OVERVIEW

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Today I would like to give an overview, both of the meeting program in general and, more specifically, on the work that is being done in the ARPA/AFML Program for Quantitative Flaw Definition. I will first briefly define the philosophy of quantitative flaw definition. I will then discuss, in a general way, some different approaches that are being used to obtain the necessary information. Finally, I will present a specific outline of the technical structure of the ARPA/AFML program. This will provide a framework to which the talks presented during the day can be related.

The type of situation that has pointed out the need for quantitative flaw definition is illustrated in Fig. 1. Consider the ultrasonic inspection of a part that is to be loaded by an in-plane stress. If a crack is oriented favorably with respect to a transducer on the surface, it will produce a very large ultrasonic reflection as shown in part a. However, if the crack is oriented at $90°$ it will produce a small reflection. The problem is that the crack which produces a small signal is much more likely to fail since it is perpendicular to the applied load. Thus, the ultrasonic indication is inversely related to the severity of the defect.
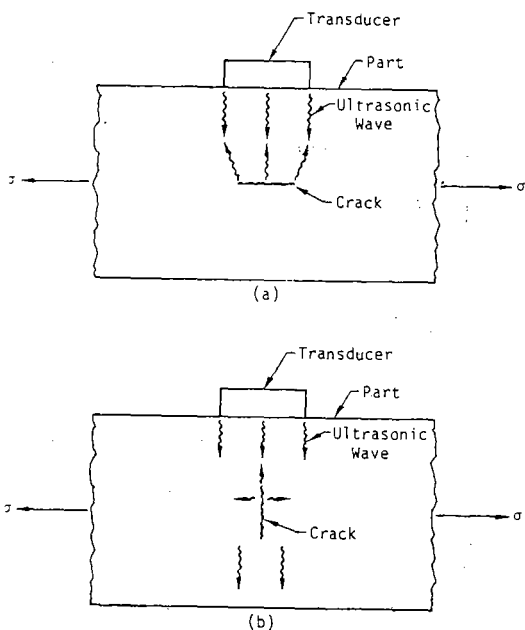

Figure 1. Comparison of ultrasonic reflections from two crack orientations. (a) crack favorably oriented. (b) crack unfavorably oriented.

This is only one example of a more general problem that is illustrated in Fig. 2. In any procedure in which the ultrasonic amplitude is chosen as the flaw indicator, a plot of detection probability versus flaw size will be quite broad. When an instrumental threshold is adjusted so that all flaws above a given size are detected with high probability, then quite a few of the flaws which are smaller will also be detected. Many parts will be unnecessarily reworked or rejected with the associated economic loss. This can only be avoided if quantitative techniques are developed so that this broad detection distribution approaches a step function.
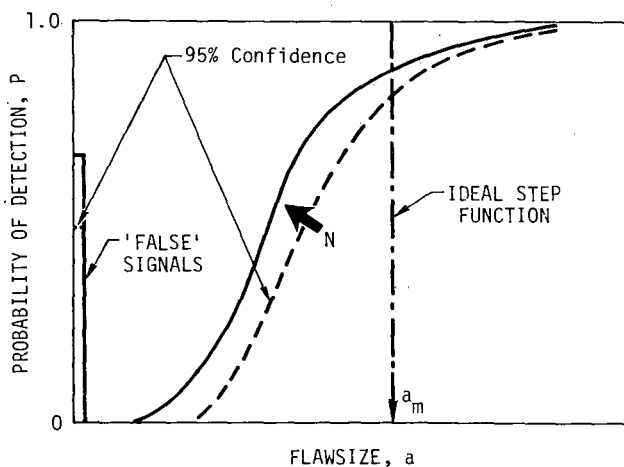

Figure 2. Probability of flaw detection for specific sensitivity setting, as function of flaw size, showing "false" signals and indicating 95 percent confidence level. Quantitative techniques will sharpen the distribution so that it approaches the ideal case of a step function.

