INTRODUCTION

There are two purposes for this introductory overview. The first of these is to describe the general thrust and nature of work of the ARPA/AFML Program to Quantitative Flaw Definition so that a common framework may be set for the results that will be presented in these proceedings. Secondly, a review of some of the highlights of the work to date is given. In this review, emphasis is placed upon the work that has been done in the development of a quantitative ultrasonics capability and the "building blocks" that have systematically been put in place in order that a firm foundation for an operative ultrasonic technology might be established. It is considered important that the reader have an opportunity to view the "building blocks" in the context of the complete ultrasonics structure, for in the course of the meeting in which expert presentations of various elements of work are given, the overall structure may not be readily apparent. It is regrettable that time simply does not permit a detailed review of all the work that has been accomplished by the program participants and members of the ARPA Materials Research Council who have contributed significantly to program progress and whose contributions and interest are deeply appreciated. The reader is encouraged to seek further information from the author or the program investigators.

PROGRAM THRUST AND BENEFITS

Even though the research work that is embodied in the ARPA/AFML program is quite specific and aimed at the accomplishment of certain goals, it is also useful and important to place this work in the perspective of a longer range goal, i.e., the evolution of a new, non-destructive evaluation technology. The requirements for this new technology have, in fact, been set for some time. Simply and briefly, they specify that the new technology shall contribute to the improved safety and reliability of components and structures at reduced cost, requirements which are at first sight mutually inconsistent and unattainable under current capabilities. It is the purpose of this section to identify and discuss the nature of research work that is necessary to accomplish this evolutionary change in inspection and evaluation capabilities and thereby provide a framework into which the results to be presented in the next several days (these proceedings) can be placed.

Perhaps the most direct way to compare existing non-destructive testing technology with the desired non-destructive evaluation technology is to examine the appropriate definitions and to comment upon their scope and content. There are significant differences that are sometimes lost in the variously used acronyms. According to current practice, definitions that are commonly (although not universally accepted) are given in Fig. 1.

**NDT:** "...the development and application of nondestructive test methods..."

**NDI:** "...the performance of inspections to established specifications or procedures using NDT methods to detect anomalies..."

**NDE:** "...the capability to assess the state of a material, a component, or a structure from a set of quantitative NDT measurements and to predict the remaining serviceability of the item in question from these measurements when evaluated in the context of appropriate failure models..."

Fig. 1 Variously used definitions.

According to these definitions, non-destructive testing (NDT) refers only to the development and application of various test methods. No emphasis is placed upon an interpretation of the results of the test and the nature of the interaction of the probing technique with the flaw or materials phenomenon in question. Without attention being given to this key area, it is impossible to make judgments as to the severity of the flaw in question.
and to the assessment of the ability of the component or structure to perform an assigned mission in its presence. This key omission lends a feeling that the test method per se is the important objective and not the results to be obtained from it. The concept of non-destructive inspection (NDI) extends the definition of the NDT technology only in the sense that it prescribes that inspections be performed in accordance with a prescribed format. This format may take the form of specifications which relate to the method, frequency, or spatial coverage of an inspection. However, the definition contains no specification for additional information that will enable the requirements for improved reliability at reduced cost to be met any more so than does the previous definition for NDT. On the other hand, the definition given for non-destructive evaluation (NDE) represents an enormous extension in scope, scientific content, and ultimate payoff from either of those given for NDT or NDI. There are essentially three new and important concepts contained within this definition that are not specifically contained in the other two. They are the concepts of quantitative measurements, the assessment of a flaw's criticality in a material or component, and the prediction of the remaining serviceability of the component because of the presence of the flaw. The introduction of quantitative test methods is an essential ingredient of the NDE test technology. Simply, the words mean that the test techniques are sufficiently advanced so that quantitative, rather than qualitative, information is available concerning the target of interest, or flaw. In a philosophical sense, the capability to perform quantitative measurements is a first principle of any scientific or engineering technology; without that capability, the history of science has shown many times over that it is impossible to advance further. In turn, this means that the nature of the interaction between the interrogating energy and the target (flaw) can be understood in terms of sound physical models, and further, that the target or flaw can be characterized and evaluated in terms of appropriate failure models. A quantitative requirement also means that essentially all current NDT techniques must be advanced significantly, for none of those in current operational practice can be classed as quantitative. The second and third concepts are completely independent of each other, and each in turn relies critically on the ability to perform a quantitative NDT measurement. More specifically, the assessment of a flaw's criticality is related to the concept of accept/reject criteria, i.e., the set of rules whereby an operator makes his decision as to whether to accept a component or to reject it. Although the need for rational accept/reject criteria has long been recognized as a necessary part of the inspector's arsenal, such criteria have not, in general, been recognized as adjuncts dependent upon the development of quantitative testing techniques. According to the definition of NDE given above and as pursued in this program, the generation of such criteria is just as essential to the performance of the NDE function as are the quantitative measurement techniques upon which they depend. The development of rational accept/reject criteria also forms a multidisciplinary marriage between the measurement procedure and materials scientists and engineers, for materials failure models (such as fracture mechanics) form the framework within which the quantitative NDT measurements can be interpreted and the flaw criticality evaluated. As will be noted later, it is in fact the combination of quantitative measurement and the capability of characterizing a flaw and its criticality under specified loading conditions that provide the "window" for maintaining the safety and reliability of a component or system under reduced cost conditions.

