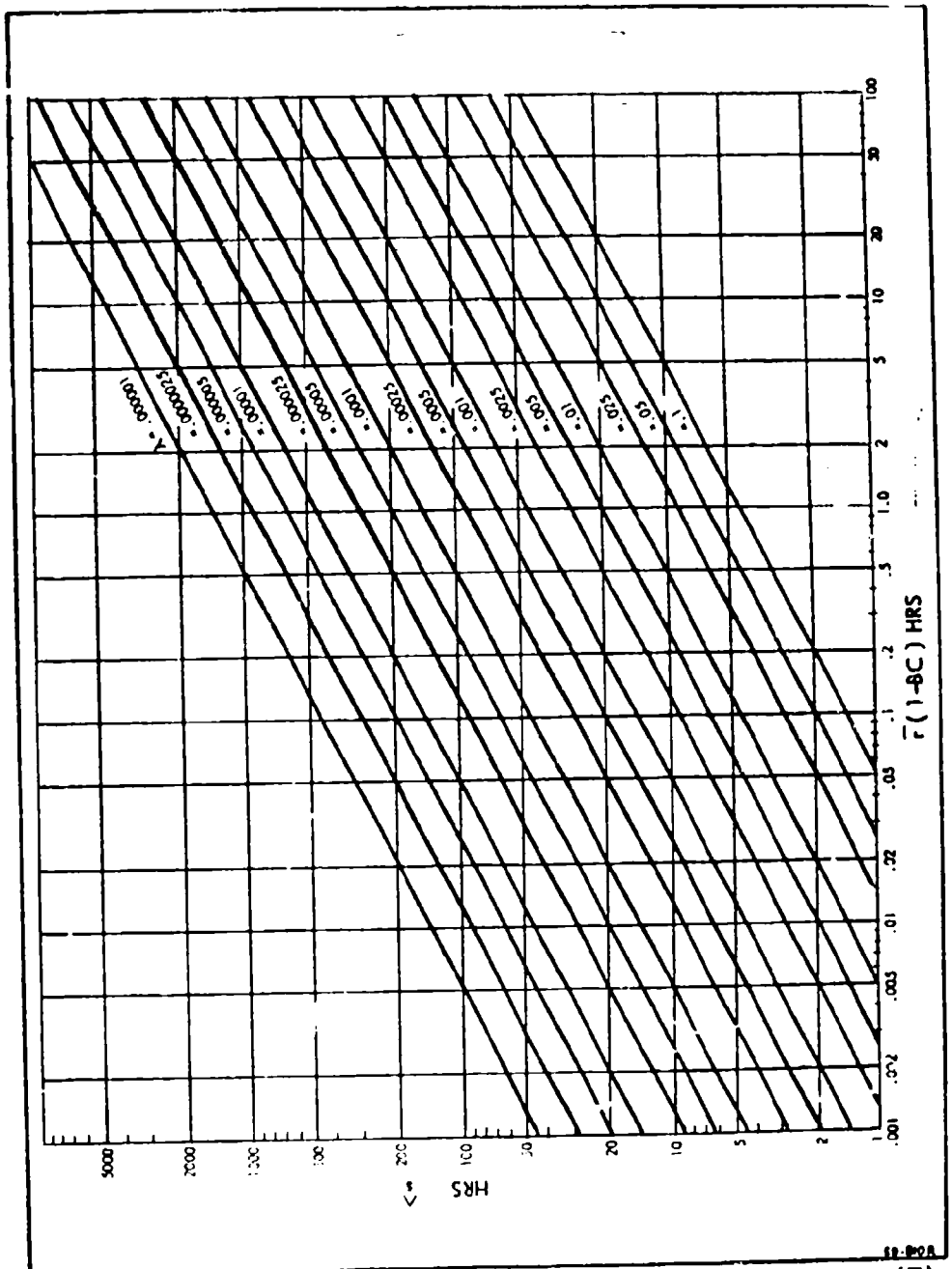


Figure 3. Optimum Checkout Interval ($\hat{s}$) as a Function of Mean Turnaround Time ($\bar{r}$), Probability of Surviving Turn-On and Checkout Stresses (BC), and Failure Rate (λ)

ASSUMPTIONS AND LIMITATIONS OF THE MODEL

A number of assumptions and limitations of importance which are implicit in the model should be emphasized at this point:

1. In-flight failures and any relationship which might exist between them and checkout frequency have been ignored. Ordinarily it may be assumed that no such relationship exists, and where it does exist is impossible to document statistically.

2. A 100 per cent checkout efficiency has been assumed, which is to say that we have considered the testing procedure to be perfect in revealing any existing flaws in either the missile or the checkout equipment itself. This assumption is probably close enought to the truth to avoid serious bias in the case of circuits and functions actually tested at the launch site, which is the model's area of relevancy.