The payoff of precisely measuring the size of a flaw is to be able to use this information in fracture mechanics models for failure prediction. By way of example, the relationship used in certain materials to predict the remaining lifetime t_r under static loading conditions when failure is controlled by crack propagation[1] is shown below.

$$t_r = \frac{2}{v_0(n-2)} \left(\frac{K_0}{\sigma_a \gamma} \right)^n \left[\frac{1}{a^{(n-2)/2}} - \left(\frac{\sigma_a \gamma}{K_c} \right)^{n-2} \right] \quad (1)$$

where $2a$ is the diameter of the flaw in the plane of propagation; v_0, n, K_0, and K_0 are parameters that define the crack propagation resistance of the material; and γ is a parameter that depends on the flaw profile along the prospective fracture

plane. It is the flaw diameter a which must be determined nondestructively. A specific example of the more general goal of quantitative NDE: to predetermine the in-service failure probability of a structural component with the best possible confidence.

There are many viable approaches for obtaining the necessary information about defect structure. In the ARPA/AFML program we have emphasized ultrasonics for a number of reasons. First, ultrasonics is a form of radiation which will penetrate structural parts so that interior defects can be interrogated. Secondly, the ultrasonic fields scattered by defects inherently contains much information about the defect structure. Finally, although other techniques are also recognized to be quite useful, it is felt that the most progress can be made by concentrating the available resources in a critical mass effort in one area.

Figure 3 further illustrates the technical goal of ultrasonic flaw definition. Ideally, we would like to find an operator, θ, which functionally relates scattered ultrasonic fields and some independently known material parameters to the failure probability of a part. One approach is to measure the size, shape, and orientation of defects and then use relationships such as the one shown in Eqn. 1 predict lifetime. In classes of materials with different failure modes, alternate but similar approaches will be needed.

SCATTERING APPROACH
TO
DEFECT CHARACTERIZATION
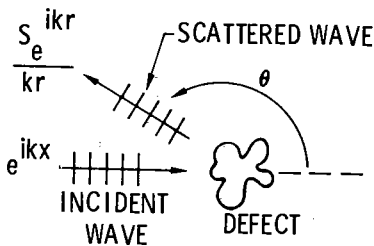
IDEALLY:

SEEK AN OPERATOR

O

SUCH THAT

$$O\{S(\theta, \omega, P) M\} \longrightarrow \text{FAILURE PROBABILITY}$$

Figure 3. Ideal Goal of Quantitative Ultrasonic Non-Destructive Evaluation.

Let us now become more specific. Table I shows some critical flaw sizes that would be expected for a wide variety of materials under typical design loads. The striking feature is the range of flaw sizes with which NDE is forced to deal. These range from 25 millimeters for a particular aluminum alloy down to 20 microns for some of the high density ceramics and even less for the more brittle glasses. We have also included the frequency for which the ultrasonic wave length is equal to the diameter of these flaws. These range from 200 KHz on up to 250 MHz and into the gigantic range.

TABLE I

CRITICAL FLAW SIZE:

$$a_c \approx \left(\frac{K_c}{Y\sigma_a}\right)^2$$

Order of magnitude estimates of critical flaw sizes in some metal and ceramic systems.

Materials		Flaw Size (mm)	Frequency for $\lambda_\ell = 2a_c$ (MHz)
Steels	4340	1.5	2.0
	D6AC	1.0	3.0
	Marage 250	5.0	0.59
	9NI4Co 20C	18.0	0.16
Aluminum Alloys	2014-T6S1	4.5	0.71
	2024-T3511	25.0	0.26
Titanium Alloys	6A1-4V	2.5	1.2
	8A1-1Mo-IV(β)	14.5	0.21
Silicon Nitrides	Hot Pressed	0.05	100
	Reaction Sintered	0.02	250
Glasses	Soda Lime	0.001	2,500
	Silica	0.003	830

This table illustrates two points which were made by Don Thompson[2] in an earlier paper in which he discussed the generic and specific aspects of NDE. From the range of defect sizes, it is quite clear that there are many special cases which are going to require their own individual solutions; it is necessary to develop some basic fundamentals which can then be applied to particular cases.