In Fig. 2 is given a schematic diagram in which the concepts of quantitative NDE discussed above are shown in relation to each other. The idealized operational NDE function is shown within the full circle; a part is received, it is inspected by a quantitative NDT technique, an appropriate physical property of a detected flaw is extracted, a judgment is made of its severity in terms of analytical models (perhaps presented in the form of look-up tables), and the part is then either returned to or retired from service. Current operational capabilities are indicated by the hashed section of the upper left quadrant only since no capabilities currently exist in the field for the exercise of the quantitative NDT measurement or application of a rational accept/reject rule. (As will be noted later, this omission leads to the "zero defects" accept/reject rule in which all flawed parts are rejected resulting in excessive costs.) Functional research topics being pursued in the ARPA/AFML program aimed at developing this methodology are shown in labeled boxes both within and to the right of the circle. Elements of these multidisciplinary topics will be presented and discussed in detail during the course of this meeting. Two exceptions to the above comments may be noted in the figure. The first of these concerns the box labeled material processes improvement. Although not a direct line item in the NDE function, this is a most important result of its development and performance. Knowledge gained as a result of the measurement and analysis of material and component failure modes provides the basis for improvement so that the failure, hopefully, may be eliminated in the first place. Secondly, the box labeled economic choice on the right side of the figure is not a line item in the NDE function either; rather, it is a management function. Its inclusion on this figure is considered important, however, for it is through the quantitative NDE function and its utilization by the designer that management has a means to inject economic choices in the form of cost-risk tradeoffs into the operational cycle.

Fig. 2. Methodology required to reach operational requirement.
Without wishing to belabor the point regarding economic choice made above, it may be worthwhile to add a few comments in this regard since the relationship of quantitative NDE to reduced cost and predictable reliability may not be generally realized. One schematic representation of these relationships is given in Fig. 3. In this figure the probability that a measurement with an NDT technique yields the correct value of a physical property \( a \) is plotted against the actual value of the property. At this point, property \( a \) can be considered general in nature, and may, for example, be as diverse in nature as a crack length, the shape and size of an inclusion, or a material strength. As NDT techniques are made quantitative, the essentially flat response (shown as non-quantitative capability) is changed to a peaked response centered at the value of the property and with a "bandwidth" determined by the error and reliability of the measurement itself. The effects of this quantitative measurement upon the relative costs of ownership of the component or system, when evaluated in the framework of rational accept/reject criteria, are shown in the lower part of the figure. This cost curve considers two effects. The first is the unnecessary cost of rejecting materials and components when a detected flaw is in actuality smaller than a critical size (the costly "zero defects" philosophy). The second is that of costly component or system failure which may result if the detected flaw is greater than a critical size. Without going into details, it has been demonstrated (and it is also somewhat obvious) that a sharpening of the measurement capability will produce a minimum in the cost curve at some value of the physical property value of concern. This value, of course, will depend upon the materials used in the component and the design requirements placed upon the component. The essential point here, however, is simply to recognize that the development of the quantitative NDE function provides a basis for the development of rational cost-risk tradeoff strategies.