3. The problem of equipment wearout has been ignored in assuming an exponential distribution of failure times. In general, the more complex the equipment and the more often it is necessary to repair it, the more likely it becomes that an admixture of old and new parts will result in a random (exponential) failure pattern over the entire life of the equipment. On the other hand, comparatively simple mechanical or electromechanical assemblies (particularly when subjected to intensive use) may exhibit a wearout pattern of failures fairly early in the program. The designer will have to make a subject evaluation of the probable danger of wearing the equipment out prematurely if he chooses the continuous monitoring mode or if he plans on very frequent checkouts.

4. The model has ignored the cost variations between different operating modes. For instance, it would probably be slightly more expensive to provide equipment for an optional countdown checkout than for a mandatory check, etc. These cost variations would probably be small compared to the total cost of the system, however.

5. The model assumes that a launch-site checkout can be interrupted at any moment to begin a countdown. This assumption is consistent with the goal for checkout systems pertaining to all missile components.

APPENDIX I
DERIVATION OF THE PROBABILITY OF ALERT STATUS FOR MODE 1 TESTING

The probability of alert status obtaining in Mode 1 operation (A_1) is equal to the amount of good time summed over all cycles divided by the total time in all cycles. We define:

s	=	interval between launch site checkouts
$\bar{r}$	=	mean turnaround time
λ	=	failure rate in the "OFF" condition
BC	=	probability of surviving turn-on and checkout stresses
v	=	expected good time, given a failure during the checkout interval

We recognized three types of cycles: the no-failure cycle, the failure during standing time cycle, and the failure during checkout cycle. Assume an exponential distribution of times-to-failure during the checkout interval, such that the probability of surviving time $s = e^{-\lambda s}$.

Then

$$A_1 = \frac{s(e^{-\lambda s}BC) + (s+\bar{r})\frac{v}{s+\bar{r}}(1-e^{-\lambda s}) + (s+\bar{r})\frac{s}{s+\bar{r}}e^{-\lambda s}(1-BC)}{s(e^{-\lambda s}BC) + (s+\bar{r})(1-e^{-\lambda s}) + (s+\bar{r})e^{-\lambda s}(1-BC)} \quad (40)$$

The mean time to failure v in a Type II A cycle (failure during standing time) is found by integrating between zero and s the derivative of the distribution function $e^{-\lambda t}$, multiplied by the time variable and adjusting to make the probability of failure between zero and $s = 1.0$

$$v = \frac{1}{(1-e^{-\lambda s})}\int_0^s t\lambda e^{-\lambda t}\,dt = \frac{1}{\lambda} - \frac{s\,e^{-\lambda s}}{1-e^{-\lambda s}}$$

Substituting this expression for v in the equation for A_1 and simplifying:

$$A_1 = \frac{1 - e^{-\lambda_s}}{\lambda_s + \lambda_r (1 - BC e^{-\lambda_s})} \qquad (1)$$

APPENDIX II

DERIVATION OF PROBABILITY OF ALERT STATUS FOR MODE 4 TESTING

The probability A_4 that the system is in alert status in Mode 4 operation is equal to total good time divided by total time, or

$$A_4 = \frac{h - d - d'}{h} \tag{41}$$

where;

h	=	total hours on-pad
d	=	downtime hours due to missile
d'	=	downtime hours due to monitoring equipment
μ	=	failure rate of missile in "ON" condition
μ'	=	failure rate of monitoring equipment in "ON" condition.
$\bar{r}$	=	mean repair time for missile
$\bar{r}'$	=	mean repair time for missile monitoring equipment

Then:

$$d = (h-d-d')(\mu\bar{r}) = \frac{\mu\bar{r}(h-d')}{1+\mu\bar{r}} \tag{42}$$

$$d' = (h-d-d')(\mu'\bar{r}') = \frac{\mu'\bar{r}'(h-d)}{1+\mu'\bar{r}'} \tag{43}$$

Substituting the expression for d' given by (43) into (42) gives:

$$d = \frac{h\mu\bar{r}}{1+\mu\bar{r}+\mu'\bar{r}'} \tag{44}$$

And substituting (44) in (43) gives:

$$d' = \frac{h\mu'\bar{r}'}{1+\mu\bar{r}+\mu'\bar{r}'} \tag{45}$$

Subetituting the values for d and d' in (44) and (45) into (41), the h term cancels out leaving:

$$A_4 = \frac{1}{1 + l\,\bar{r} + l'\,\bar{r}'} \qquad (6)$$

APPENDIX III
ALTERNATE MODEL FOR DETERMINING OPTIMUM LAUNCH SITE CHECKOUT INTERVAL

Let A_1 = the probability that the primary unit is "on the alert"; that is, operable.