Table II defines the two classifications into which approaches for defect characterization can be divided. Imaging systems are designed to process the ultrasonic fields in such a way that a geometric outline of a defect is produced. This is very appealing since a visual display of the defect is easily interpreted by an operator. For good performance, a number of conditions must be satisfied. The wave length should be considerably less than the dimensions of the defect in order to obtain the resolution necessary to specify detailed shape. Results are best when the defect has a relatively rough surface with respect to the ultrasonic wave length so that the scattering is diffuse. Ideally, the object should have no elastic resonance.

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Table II

FLAW CHARACTERIZATION CONCEPTS

TYPE OF MEASUREMENT	GOAL	CONDITIONS FOR BEST PERFORMANCE
IMAGING	DIRECTLY DEFINE GEOMETRIC OUTLINE	· WAVELENGTH < DIMENSIONS · SURFACE ULTRASONICALLY DIFFUSE · OBJECT HAS NO MAJOR ELASTIC RESONANCES
SCATTERING	DEDUCE KEY GEOMETRIC FEATURES FROM PARTICULAR DETAILS OF SCATTERED FIELDS	· DIMENSIONS < WAVELENGTH · SPECULAR OBJECTS · RESONANCE OBJECTS OR ANISOTROPIC MEDIA

The philosophy of scattering techniques is somewhat different. These are designed to enable one to deduce key geometric features of defects from particular details of the scattered field. They can be applied over a wider range of wave lengths. They can be used when the object is a specular reflector, and the presence of elastic resonances within the defect may give useful information about its structure.

Imaging and scattering approaches share a common foundation as illustrated in Fig. 4. Consider for simplicity a situation in which an ultrasonic wave is being scattered by an object consisting of two points. A pair of spherically spreading wave fronts will leave the object and, in the far field will be superimposed to form an interference pattern. Various defect characterization techniques are simply particular ways of processing this scattered field. For example, in an imaging system one inserts a lens or some electronic equivalent thereof to focus all of the rays leaving one point on the object to a single point in the image plane. Mathematically speaking, this is equivalent to taking a Fourier transform of the far field scattering pattern. However, as will be presented in later papers, other operations on the scattered fields can yield useful information. For example, defect sizes can be inferred directly from the spatial frequencies of the farfield scattering. Also, certain adaptive, nonlinear processing techniques are showing considerable promise.

Let us now turn to some of the specifics of the ARPA/AFML program on quantitative NDE. This discussion is aided by reference to a model defect characterization system as shown in Fig. 5. Here, a transducer array is shown illuminating a part placed in a water bath with longitudinal waves. Both longitudinal mode converted shear waves will be scattered by a defect within the part as these waves reach the part surface. The longitudinal wave will be refracted and the shear wave will be mode converted into longitudinal waves in the water. Hence, the array will pick up signals arising from both the direct L → T scattering. Some signal processing is then often necessary to improve signal-to-noise ratios and to compensate for transducer frequency response and geometrical effects. Finally, signal interpretation is needed so that a decision can be made to determine whether the part is to be accepted or rejected.

DEFECT CHARACTERIZATION SYSTEM
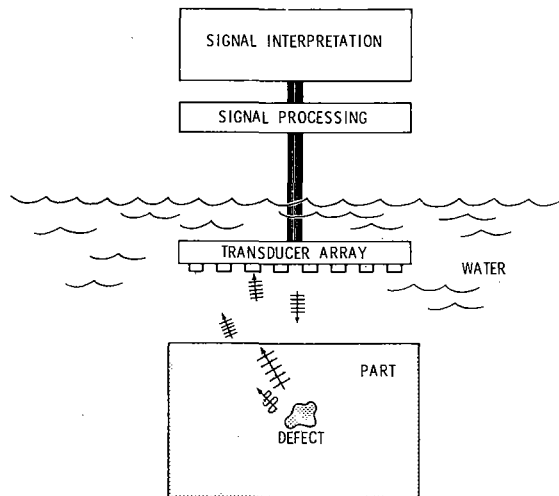
Figure 5. Model system for quantitative flaw characterization showing key components needed.