The benefits to be derived from evolution of a quantitative NDE discipline and its reduction to practice are both numerous and far-reaching. They may be summarized by recognizing that quantitative NDE, as defined above and as pursued in this program, provides:

- Non-arbitrary "tools and rules" for operational use with the potential for improved efficiency and automation.
- A rational basis for the development of more effective cost-risk tradeoff strategies.
- A necessary building block for the development of an effective predictive design technology.

It should also be recognized that the NDE technology as discussed herein can be viewed as a technological "missing link" that serves to bridge the operational gaps between materials science/engineering, device engineering and the physical/mathematical sciences. These multidisciplinary components are needed as elements of this evolving technology.

In the first part of this paper, a generalized view of the thrust and goals of the ARPA/AFML program was given; it is the purpose of this portion of this overview to highlight more specific accomplishments that have been gained during the course of the program. As noted in the introduction, particular attention will be given to the work that has been done to produce the "building blocks" of a quantitative ultrasonic capability, its coupling to fracture mechanics, and their organization into an operative systems concept.

The research work in the ARPA/AFML program is separated into three projects. Because of space and time limitations, a detailed review of the many accomplishments in these three projects by the various program participants cannot be given here. Rather, a listing of the accomplishment and the principal investigator will be given. The reader is encouraged to seek details from this and other program reports and from the principal contributors and their publications. It is to be emphasized that key contributions have also been made to this work by members of the ARPA Materials Research Council who are not officially participants in the ARPA/AFML program. In particular, it is a pleasure to acknowledge the important contributions made by W. Kohn, B. Budianski, J. Rice and R. Thomson.

![Fig. 3. Cost benefits of improved quantitative physical property measurement.](image-url)

- Quantitative Ultrasonics:
  - Theory (J. Krumhansl, J. Gubernatis, E. Domany, J. Rose, J. Achenbach, V. Varadan)
  - Sample development (N. Paton)
  - Experimental procedures and data acquisition (B. Tittmann, R. Elsley, L. Adler)
  - Inversion techniques (J. Richardson, J. Krumhansl, J. Rose, N. Bleistein, A. Mucciardi, G. Kino, K. Lakin)
  - Extraction of flaw parameters that permit "bridging" to fracture mechanics (J. Richardson, J. Krumhansl, J. Rose, G. Kino, with key inputs from W. Kohn, B. Budianski, J. Rice, and R. Thomson)
  - "Stand alone" items available for ultrasonic improvements:
    - EMAT technology (R. B. Thompson, C. Fortunko, C. Vasile, B. Maxfield)
    - Inverse filters (R. M. White)
    - Integrated transducers (R. M. White)
    - Procedures and apparatus for transducer characterization (K. Lakin, B. Tittmann, R. Elsley)
    - New concepts for ultrasonic standards (D. O. Thompson, R. B. Thompson, B. Tittmann)
    - Variety of computer-aided signal processing techniques (R. Elsley)
    - Acoustic imaging techniques (G. Kino, K. Lakin)

Project II. - Quantitative Methods for Measurement of Surface Flaws.

- Ultrasonic techniques for sizing and determination of fracture mechanics parameters for surface flaws (B. Auld, G. Kino, B. Tittmann, O. Buck)
- Quantitative eddy current development (B. Auld, C. Fortunko, A. Bahr, T. Kincaid)

Project III. - Techniques for Measurement of Strength Related Properties in Advanced Materials

- Moisture diffusion analysis (including damage assessment) for composites (D. Kaelble)
- Acoustic emission of composites and a probable capability for remaining life predictability (L. Graham)

- Development of ultrasonic measurement techniques, including inversion procedures, for evaluation of finished adhesive bonds (G. Alers, F. Chang, K. Fertig)
- Generation of accept/reject criteria for ceramics (A. Evans, J. Richardson, K. Fertig, G. Kino, R. Addison, J. Schuldies).
- Acoustic residual stress determination in ferrous materials (R. B. Thompson)
- Non-linear ultrasonic detection of microcracks in Al alloys (O. Buck)

Quantitative Ultrasonics - A goal of project I of the ARPA/AFML program has been the development of a fundamentally correct structure for a quantitative ultrasonics technology that will help alleviate the various limitations of the current technology and which may be coupled directly to rational sets of accept/reject criteria as noted in the first part of this paper. In this section the technical approach that has been pursued will be outlined together with a limited description of the various "building blocks" that have gone into it.