BC = the probability that the primary unit survives turn-on and checkout stresses.

F = mean time to return the system to service in case of failure of the primary unit.

s = the time interval between checkouts (in hours).

λ = failure rate per hour of the primary unit under analysis.

Assume that the probability of no failure in time s follows the negative exponential distribution, $e^{-\lambda s}$. For values of the product λs less than about 0.25, the series approximation $(1 - \lambda s)$ for $e^{-\lambda s}$ gives satisfactory results, and this substitution is employed.

We regard all cycles as being of equal length s. There are three types of cycles; no failure, failure before checkout, and failure during checkout. The latter two types require average downtime for repair or replacement (or turnaround time) of F hours.

Since all cycles are of equal length the probability of alert status is the sum over each type of cycle of the fraction of time "on the air" times the probability of occurrence of the cycle, or,

$$\left(\begin{array}{c}\text{Probability of} \\ \text{alert status}\end{array}\right) = \sum_{\text{All cycles}} \left(\begin{array}{c}\text{Fraction of} \\ \text{time good}\end{array}\right) \cdot \left(\begin{array}{c}\text{Probability} \\ \text{of occurrence}\end{array}\right)$$

This turns out to be

$$A = (1 - \lambda s)\, BC + (1 - \lambda s)\,(1 - BC)\frac{s - F}{s} + \lambda s \left(\frac{\frac{s}{2} - F}{s}\right) \quad (46)$$

$$= 1 - \frac{\lambda s}{2} - \frac{F}{s}\,(1 - BC) - BCF\lambda$$

Differentiating Equation (46) with respect to s, we have:

$$\frac{dA}{ds} = \frac{-\lambda}{2} + \frac{(1 - BC)\,\bar{r}}{s^2}$$

Setting this expression equal to zero yields the value of x which maximises A:

$$s = \sqrt{\frac{2\bar{r}\,(1 - BC)}{\lambda}} \qquad (8)$$

RELIABILITY OF THE FUTURE RANGE INSTRUMENTATION COMPLEX AT WSMR

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In considering reliability, it is important that one realize why it is so vital to the operation of the range. There are three main reasons why a high reliability of a missile test range must be established. Briefly these are:

(1) The cost of missile development. This amount varies; but in any event, it represents a sizeable amount ranging up to the order of a million dollars per test.

(2) The cost of operating the range. Specific figures of range operation are included in the following pages, and it will be noted that the sum is significant.

(3) The time invested in missile research. In the national necessity to keep pace in missile development, time is one of the most important medium spent. Being irreplaceable, such an investment must be utilized to the maximum degree.

Up to the year 1958, the instrumentation complex at White Sands Missile Range was improved through the development of individual systems. If their potentialities warranted, existing instrumentation systems were gradually improved. Other systems with poor capabilities and potentialities were abandoned. When a new system evolved that appeared suitable for the range, it was installed on a trial basis to determine its capabilities and it was either retained or removed after comparing it with a current standard. In this manner of growing, a slow improvement was realized. To compare the capabilities of the past with the present is difficult because standards of excellence have improved because data handling has changed and improved, and because the actual method of measurement and the thing measured may not be exactly the same now as they were originally. But considering all of the variables, it is conservatively believed that our overall accuracy is at about 3 times what it was in 1950. In other words, in situations where we were able to measure the velocity of a missile to within plus or minus 15 feet per second in 1950, we are able to measure it within plus or minus 5 feet per second at present. The near future indicates that we will soon need to measure velocity to within plus or minus a small part of a foot per second. In addition to better measurements, the capability of the range to complete more firings has increased about 25% a year. Last year the range completed approximately 2400 hot firings. The need for handling a still greater number of firings per year is in prospect.

The growth and improvement of the range has been accomplished by various groups working to realize more of the inherent capabilities of their assigned instrumentation systems. The complexity and amount of the instrumentation systems have greatly increased over the years until the point has been reached where it is necessary to have a well-integrated range instrumentation system to keep pace with increasing requirements. To achieve this and a radically new concept of a unified range instrumentation complex has been conceived for WSMR. For this concept, the term ARTRAC has been coined. It is an abbreviation for "Advanced Range Testing, Reporting and Control." A general outline plan for the ARTRAC System was published 15 March 1959 by the Integrated Range Mission, WSMR.

Reliability was a paramount consideration in the formulation of the ARTRAC plan just as it would have been in devising any other operational control plan. Reliability and dependability are extremely important at White Sands Missile Range since the basic reason for having a missile range is to make measurements and, if they cannot be depended upon, the range serves no purpose. The costs of range time also emphasize the need for high reliability. Twenty-seven thousand dollars per hour is the figure set for the cost of operating this range. At this rate two minutes are worth $900. One single POGO target missile varies in cost from $3000 to $5000 per round. Because of these and other considerations, the important matter of reliability deserves careful planning to assure its achievement. This paper will present the principles and the planning that have been used in the ARTRAC concept to increase the reliability of operation for the instrumentation complex above that of the individual instrumentation systems.