I would now like to briefly describe the research tasks going on in each of these areas and indicate their interrelationships. We have used the diffusion bonding technology to produce a set of samples with well characterized defects in their interior. Figure 6 shows the particular set that we have chosen. Included are spherical cavities, oblate (pancake-like) spheroidal cavities of two aspect ratios, 2 to 1 and 4 to 1, prolate (cigar-like) spheroidal cavities again with 2 to 1 and 4 to 1 aspect ratios. We have also reported previously some work on flat bottom holes. In addition, we have recently made some circular and elliptical cylindrical cavities of large diameter to height ratios similating cracks.

COMPARISON OF IMAGING AND SCATTERING APPROACHES

$$A(x) \simeq e^{j\phi(x)} \int_{-\theta_m}^{\theta_m} S(\theta) e^{jkx\theta} d\theta$$

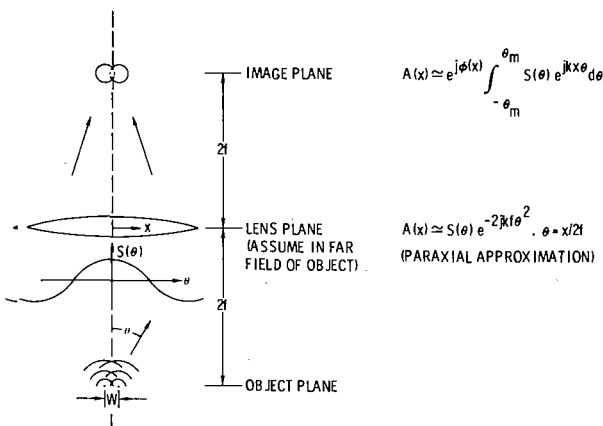$$A(x) \simeq S(\theta) e^{-2jkf\theta^2}, \quad \theta = x/2f$$

(PARAXIAL APPROXIMATION)

Figure 4. Comparison of Imaging and Scattering Approaches. A(x) is the field amplitude that would be measured in a given plane.

FLAT BOTTOM HOLE
TYPE 1 DEFECT
400, 800, 1200 μ DIA

SPHERICAL CAVITY
TYPE 2 DEFECT
400, 800, 1200 μ DIA

OBLATE SPHEROID
TYPE 3 DEFECT
800 μ DIA.
200, 400 μ HIGH

PROLATE SPHEROID
TYPE 4 DEFECT
1600 μ HIGH
400, 800 μ DIA

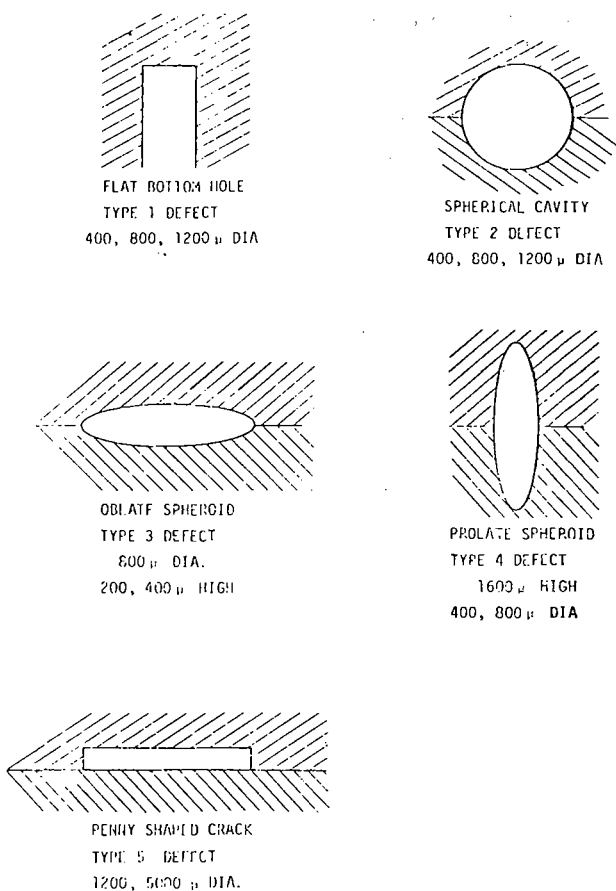PENNY SHAPED CRACK
TYPE 5 DEFECT
1200, 5000 μ DIA.