The philosophy of the technical approach adopted for the construction of a quantitative ultrasonics capability is illustrated in Fig. 4. A set of procedures were established whereby the capability was built up from fundamental building blocks which began with the development of a theoretical understanding of the basic interaction of the ultrasound with the flaw. The development of approximate theories has been emphasized in this program because the number of flaw shapes which can be treated by exact techniques is extremely limited and because of the desire to extend the work to real flaws of complex shapes. A second major building block involved the performance of verifying and/or guiding experiments on a set of controlled samples in which flaws of carefully determined size and shape were placed. Close interaction between theoretical and experimental work was maintained to the advantage of both in this work. The third major building block in this construction involved the development of suitable and efficient inversion techniques, i.e., those procedures whereby flaw parameters are extracted from the data. An analogy to an integral equation has been used. The theory can be viewed as the kernel of the integral equation which relates ultrasonic measurements to physical parameters of the flaw. By solving the equation by whatever means is appropriate, a relationship that predicts the size, shape, and orientation of the defect in terms of certain measurable can be developed. The fourth major step then comes in verifying that these extracted values compare favorably with known values of the flaw parameters. The importance of the precisely controlled samples becomes apparent at this juncture. Finally, having determined the flaw parameters relative to size and orientation, flaw failure parameters which are of significance in fracture mechanics and failure prediction have been attained. Thus, a construction for a quantitative ultrasonics capability has been developed which extends from a knowledge of the fundamental ultrasound-flaw interaction to a determination of
the flaw's stress intensity factor, a key parameter for failure prediction. Selected highlights of these developments will be given in the following discussion.

HOW DOES SOUND INTERACT WITH FLAWS?

EXPERIMENTAL MEASUREMENTS ON CONTROLLED SAMPLES

DATA

PREDICTOR

FRACTION MECHANICS

CLASSICAL INTERACTION

APPOROXIMATE THEORIES

KERNEL

INVERSION PROCEDURE DEVELOPMENT

Fig. 4 Building blocks of quantitative ultrasonic technology.

Theory - The development of theoretical models has been governed by two considerations. First, it was necessary to base the models upon correct solutions to elastic wave scattering problems in solids as opposed to the use of analogies to scalar models developed for fluid media. An extensive literature exists in the latter case because of the practical importance in sonar. However, this information cannot be directly transferred to the solid case in which such effects as mode conversion play an important role. Second, approximate models have been emphasized. Exact solutions are available for a few simple geometries, but these theoretical models are not readily generalized to more complex shapes. Since it is the intent to provide the theoretical techniques necessary for the characterization of real flaws, the model development and approximations have been selected so that they may be extended as needed.

The major theoretical effort has been performed at Cornell University by Prof. J. A. Krumhansl and several students. They have used an integral equation formulation of the scattering problem and developed a series of approximate techniques. The first, and simplest, is the Born approximation. In this approach, the incident plane wave solution to the wave equation is used as the first approximation to the solution and the scattered fields are derived by substituting this for the actual solution within the integral. The results are rigorously correct only for weakly scattering defects, i.e., inclusions whose properties do not differ too greatly from those of the host medium. However, the results have been found to agree well with many experimental features over a much broader range of conditions.

In a series of papers, Krumhansl, Gubernatis, Domany, Huberman, Teitel, and Rose have explored a series of other approximations for both three-dimensional volumetric and two-dimensional, crack-like flaws. Included have been the quasi-static approximation which gives the rigorous result in the limit or long wavelength, and an extended quasi-static approximation which is a combination of some of the features of both the Born approximation and the quasi-static approximation to extend the range of validity of each. Each of these approaches is primarily applicable when the wavelength is comparable to, or greater than, the dimensions of the flaw. On the other end of the spectrum, Prof. L. Adler at the University of Tennessee and Prof. J. Achenbach at Northwestern University have studied application of the geometrical diffraction theory of Keller to the elastic wave case.