1. Reliability through the ARTRAC structure

A missile range 140 miles long and 30 miles wide operated in one section by a private company and in the other section by civil service personnel presents a formidable operating and control problem. One means of increasing reliability through use of a control structure is to make parallel use of several different types of instrumentation systems - each of which is capable of providing the same data. Then, through proper control and coordination of all systems, range reliability will be increased by the continuous selection of the best operational procedures and data as the flight progresses. Operation in this manner not only improves the reliability of measurements for customers, but it also improves such inner range functions as safety monitoring of missile flights.

A control structure can increase reliability of an extremely accu ... or critical instrumentation system by assuring that the needed data for support of the system will be available when required. A control structure which provides for processed data to be fed back to the range locations where it is needed will increase the reliability of the overall operation. A simple example of one system supporting another is that of the narrow-beam tracking radar needing coarse data from the search radar to find the target.

Through proper coordination of all systems the desired data can be obtained from any one operational system. This unification approach was chosen for ARTRAC. ARTRAC will establish a single control structure throughout the instrument complex. This structure will consist of three branches: the command control system, the data system, and the timing and communications system.

2. Command Control System

The control structure for the future range will be a continuous chain of control positions with clearly defined control responsibilities extending from the top range controller down to the simplest control points for the operations of measurements, missilery, targetry, and safety. The control structure for ARTRAC downward from the top consists of five echelons or levels. This control chain will insure prompt implementation of control decisions both for normal operations and emergency cases and thus will contribute to orderly progress of a mission. Control of an operation will be governed by the entire set of decisions and agreements derived from pre-mission planning and scheduling. The objectives of control are to implement these decisions throughout the period just prior to, during, and immediately after a missile flight and to make any decisions not anticipated in the pre-mission planning.

Under normal operating conditions, control responsibilities will be delegated. Directives and instrumentation assignments issued by the range control center are to be translated into system and equipment orders by the various operations at their individual levels. Decisions will be delegated to the lowest practicable level. Reliability will be increased by avoiding over-concentration of control decisions upon a single individual since responsibility will be delegated to an intermediate supervisory structure.

During an emergency, it is realized that the lower echelons of control are not always fully aware of the situation at higher echelons. As a precaution, for such cases, ARTRAC will give each higher echelon controller a choice of over-riding subordinate decisions if he believes it to be necessary. This will be accomplished by continuously displaying information about the overall operation at the higher echelon of control and providing for direct channels to effect any decision. Thus reliability of control will be increased by back-up through direct control channels.

Missions which require simultaneous use of all of the facilities and range area are not the only types tested at White Sands. The extent of the areas available promotes the simultaneous use of various parts for separate missions. Controlling such multiple missions from a central point is not desirable when one person is responsible for all decisions. Heavy stress would fall upon such an individual and endanger the success of all missions. To avoid undue concentration of responsibility for managing simultaneous operations, under ARTRAC mission-control-centers will

be established in several areas of the range. Each of these centers, headed by a controller, will be responsible for the activities in its individual area. Overall coordination will be the task of the chief controller, but the complex multiple operations will be divided into several simpler operations which are easier to control and thus will have higher reliability.

3. Data System

Achievement of the use of automatic data evaluation and selection procedures will be a very important mile-stone in attaining higher reliability. Properties of good data are reasonably well known for certain systems, and data can be evaluated on the basis of these properties. As a simple example, if a certain maximum noise level was specified, data could be accepted or rejected from various sources until the optimum was selected. The procedure of using data from one system to improve data collected by a second system will also be further exploited. Such a procedure results in a more reliable output than can be produced by one isolated system. Thus the strongest capabilities of the different systems are combined to realize the maximum reliability available.

The ARTRAC unified data system will further increase the reliability of the instrumentation by combining instrumentation systems in other ways. Some systems are very reliable in operation but provide a coarser type of data, while some, which provide a finer type of data, are very susceptible to operational and interpretive errors. For the unified data system of the future range, a very accurate system will be backed by a very reliably operating system, so that, in case of failure of the first, there may be assurance that at least coarse data will be obtained.