Figure 6. Cavities placed on the interior of a
titanium block by diffusion bonding
techniques.

A few words should be said about the philosophy
of the choice of the defect types. We have chosen
these simple shapes because they are amenable to
theoretical analysis. We feel that a firm theore-
tical foundation is a very important prerequisite
of a quantitative NDE capability. Although these
cavities have simple shapes, it should be noted
that the limiting case of the oblate spheroid is
a thin crack. Hence, we can project what will
happen for that technologically important case from
the solutions that are presently developing.

Due to time limitations, there will be no
paper on the preparation of samples using diffusion
bonding. However, in addition to preparing samples
in titanium 6Al-4V alloy, new techniques have been
developed for bonding certain steel alloys (as
reported last year[3]), and also, more recently,
aluminum.

Figure 7 illustrates the importance of develop-
ing a sound theoretical basis with which to inter-
pret ultrasonic scattering experiments. This
compares the solutions for scattering by spheres[4]
for several cases that might initially be imagined
to be quite similar. In the lower left-hand figure,
the angular dependence of the scattering from a rigid
sphere in a fluid is shown. This is obtained from

the solution of a scalar wave equation with clamped
boundary conditions at the sphere surface. The
lower right-hand shows the scattering from a cavity
in a fluid as obtained from a solution of a scalar
wave equation with pressure-free boundary conditions
on the surface of the sphere. The upper right-hand
shows the solution that applies to a cavity in a
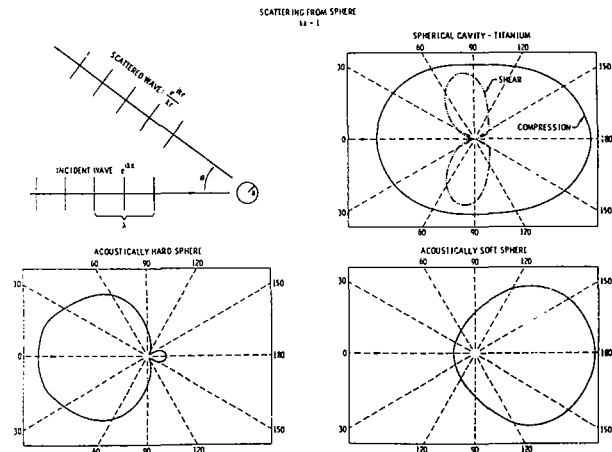solid. This requires solution of a vector wave
equation.

Figure 7. Comparison of the scattering from spheri-
cal obstacles in fluids and solids
when ka=1.

It is immediately evident that there are tre-
mendous differences between the three cases. If
one wishes to develop quantitative systems for
interpreting scattered fields, then the appropriate
solutions must be available.

Figure 8 shows some of the scattering solutions
that have been obtained and illustrates how these
might be used to design a defect characterization
system. These are the results of the theoretical
efforts of Krumhansl, Gubernatis, Domany, et al at
Cornell University[5]. The basic scattering geometry
and coordinates of the plot are shown at the top
of the figure.