The Born approximation has led to a number of important insights and results. Because of its simplicity, the results separate into a product of three factors -- one proportional to the square of the frequency, one determined by the elastic constants of the flaw, and one determined by the shape factor (a function which can be recognized as the spatial Fourier transform of a characteristic shape of the flaw). The approximation thus defines a clean path for reconstructing the flaw shape from experimental data. This is an important result. Secondly, use of the approximation has provided a way to visualize the scattering patterns rather easily. Examples are shown in Fig. 5. Here, isographic projections of equal scattered amplitudes are plotted for the scattering of a broadband longitudinal wave pulse from a sphere and an oblate spheroid at 45° incidence. The differences in the signatures of the direct, longitudinal-longitudinal scattering and the mode converted, longitudinal-shear wave scattering are striking. From this kind of information it has been possible not only to identify features of flaws, but also to estimate the transducer apertures required to differentiate between various flaw types and orientations.

Fig. 5 Insight into flaw-ultrasound interaction.
Experimental Technique - In order to carry through the approach outlined above, it was necessary to make measurements on samples in which flaws of known size, shape, and orientation have been placed. A procedure utilizing a diffusion bonding fabrication was selected to achieve this purpose. In this procedure, developed by N. Paton at the Science Center4, two pieces of titanium alloy were carefully prepared with mating surfaces flat to within four optical bands. The desired defect was then machined accurately into the mating surfaces. Following this step, the two halves of the sample were carefully assembled in a mating jig and placed under pressure at approximately 1500°F. The bonding pressures were kept low in order to limit the specimen strain thereby preventing significant distortion of the machined defect geometry. Under these conditions, grain growth occurs across the bonding plane and produces a bond line which is indistinguishable from the parent metal both ultrasonically and metallographically. Most of the samples prepared in this way have utilized the titanium alloy Ti-6Al-4V since it is an aerospace alloy of interest and because of the fact that at the bonding temperature it dissolves residual surface oxides (thus assuring a good bond). Special techniques have also been developed for producing such intentionally defected specimens from steel and aluminum alloys.

In Figs. 6 and 7 are shown a micrograph of a cut through a finished sample in which a hemisphere was embedded and a schematic showing the various kinds of void defect cavities that have been prepared. The micrograph demonstrates the metallurgical invisibility of the bond line nicely. Most of the defected samples, as shown in Fig. 7 have been prepared so that the defects retain one axis of symmetry. Thus, the set includes spherical cavities of different diameters and spheroids of revolution (both prolate and oblate). The size range varies from a 200 μm by 800 μm oblate spheroid to a 1600 μm by 400 μm prolate spheroid, thus producing a significant range in the aspect ratio of the spheroids. This range is sufficient to permit an examination of the limit as the spheroid of revolution approaches a crack-like flaw.

These defects have been placed in two sets of samples with different exterior shapes. One set is a right circular cylinder with a 2.5 cm height and a 10.2 cm diameter. The other set has a "doorknob" or "trailer hitch" shape as shown in Fig. 8. In these samples, the exterior surface is a sphere of 2.8 cm radius with the defect at its center. This feature makes it possible to perform fundamental measurements of the angular dependence (as well as the frequency dependence) of the ultrasonic scattering since transmitting and receiver transducers could be placed at nearly arbitrary angles without changing the ultrasonic path length. These measurements were further facilitated by a precision goniometer and the use of machined buffer caps which match the flat end of the transducers to the curved surface of the sphere. The data obtained in this idealized geometry were used both as a check on the theory and as a reference against which the data on the cylindrical samples could be tested to insure that correction for refraction and diffraction effects have been properly made. The development of such corrections is a crucial step in transferring the basic research results from the laboratory into field usable techniques for use on parts of complex shape.
Detailed measurements were made by B. Tittmann at the Science Center and L. Adler at the University of Tennessee on samples containing all of the defect geometries shown in Fig. 7. Figure 9 illustrates the excellent agreement that exists between the exact theoretical predictions of the angular dependence of the scattering from a spherical inclusion and the experimental measurements. This agreement established that an exact calculation based on isotropic elasticity models applies satisfactorily to the polycrystalline, two-phased titanium alloy used in this work and that measurements could be made with a high level of precision. This latter point was strengthened by the fact that there were no adjustable parameters in the comparison. The data were corrected for the efficiency of transduction, attenuation of ultrasound, and diffraction to yield an absolute measure of scattering amplitudes. In this regard, it should be noted that experimental points are presented that were taken with either a single transducer in the pulse-echo mode (solid point at 180°) or a pair of transducers (open points). In addition to illustrating the agreement between experiment and exact calculations, the results demonstrated a calibration procedure that can be used to ensure that a quantitative experimental system is properly functioning.