An example is found in the resolution of the ambiguities of an otherwise highly accurate system. Here failure to resolve the ambiguity would cause failure of the system, but the operation of the resulting combination may be made highly reliable through providing ambiguity resolution through the other -- even though crude -- system. As an example, the DOVAP system is extremely accurate in measurements of velocity and position. However, each usable DOVAP measurement depends on the history of the previous measurements. Using DOVAP only, an error made in the first calculations would be carried throughout the remaining computations. A second instrumentation system would be of value to determine that the bias errors (resulting from an operational difficulty such as the momentary loss of the DOVAP signal, etc.) would not exceed some minimum excursion. DOVAP could then continue to provide accurate data on position and velocity.

During the gradual implementation of ARTRAC on the range, the portion of the data reduced in real-time will be increased with the ultimate goal of achieving most of the data reduction in real-time. However, even where real-time data is necessary, data at the various points throughout the

system will be recorded for back-up purposes. Only after the data has been obtained and the mission thoroughly evaluated will these recordings be erased or destroyed.

The data reduction task imposes such a heavy workload on the computing facility that a single computer would have to be extremely complex to perform all data reduction. Failure of this central computer would completely interrupt the data flow during the time the computer was being repaired. For this reason, ARTRAC data reduction will be accomplished using a group of computers, both for real-time and post flight reduction. These computers can rapidly be programmed for the various data reduction procedures in use at WSMR. The computer to be used normally for post-flight analysis will also be capable of being programmed rapidly. In case of failure of the computer engaged in real-time processing, the task might be rapidly reassigned to a computer ordinarily used for post-flight analysis. Since a delay of the post-flight analysis is not critical, the reliability of the overall computing facility will be greatly increased without employing costly equipment for back-up purposes only.

In the area of data presentation equipment, duplicate equipment will be provided. However, the back-up equipment for real-time data display will be kept to a minimum by utilizing general purpose equipment that may be used for the presentation of more than one kind of data. One single piece of equipment will then serve as back-up equipment for a series of display devices.

4. Communications and Timing

To provide flexibility and control, the communications system of ARTRAC will have only one main switching location. All communication lines will converge from the various areas to the one point. Lateral communication will be provided by switching at the central point. Such concentration of equipment will provide a less expensive means for obtaining a redundancy of spare circuits and spare equipment for use in the event of failure of the regular gear. Reliability is to be provided by a sound compromise between a system utilizing only working circuits and a system with 100% spare circuits.

With emphasis being placed on automation, voice-communication traffic will be much less under the proposed ARTRAC plan than at present. The circuit time required by voice traffic in ARTRAC is expected to be about one-fifth the amount used at present. Status information and countdown time will be provided by the automated portion of the communication system. More extensive use of teletype will be applied for rapid dissemination of control information. The lightly used voice circuits will supplement the status channels. In emergency cases, these voice channels may be used for maintaining the proper flow of information to keep the range in an operational status.

Timing signals now utilize radio channels as well as wire line channels and a sufficient number of spare channels will be provided to assure reliability. The timing signal itself will be a pulse code which permits separate interpretation of each pulse group as a certain time mark without relying on the preceding time mark. Any drop-out of the timing signal will therefore have no effect beyond the first mark received after such a drop-out.

5. Future Developments

The ARTRAC plan is to be the first step in a continuing process of defining, achieving, and refining an integrated system for range instrumentation. Subsequent revisions will make further advances toward a more efficient and unified system. Certainly all future revisions will be made with proper consideration for reliability. The instrumentation systems are to be considered as replaceable blocks; some may be added and some phased out to maintain a continuously high capability. In a unified combination, the adding of a block is to be accomplished through consideration of its contribution to the whole complex plus its relationship to any other instrumentation.

Redundancy does not always strengthen overall system reliability. Suppose telemetry is the main source used to supply information regarding the pitch of a missile. If an optical system were added to also supply information regarding pitch, the reliability of the overall instrumentation would surely be increased. However, if instead of the optical back-up, a modulated signal were used to make it possible for both DOVAP and a second ITS system to also supply pitch information, then (counting telemetry) three electronic systems would be supplying pitch information; but all three systems might be dependent on one stabilized reference device in the missile, and all three would be dependent on a single missile power supply. Thus, the redundancy in this case would probably not aid the reliability of the overall system a great deal.

The human factor is also a consideration which often adversely influences the reliability of the range. It cannot be overlooked since a great many times the success or failure of a mission will depend on human operators making decisions. The reducing of the human influence can be accomplished by reducing the degree of responsibility and simplifying the tasks of the operating personnel.

6. Conclusions

We have shown in the preceding discussion that equipment reliability is not the sole factor in determining the reliability of the range instrumentation complex. Individual instrumentation systems can be combined in such a way that the overall reliability of the complex becomes much larger than that of its portions. These considerations have greatly influenced the ARTRAC plan which provides for the implementation of a truly advanced instrumentation concept at WSMR.

