NEW PROCEDURE FOR CALIBRATING ULTRASONIC SYSTEMS FOR QUANTITATIVE NDE

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The presently used ultrasonic standard for calibrating ultrasonic systems is the "flat bottom hole." In view of some dissatisfaction by many, we sought to apply the results of our scattering studies to explore the possibility of coming up with an alternative. This is a proposal for a new standard, and as I go through the discussion, please keep in mind that this work is still very much in its infancy.

Our objectives in this study were, first, to develop an overall <u>system</u> calibration; secondly, to develop a technique that has sufficient dynamic range so that a linearity check is meaningful with no degrees of freedom; and thirdly, to develop a technique so that the system can be calibrated and compared to the theoretically known expectations.

Before we begin this discussion, I would like to make two definitions to orient the audience. We define the "calibration standard" as an ultrasonic standard solely employed to ensure equipment is functioning according to its specifications. The "reference standard," on the other hand, we define as a library of scatterers of different shapes used to aid in the identification of an unknown defect after the ultrasonic system has already been calibrated with the use of the "calibration standard."

If we look at a typical ultrasonic system and write down the characteristic equation keeping track of all the losses, we have to take into account the following items: the electrical signal available at the terminals of the receiving transducer is equal to the electrical signal fed into the terminals of the transmitting transducer times the transfer function or the loss in conversion from electrical to acoustic energy; the losses due to propagation in the medium whether they are attenuation or beam spreading; the losses upon scattering from the standard defect; again, the propagation losses in the return path and the conversion from the acoustic signal to the electric signal. This equation is presented in Fig. 1, together with a schematic identifying the terms discussed. This equation will be employed shortly, but first the scattering term $S(f,a,\theta)$ is treated in more detail. What we would like to propose is that we use a sphere as the calibration standard and use, for example, the diffusion bonding technique to build such a sphere into a solid material.

Transmission Scattering Detection

$$A_R(f,a,\theta) = \underbrace{A_T(f)\,T_T(f)}_{}\,\underbrace{M_1(f)}_{\text{Transmit Path}}\,S(f,a,\theta)\,\underbrace{M_2(f)}_{\text{Return Path}}\,T_R(f)$$

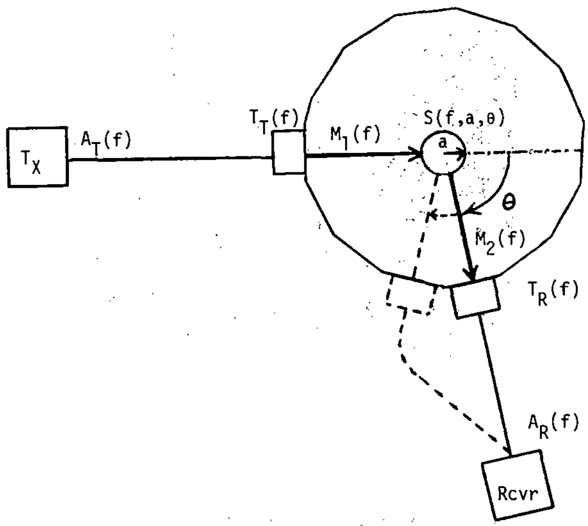


Figure 1. Characteristic ultrasonic equation.

Figure 2 is an example of what the diffusion bonding process is able to do. We see here a micrographical cross-section of a hemisphere and notice that the hemispherical shape is maintained intact and that the bond line has disappeared with grains having grown across the bond plane.

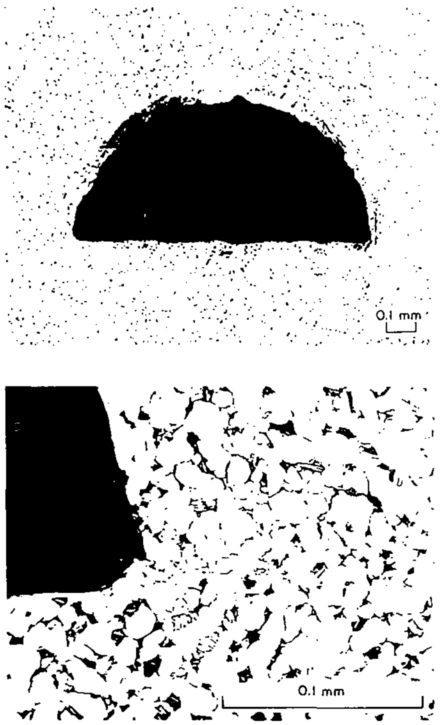


Figure 2. Micrograph of the cross-section of a hemispherical cavity produced by diffusion bonding of two machined sections of Ti-alloy. The lower figure shows an enlargement of the section where the bond was made and demonstrates the complete disappearance of the bond line by grain growth across it. The top figure is a mosaic of several micrographs.