The plots are projections of the scattered
fields. The center of each plot corresponds to
direct backscattering while the periphery shows the
scattering at 90°. The information is presented in
a contour representation, with regions of constant
scattered amplitude shaded in like fashion. The
left hand column illustrates the scattering by a
spherical cavity. The upper plot shows the longi-
tudinal to longitudinal (L→L) scattering, while
the lower plot shows the longitudinal to transverse
scattering (L→T). As would be expected, the results
are symmetric. The L→ L scattering is strongest
in the back scattered direction and becomes pro-
gressively weaker as 90° is approaches. The L→T
scattering has just the opposite behavior. The
right hand column shows similar results for an
oblate spheroid inclined at 45° with respect to
the incident wave. Here, the L→L scattering is
greatest in the downward direction, but not exactly
at   90° as would be predicted by specular reflec-
tion. Likewise, the L→T scattering follows intui-
tion. These plots provide a quantitative template

which can be used in designing experimental systems, for example, in selecting the frequency and aperture required to distinguish between certain classes and orientation of defects.

SCATTERING GEOMETRY

COORDINATES OF POLAR REPRESENTATION OF SCATTERED FIELDS

CONTOURS OF CONSTANT A_S

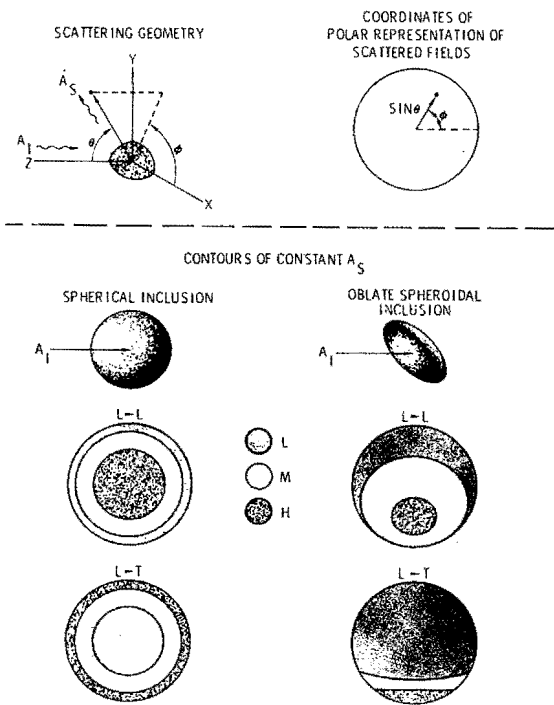SPHERICAL INCLUSION

OBLATE SPHEROIDAL INCLUSION

Figure 8. A contour representation of the elastic fields scattered by a spherical cavity and an oblate spheroid. The shadings designated as L, M, and H indicate low, medium, and high scattering amplitudes.

The remainder of the tasks can best be described with reference to Fig. 5. The importance of theoretical understanding of the scattering of the ultrasound by the flaw has already been discussed. In addition, it is important to develop the experimental techniques necessary to both test the theories in ideal samples and to apply the test techniques to real parts. Tittmann[6] and Adler[7] will present such results.

Transducers form an important element of any defect characterization system. It is at this point that much information can be lost. The ultimate transducer may well be the array along with appropriate electronic components to steer and shape the resulting beam. Array transducers developed as parts of other programs will be mentioned in the papers by Kino[8] and Posakony[9]. However, most present work is performed using single element transducers. Lakin[10] discusses the development of apparatus and analytical techniques to quantify their performance. Tiemann[11] also describes some advanced transducer development that has taken place at General Electric.

Once the ultrasonic information has been converted into electrical signals, signal processing is necessary to optimize bandwidth, signal-to-noise ratios and other parameters. White[12] describes the use of surface acoustic wave filters to increase resolution and Newhouse[13] presents his most recent results in the processing of random noise signals.

The final step, and one of the most critical ones, in a defect characterization system is the interpretation of the data. Kino[8] and Posakony[9] describe imaging systems designed for this purpose. In their studies of scattering, Tittmann[6], Adler[7], and Krumhansl[15] have also developed some preliminary interpretive schemes. Finally, Mucciardi presents some exciting results demonstrating the power of adaptive nonlinear learning procedures in measuring the size of fatigue cracks.