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Lower, John A. - Hercules Powder Co.
Lowrie, W. O. - Martin Co.
Lundholm, Jere L. - Arthur D. Little, Inc.
Lutener, Oral C. - Fort Bliss
Lyle, Douglas A. - Western Electric Co.

MacCarley, J. A. - Marquardt Aircraft Co.
MacClemmy, George L. - United Testing Lab.
Macho, Edward John - North American Aviation, Inc.
Maertens, Thomas F. (Maj.) - Office of Secretary of Army
Maitzen, Donald R. - The Martin Co.
Mallon, Patrick J. - Hughes Aircraft Co.

ATTENDANCE LIST

Marcrum, Robert H. (1/Lt.) - Fort Bliss
Marko, Frank - Frankford Arsenal
Martin, C. C. (Capt.) - Fort Bliss
Martin, Harry Ward - Sperry Gyroscope Co.
Martin, Justin E. (Capt.) - Fort Bliss
Marzec, Leonard Edward - Canadian Joint Staff
Masterson, Robert James - Martin Company
Matosoff, Henry I. - Cannon Electric Co.
Matthews, Charles W. (Lt. Col.) - Fort Sill
Mayer, Matthew A. - General Motors
Mayes, Richard A. - United Electrodynamics Inc.
McCachern, William Y. (Lt. Col) - Fort Bliss
McCallum, Hargro - Frankford Arsenal
McClure, Julius Young - Convair
McCool, William A. - WSMR
McCormac, Billy M. (Maj.) - USCONARC
McCracken, Bruce O. - General Electric
McDonald, Robert C. (Col.) - Fort Bliss
McGinnis, Frank - Sperry Gyroscope Co.
McGlothlin, William Herschel - Rand Corp.
McKinzie, Melvin A. - Wright-Patterson AFB
McLaughlin, Charles E. - Wright-Patterson AFB
McMaster, Alexander C. - Convair
Meikle, Donald K. - Chrysler Corp.
Meister, David - Convair
Mellnik, Stephen M. (Brig. Gen.) - Fort Bliss
Menges, William Randall - Burroughs Research Center
Mercurio, Saluatore P. - General Electric
Merritt, Robert B. - General Electric
Mika, Stanley E. (M Sgt.) - Fort Bliss
Millard, Guy A. Jr. - U. S. Naval Ordnance Test Station
Miller, Thomas Kenneth - Gilfillan Bros., Inc.
Miller, William F. - Navy Weapons
Mitchell, James W. - Frankford Arsenal
Mitman, Henry D. (Capt.) - ARGMA
Moehle, Frederick L. W. - The Johns Hopkins University
Monroe, William Ransom - Convair
Moore, Victor E., Jr. - Douglas Aircraft Co.
Morris, Jack C. (Maj.) - HAFB
Morrison, Edward John - Texas Instruments, Inc.
Morrison, Stephen C. - Space Technology Labs., Inc.
Moskovitz, Abraham I. - Aerojet General
Moskowitz, Arthur - North American Aviation, Inc.
Murray, Kenneth W. - General Electric
Murray, William A. - Goodyear Aircraft Corp.
Mutch, William Warren - Naval Research Lab.
Myers, Robert Eugene - Minneapolis-Honeywell

ATTENDANCE LIST

Myles, Clyde Wesley - McDonnell Aircraft Corp.

Nagy, George - Goodyear Aircraft Corp.
Neese, James Arthur - McDonnell Aircraft Corp.
Nelson, R. W. - WSMR
Newell, Joseph C. (Lt. Col.) - Fort Bliss
Nichols, Robert W. - General Electric
Nielsen, K. L. - General Motors Corp.
Nietsch, Herman E. - Robinson Technical Products
Norland, Raymond J. - Wright-Patterson AFB
Nottingham, Ralph B. - North Electric Co.

Oakley, Paul D. - Diamond Ordnance Fuse Lab.
Odell, Patrick L. - Kirtland AFB
Oelke, Harlan J. - Diamond Ordnance Fuse Lab
Okun, Abe M. - RCA
Orkand, Donald S. - Picatinny Arsenal
Orvis, Derrell Boyd - Philco
Osborn, Miles - WSMR
Owen, Norman B. - Fort Bliss