As we know from scattering studies, the sphere is ideally suited for use as reference scatterer in the sense that it can be treated by exact theoretical calculations as exemplified in Fig. 3. Here the solid line shows the scattering term $S(f,a,\theta)$ as a function of the scattering angle for a tungsten carbide sphere, whereas the dashed line shows it for a spherical void. We see that the total variation in $S(f,a,\theta)$ is about 15 to 25 dB so that with one defect we have enough dynamic range for calibration purposes.

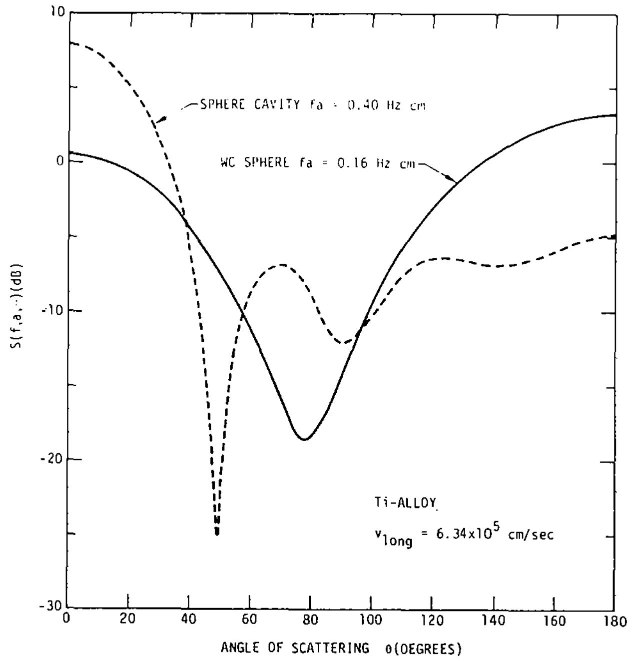


Figure 3. Master curves for the angular dependence of the theoretical scattering function for spherical cavity and a tungsten carbide circle inclusion embedded in Ti-alloy.

In Fig. 4, we have rewritten the ultrasonic characteristic equation by specifically including beam spreading, attenuation, and a new figure of merit for the transducer, namely, the G factor.

$$\frac{|A_R(f,a,\theta)|}{|A_T(f,a,\theta)|} = \underbrace{\frac{va}{fR^2(4\pi)^{3/2}}}_{\text{Diffraction}} \, \overbrace{|S(f,a,\theta)|}^{\text{Scattering}} \, \underbrace{\sqrt{G_T(f)\,G_R(f)}}_{\text{Transducers}} \, \overbrace{\exp[-2R\alpha(f)]}^{\text{Attenuation}}$$

Identification of G:

G is the gain of the transducer and is defined as the power per unit solid angle in the forward direction in terms of power delivered to the transducer terminals.

$$(A_R)_{dB} - (A_T)_{dB} = (P_\ell)_{dB} + (S)_{dB} + (G_T)_{dB} + (G_R)_{dB}$$

$$(A_R)_{dB} - (A_T)_{dB} = 20 \log_{10} \frac{|A_R(f,a,\theta)|}{|A_T(f,a,\theta)|}$$

$$(P_\ell)_{dB} = 20 \log_{10} \frac{va \exp(-2R\alpha)}{fR^2(4\pi)^{3/2}}$$

$$(S)_{dB} = 20 \log_{10} |S(f,a,\theta)|$$

$$(G_T)_{dB} = 20 \log_{10} \sqrt{G_T(f)}$$

$$(G_R)_{dB} = 20 \log_{10} \sqrt{G_R(f)}$$

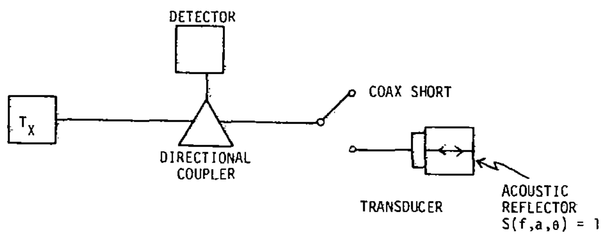
Figure 4. Characteristic equation for ultrasonic system.