One of the problems with the system shown in Fig. 5 is the water bath. Making measurements in a tank is a slow and cumbersome procedure which is particularly difficult for components in service. Szabo[15], Moran[16], Maxfield[17], and Thompson[18], join to present a mini-symposium on alternate transducer, the transducer which operates with no contact and hence, avoids this problem.

The concepts just outlined are new, but they are already finding application. In a previous paper, Evans[19] described how they are being used in the development of inspection techniques for ceramic materials. In addition, Tittmann[20] will describe the development of new ultrasonic standards and calibration techniques based on these principles.

As Don Thompson said previously, the first year of our ARPA/AFML program was characterized by the individual efforts by a number of investigators to establish basic capabilities. A number of these people had not previously been a part of the NDE community but had expertises that were directly applicable. During last year, and as described in the following papers, these people have now joined together in many group efforts. Krumhansl, Adler and Tittmann have had strong interactions in the development of quantitative measurement techniques. Other interactions will also become evident. The second year has thus been characterized by a joining together to form teams directed towards the solution of common problems. During the next year we will be continuing and consolidating this effort to demonstrate the ability to nondestructively measure fracture critical parameters of certain classes of defects based on a firm fundamental understanding of the basic measurement phenomena. More work will be needed to develop a comprehensive system, but the basic procedures will have been demonstrated. As shown in Fig. 9, what is ultimately needed is the development of quantitative accept/reject criteria based on the combination of results such as these with appropriate fracture mechanics or other failure prediction analyses. This marriage can take place in a future program based on the foundation now being developed.
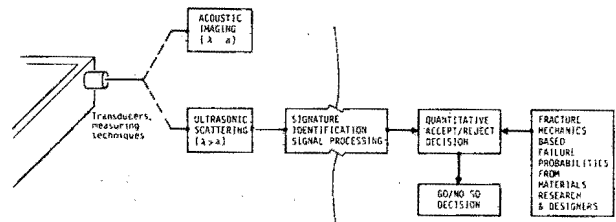

Figure 9. Steps required to incorporate quantitative accept/reject criteria with ultrasonic NDE to make Go/No Go decisions.

References

1. R. Bruce Thompson and Anthony G. Evans, "Goals and Objectives of Quantitative Ultrasonics," IEEE Trans. on Sonics and Ultrasonics, SU-23, 292 (1976).

2. D. O. Thompson, "Introduction Remarks", this proceedings.

3. N. E. Paton, "Ultrasonic Samples Using Diffusion Bonding Techniques," Proceedings of the ARPA/AFML Review of Quantitative NDE, AFML-TR-75-212, p. 89 (1976).

4. E. R. Cohen, private communication.

5. J. Krumhansl, E. Domany, P. Muzilcar, S. Teitel, D. Wood, and J. E. Gubernatis, "Interpretation of Ultrasonic Scattering Measurements by Various Flaws From Theoretical Studies", this proceedings.

6. B. R. Tittmann, "Measurements of Scattering of Ultrasound by Ellipsoidal Cavities", this proceedings.

7. L. Adler and D. K. Lewis "Models For The Frequency Dependence of Ultrasonic Scattering From Real Flaws", this proceedings.

8. G. S. Kino, "The NDT Program at Stanford University", this proceedings.

9. G. J. Posakony, "Near Real Time Ultrasonic Pulse Echo and Holographic Imaging System", this proceedings.

10. K. M. Lakin, "Characterization of Piezoelectric Transducers", this proceedings.

11. J. J. Tiemann, "A Practical Approach to Fabricating Ideal Transducers", this proceedings.

12. R. M. White, "Signal Processing With SAW Devices", this proceedings.

13. V. Newhouse, "Adaptive Deconvolution To Improve Resolution Independence of Bond Width", this proceedings.

14. A. N. Mucciardi, "Measurement of Sub-Surface Fatigue Crack Size Using Nonlinear Adaptive Learning", this proceedings.