Pabst, William R. - Bureau of Weapons
Page, W. W. - WSMR
Patterson, Melvin A. - Bendix Aviation Corp.
Paulsen, Frank - Packard-Bell Electronics
Peck, Donald S. - Bell Telephone Lab.
Pierce, Chester - Air Research and Dev. Comm.
Pendry, R. A. (Sq. Ldr.) - British Joint Service Mission
Penfold, Lyle Elmer - Consolidated Western Steel
Peratino, George S. - Bureau of Naval Weapons
Peterson, Kendall (Maj.) - Fort Bliss
Peterson, N. Marcus - Sperry Utah Engineering Lab.
Phelps, Robert Chapman - General Dynamics
Phillipps, Elmer Albert, Jr. - Whittaker Gyro
Polking, Urban H. - WSMR
Pollock, Stanley I. - U. S. Naval Ordnance Lab.
Porter, Donald K. - Fort Bliss
Powell, Harry R. - Space Technology Labs., Inc.
Powell, Roger D. (Capt.) - USARADSCH
Power, G. W. (Brig. Gen.) - Fort Bliss
Powers, Aaron B. - U. S. Naval Ordnance Lab.
Procassini, Andrew Anthony - Motorola
Provencio, Paul - WSMR

Raines, Martin L. (Lt. Col.) - NASA Space Task Group
Randall, Thomas R. (Capt.) - Fort Bliss
Rasmussen, M. I. - WSMR
Ray, Jack Burton - Convair

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Ray, John - Bureau of Weapons
Read, John Henry Fredrick - Canadian Joint Staff
Reeve, Edward A. - IBM
Reinicke, Herbert G. - North Electric Co.
Rice, H. R. (Maj.) - Fort Monroe
Rice, John A. - Raytheon Mfg. Co.
Richardson, James D. - Electro-Mechanical Res., Inc.
Riedasch, Nelson - Boeing Airplane Co.
Risk, Donald Leslie - Convair
Rivera, James B. - RCA
Roberts, Arnold N. P. (Maj.) - Dept of Army
Roberts, Donald B. (Col.) - Dept of Air Force
Roberts, Ernst E. (Capt.) - Fort Bliss
Roberts, Ray O. (Lt. Col) - HFAB
Roberts, William M. - Aberdeen Proving Ground
Roddy, Francis J. (Lt. Col.) - Fort Bliss
Rogers, James P. - USAADHRU
Rollin, Russell A. Jr. - University of Michigan
Romig, Harry G. - Hoffman Labs. Div.
Rooten, Albert (Capt.) - Norton AFB
Roper, Kenneth (Capt.) - AF Ballistic Missile Agency
Rowe, Geoffrey C. - Canadian Joint Staff
Rumin, Clifford H. - Bureau of Naval Weapons
Rumer, William Isaac - Rand Corp.
Rupe, Jesse C. - USAADHRU
Rush, Robert I. (Maj.) - Fort Bliss
Russell, Charles Woodrow - Republic Aviation Corp.
Russell, James Clifford - Raytheon
Russell, Sam C. (Maj. Gen.) - Fort Bliss
Rutter, George W. (Maj.) - Wright-Patterson AFB

Safford, Edward J., Jr. - Fort Bliss
Sager, Wesley C. (Lt. Col.) - Fort Bliss
Schulze, Henrich A. - Redstone Arsenal
Schmidt, Harry P. - NOTS, China Lake
Schmidt, Robert Eugene - Raytheon Mfg. Co.
Schuldenfrei, Marvin - Bureau of Naval Weapons
Schwinge, Heinz T. - HAFB
Searle, Richard J. - Bendix-Pacific
Seeger, Donald E. - Picatinny Arsenal
Sewell, Walter E. (Col.) - Office of Ordnance Research
Shanley, Thomas J. B. (Col.) - Dept of Army
Shapero, Albert - Stanford Research Inst.
Shenk, Donald H. - Redstone Arsenal
Sheridan, Frank L. - Wright-Patterson AFB
Sheridan, John P. - Sprague Electric Co.
Sherburne, R. K. (Dr.) - WSMR
Shonerd, Clyde - WSMR
Shutt, Phillip S. - WSMR