For more general defect types, exact calculations become increasingly difficult, and the approximate theories discussed above were used. The spherical geometry was used as a reference case in which these models could be compared against the well established exact result. As noted, the Born approximation is rigorously valid only for inclusions whose properties are similar to those of the host medium. However, it was found that it makes many useful predictions outside of this regime. For example, even for a cavity, it is found to make good predictions for the angular variations of scattering for angles near the back-scattered direction and for relatively low frequencies, i.e. $ka \approx 1$ where $a$ is the sphere radius. The detailed frequency dependence of the result was found to have systematic errors but, when averaged over a set of frequencies which comprised the broadband ultrasonic pulse, the results were again quite useful.

These results, deduced for the case of the sphere by comparison with experiment for both exact and approximate models, have been further investigated in the spheroidal geometry by a direct comparison of experiment and the approximate theory. In general, the same conclusions have been drawn. For example, Fig. 10 is a comparison of the back-scattered power from a pancake-like, 800 μm x 400 μm oblate spheroidal cavity. In this case the theoretical predictions were averaged over a range of frequencies corresponding to those produced by the transducer, and excellent agreement was obtained.

Other measurements at higher frequencies on crack-like flaws have established bounds on the geometrical diffraction theories. Both the theoretical and experimental work are continuing to increase the regime in which satisfactory agreement exists.

Inversion - The inversion techniques which have been investigated can be divided into three general classifications. One set of approaches, of which imaging is the most familiar example, is intended to reconstruct the detailed shape of the object. These approaches can, in general, be viewed as the reconstruction of the defect shape function from measured spatial Fourier components. Work devoted to the development of imaging systems...
The calculated characteristic function, $\gamma(r)$ for a spherical void in Ti is shown and compared with the exact result shown by dotted lines.

A comparison of the predicted and known flaw parameters is given in Table I. It will be noted that the agreement is quite good, particularly in view of the approximate nature of the theory used in the training process. It can be anticipated that the use of more accurate approximations in the future will improve this performance further.

A third approach to the inversion problem has been made in the regime where the ultrasonic wavelength is large with respect to the flaw size, a regime of practical importance. Here the problem is again nonlinear, but analytic techniques can be used in the limit of long wavelength to solve the forward scattering problem in closed form. In particular, for a general flaw, it has
be deduced from the set of coefficients $A_i$. The parameters of the flaw are then deduced from the set of coefficients $A_i$ using an estimation theory approach. This methodology was applied to one of the backscattered signal at angles of 15°, 30°, 45°, 60°, 75°, and 90° with respect to the symmetry axis of the ellipsoid. The results of the prediction of the ellipsoid dimensions and orientations are amazingly accurate, clearly demonstrating that the potential of this new approach for defect characterization is high. Details of this work will be presented later in this meeting.

Fracture Mechanics - The last remaining "building block" shown in Fig. 4, Fracture Mechanics, has been a subject of major activity this past year. As noted earlier, the purpose of this effort is that of extracting numerical values of flaw parameters that have in the past been determined only through destructive tests. Success in this endeavor has to be regarded as a significant step. Since detailed reports of these activities will be presented at this meeting, only summary comments will be given here. Two approaches have been taken for the determination of the stress intensity factor. One of these is a direct approach in which the stress intensity factor can be calculated from the values measured for the flaw parameters. This approach has been used by Richardson and Tittmann (these proceedings). A second approach has been used by King et al (these proceedings) in which extensive use has been made of the theoretical calculations of Budianski and Rice. Both of these approaches have been very successful in producing values for the stress intensity factor of the measured values.