15. T. L. Szabo, "Surface Acoustic Wave Electromagnetic Transducer Modeling and Design for NDE Applications", this proceedings.

16. T. J. Moran, "Characteristics and Applications of Electromagnetic Surface Wave Transducers", this proceedings.

17. B. W. Maxfield and J. K. Hulbert, "Optimization and Application of Electrodynamic Acoustic Wave Transducers", this proceedings.

18. R. B. Thompson and C. M. Fortunko, "Optimization of Electromagnetic Transducer Systems", this proceedings.

19. A. G. Evans, B. R. Tittmann, G. S. Kino, and P. T. Khuri-Yakub, "Ultrasonic Flaw Detection in Ceramics", this proceedings.

20. B. R. Tittmann, "New Procedures for Calibrating Ultrasonic Systems for Quantitative NDE", this proceedings.

PROF. VERNON NEWHOUSE (Purdue University): Well, that certainly raised a lot of thoughts in my mind about the philosophy of approach. This talk suggests that we should try to characterize individual defects. It seems to me that this is a very interesting program. The risk is: will we be able to characterize a defect that is in a real environment with lots of multiple reflections? And will different defects have enough differences in their spectra so that one can separate them? And, of course, I'm sure you will keep in mind that there is the other approach, which I suppose will be talked about this afternoon, of actually trying to image things with very small wave lengths. We're faced with an interesting situation since in the next few years we won't know which of these techniques will be most successful where.

Now, I understand there are a few people who have some questions or comments.

DR. ARDEN BEMENT (ARPA): There are a couple of caveats I'd like to comment on, which probably don't need to be made in this audience. Referring to your table of critical flaw sizes, I think it's obvious that what you really have, if you can measure that flaw size, is a prediction for zero remaining life. So, one has to do, perhaps, an order of magnitude better than that in order to measure a size that will have a remaining in-service life of practical importance.

Also, in many cases the real problem is the opening up of a tight flaw with interconnected ductile ligaments during service and also the interconnection of co-planar, closed porosity to form an interconnected flaw. So, the problem gets much more difficult than just measuring a single isolated definable flaw.

DR. THOMPSON: We certainly agree with both those comments. Those are extremely difficult problems. We feel the successful solution of those problems is only going to be obtained after we have developed the fundamentals for the much simpler cases which we are presently addressing.

DR. NELSON HSU (University of Kentucky): I have a very long question. The philosophy of using the scattering field measurements to replace the pulse echo technique is right. But the reason is that if the flaw has a specific orientation, the use of a one directional measurement cannot always detect the defect. However, if you use the scattering technique you have to place the transducer at different angles to measure the scattered field. If the geometry is such that you can do that, then at the same time you could place a single transducer at different angles and actually just measure the pulse-echo back scattering. I don't know which technique gives more.

DR. THOMPSON: The basic point I want to make is we do have to gather a lot more information than is presently used. I think the approach you describe is one particular example of what I would call a scattering approach. I think we're in basic agreement. One has to make more than one single measurement and in addition needs a systematic way of interpreting the information.

PROF. NEWHOUSE: I think I would also like to make two comments on that last question. One is you can look at the scattered waves over a range of angles or you can vary the frequency and look at one angle. These are two dual techniques in a sense. By varying the frequency and seeing what spectral peaks you get, you should get the same information as is contained in these diagrams of radiation scattered over many directions. I see somebody shaking their head, so perhaps the information isn't quite pure.

Also, getting information about the scattering of one particle or one defect ought to be helpful in trying to tackle the problem of getting the spectra that comes from a series of grains so as to get more information about grain structure. And I think we ought to keep in mind there that the x-ray crystallographers, as we all learned shortly after high school, have been successful mainly in interpreting the spectra from periodic arrays or quasi-periodic arrays. So that here in the ultrasound, we are tackling a problem that has not yet been successfully solved by the x-ray people.

At this point I would like to call on the next speaker, Professor Lakin of the University of Southern California to talk about transducer characterization.