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Simon, Henry (Maj.) - Dept of Air Force
Sjoberg, John Calvin - Avco Corp.
Skawienski, Theodore L. (Lt. Col.) - Eglin AFB
Smith, Chandler C. (Lt.) - Sandia Base
Smith, C. D. (Dr.) - The Mitre Corp.
Smith, Marion P. - Minneapolis-Honeywell
Smith, Richard E. - Bendix Products Co.
Smith, Robert G. - USAADHRU
Snodgrass, John W. - Martin Co.
Snow, Edward O. - WSMR
Spangler, Richard S. (Col.) - Fort Bliss
Spears, Otis Sheldon - Fort Sill
Spencer, Milton T. (Capt.) - Sandia Base
Spergel, Jack - Fort Monmouth
Stevens, John D. (Col.) - Hq. Air Defense Center
Stallard, Robert L. - Martin Co.
Steele, Orvie A. - HAFB
Steinberg, Alvin - Redstone Arsenal
Stember, Lawrence H., Jr. - Battelle Memorial Institute
Stempler, Samuel - The W. L. Maxson Corp.
Stenglein, Thomas A. - Lo[illegible]h Corp.
Stephan, Martin H. - The Johns Hopkins University
Stephens, Floyd R., Jr. - Firestone Tire & Rubber Co.
Sternberg, Irving Paul - Telecomputing Corp.
Steven, Martin H. - John Hopkins University, APL
Stevens, John D. (Col.) - Hq. Air Defense Center
Stevens, Martin - General Electric
Stevens, Paul M. - Ford Motor Co.
Stewart, Arlington Kenneth - Raytheon Mfg. Co.
Stoller, David Samuel - Rand Corp.
Storer, Robert L. - Rocketdyne
Strick, Paul J. - Wright-Patterson AFB
Strider, Thomas P. (Capt.) - Fort Bliss
Strobel, Howard McClane - NY Naval Shipyards
Studdard, James L. - Redstone Arsenal
St. James, L. N. - Bell Telephone Labs.
Sundt, William M. - Atomic Energy Commission
Surber, J. W. (1st Lt.) - ADC to DCF
Sussman, David L. - Fort Monmouth
Swain, James W. (Maj.) - Fort Bliss
Sweimler, Donald J. (Capt.) - Ent Air Force Base
Swift, Edward C. - Pratt & Whitney Aircraft

Tanner, Joseph J. (Maj.) - Fort Bliss
Teresi, James Madison - Convair
Thames, Torben O. - NA Aviation, Inc.
Thomas, Charles R. - Chance Vought Aircraft

Thomas, James W. - U. S. Naval Ordnance Lab.
Thompson, Francis A. - Bureau of Weapons
Thompson, William B. - General Electric
Thorgersen, Harold L. - USAADHRU
Thrower, Martha W. - Redstone Arsenal
Townsend, Alan R. - Allison
Truelove, Alan John - General Electric

Ulanowicz, Emil W. (Maj.) - Fort Bliss
Ullman, Richard - Ford Instrument Co.
Ulrey, Roy C. - Wright-Patterson AFB
Upton, Albert P. - Minneapolis-Honeywell

Vanderbeck, John P. - U. S. NOTS, China Lake
Van Der Horck, Max J. - Ramo-Wooldridge
Varney, Zenas Joseph - McDonnell Aircraft Corp.
Vaughan, William H. (Maj.) - Fort Bliss
Verbeck, William M. - Melpar, Inc.
Vernon, William Burke - Boeing Airplane Co.
Vezeau, Waldo A. - Emerson Electric
Vogel, William R. - Ordnance Weapons Command
Voosen, Bernard John - Rand Corp.

Wagner, Robert L. - Picatinny Arsenal
Walker, Peter Gautier III - Gilfillan Bros. Inc.
Walters, Allie L. (Capt.) - Fort Bliss
Watson, John W., Jr. (Capt.) - Fort Bliss
Watts, Norman W. - U. S. Naval Weapons Lab.
Webb, Willis L. - WSMR
Webster, Sammie L. - Hughes
Welch, Paul W., Jr. - WSMR
Welker, Everett Linus - Arinc Research Corp.
Wendt, Robert R. - Bendix Aviation Corp.
Wertz, Clyde E. (Lt. Col.) - Fort Bliss
West, Einar (Dr.) - Hercules Powder Corp.
Weymouth, Albert K. - Dept. of Navy
White, David - Sperry Utah Engineering Lab.
White, W. T. - Sperry Gyro
Whiting, Sanford V. - Fort Bliss
Wiegand, Walter J. - Hughes Aircraft Co.
Wier, James Edward - Temco Aircraft Corp.
Wierzbicki, Stanley T. - Watertown Arsenal
Williams, Jerry R. (1/Lt.) - Fort Bliss
Williams, Ralph I. (Lt. Col.) - Fort Bliss
Williams, Robert T. - Arinc Research Corp.
Williams, Wyman L. - USAADRHU
Willing, Walter R. (Capt.) - Canadian Joint Staff

ATTENDANCE LIST

Wilson, Thomas W. (Maj.) - Redstone Arsenal
Wirth, E. - Ford Motor Co.
Wittingn, Edward G., Dr. - Office of Secretary of Army
Wood, Arthur E. Jr. - Leach Corp.
Wood, Ernest C. - Office of Secretary of Defense
Wray, Stanley T. (Maj. Gen.) - Wright-Patterson AFB
Wright, Albert N. - USAADHRU
Wrobleski, William J. - University of Michigan

Yetter, William P. - North American Aviation

Zabriskie, Hollis C. - HAFB
Zandstra, Thomas, Dr. - WSMR
Zlomke, Clayton G. - Rocketdyne
Zorger, Paul Harvey, Sr. - Ramo-Wooldridge, Inc.
Zqicker, Vernon M. - Allison
Zucker, Burton D. - Ford Instrument Co.