Summary - The systematic and logical procedure outlined in Fig. 4 has been used to develop a quantitative ultrasonic structure utilizing three new approaches to flaw characterization involving generalized imaging, adaptive learning, and long wavelength scattering. Each of them is built upon results traceable to first principal interactions, and in each case, preliminary results which demonstrate the feasibility of the approach have been obtained. Further work must be designed to make specific improvements in each and to reduce them to practice. It is important to realize that an entire structure for quantitative ultrasonics has been demonstrated which can be direct-coupled to failure predictive techniques. This overall result must be considered an important accomplishment and a foundation for a new inspection technology.

REFERENCES


DISCUSSION

Neil Paton (Science Center): My name is Neil Paton, and I have a question for Tom Moran. He mentioned the rejuvenation of disks and specifically titanium disks. I would like to know, first of all, do you have any methods in mind for rejuvenation of those disks; and, secondly, is it just titanium in which you're interested, or are you also interested in nickle base super alloys? If so, what methods do you have in mind there?

Tom Moran (AFML): I can't answer.

Don Forney, Chairman (AFML): Harris, could you answer the question? Harris Burte is the AFML Chief Scientist. If he doesn't know the answer, we're all in trouble.

Harris M. Burte (AFML): The answer is quite a bit. There are a variety of things being explored at different levels. I am sure you're familiar with some of them, Neil. One approach assumes that a discrete flaw can be closed with isostatic pressure. If it happens to be a surface flaw a coating may be put on it so that we can bridge that flaw and still enable us to close it up. Another approach goes back 10 or 15 years based on a wide variety of investigations that say we need to understand some of the reasons that may lead to fatigue crack initiation. For example, by providing suitable heat treatment to the material at a particular stage of life we can rejuvenate the material and essentially extend its life if, in fact, we don't also give ourselves more problems in doing that by putting in residual stresses. I can't give you a simple answer to it because it is a very broad field. It doesn't have one specific approach. If anybody is interested in these particular items, I suggest they make appointments with some of the various people in the laboratory, either through Dr. Norman Tallon or myself.

Don Forney, Chairman: This rush of hands in the air, I can hardly hear. Yes?

Gerald C. Gardner (University of Houston): I would like any of the three to comment on the aspect of accept/reject criteria. We have fallen into the pattern of considering that to be a dichotomous decision, either yes or no, but in point of fact if you had an adequate mechanical performance predictive technology, you ought to be able to classify a component, not simply in terms of whether it will or will not fail, but rather in terms of what service regimes it will perform adequately at acceptable levels of risk. This means that you're really making a multistaged decision rather than a simple dichotomous one, and I would just like to hear any one who wishes to comment on the relevance of the comment that I just made.

Don Forney, Chairman: Mike volunteered.

Mike Buckley (ARPA): I think we're saying the same thing. There is a probability of failure at all levels of different modes of operation. Different constraints, etc., have to be factored in, but eventually, it comes down to making a decision in a given anticipated environment or mission profile. So you do have to eventually make a decision. We're really talking about making a conscious one, knowing all the variables and their probabilities of failure, but eventually, it does have to become, "I will put it into service or I won't know what the risk is."

Don Forney, Chairman: I might add that as a matter of fact we do either knowingly or unknowingly utilize this idea, Gerald. There have been many occasions in the military aircraft category, if you will, where we have flown aircraft in limited control flight conditions because of either a limitation in the strength of a component or the fact that we don't know the strength of a component pending tests. In actual fact we have frequently flown with restrictions.

Gerald Gardner: You constrain the envelope.

Don Forney, Chairman: That's right. We constrain the envelope. Military aircraft have red lines. We can fly them faster. We can drive the engines harder and make the aircraft fly faster, but it is unsafe. So every aircraft that I know of has a red line. That, in a sense, is a criterion.