For the transmitter, G is defined as the power per unit solid angle in the forward direction in terms of the power delivered through the transducer terminal. For the receiver transducer, G is the maximum power delivered to the load matched to the transducer transmission line of assumed zero loss when the power per unit solid angle incident on the transducer is known.

This definition, then, is the backbone for evaluating this expression and effectively lumps into one parameter all the processes and losses involved in taking electrical energy from the input terminals into the acoustic energy of the main beam as it propagates in the medium normal to the transducer face. The G factor is analogous to the gain of an antenna in radar and becomes a figure of merit. It is unitless since it is a ratio and may be best expressed in dB.

In the lower portion of Fig. 4, all the terms of the characteristic equation are given in units of power, i.e., dB, and one may identify the difference between the received and transmitted signal in terms of the losses due to propagation, scattering, and the G factors of the two transducers.

Before I continue, I think I really should describe how one can measure the G factor shown in Fig. 5. The equipment needed is a transmitter, directional coupler, detector, coaxial short and a transducer coupled to some acoustic reflector.



(1) Coax. short: signal detected = (A_T)dB

(2) Transducer as load: signal detected (1st echo) = (A_R)dB

$$2(G)_{dB} = \left[(A_R)_{dB} - (A_T)_{dB}\right] - (S)_{dB} - (P_\ell)_{dB}$$

where $(S)_{dB} = 0$

Figure 5. Measurement of G-factor.

The first step is to use the coaxial short as a load and then the detected signal is simply the transmitted signal (A_T)dB. The second step is to use the transducer and acoustic reflector as a load. which gives the first echo as the measured signal. From the difference between these two measurements, the scattering function of the acoustic reflector, and the propagation loss in the material, we can derive the G factor.

One acoustic reflector that may be used is simply the back surface of the sample for which the scattering function is essentially zero dB. Another reflector could be a diffusion bonded sphere for which the scattering function is very well specified as has been shown earlier.

Figure 6 presents a number of G factors measured in the way described above for a variety of commercial transducers at various frequencies. We will be using some of these G factors in the calculations later on.

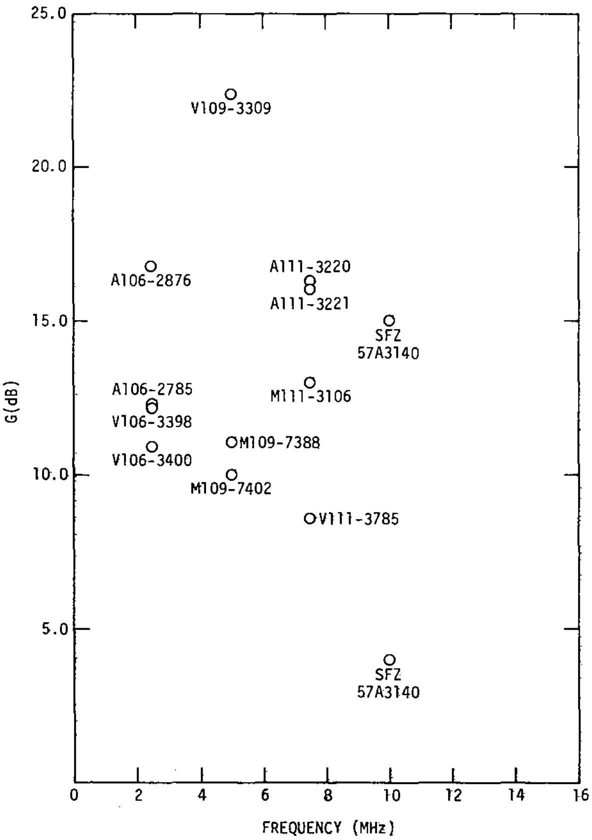
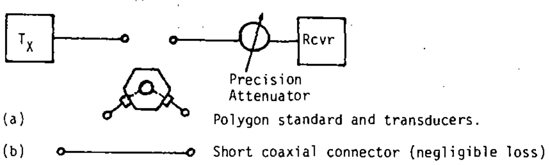


Figure 6. G-factors for a variety of commercial transducers.

Figure 7 presents the required equipment and information to carry out a calibration. First one uses a substitution bridge with a precision attenuator to measure the insertion loss of the polygon standard and transducers to obtain (A_R)dB-(A_T)dB.

REQUIRED EQUIPMENT AND INFORMATION

A. Substitution Bridge:



$(A_R)_{dB} - (A_T)_{dB}$ = Att. Rdg. (a) - Att. Rdg. (b).

B. Reference table for choice of Standard:

f (MHz)	fa=0.40 Hz cm Cavity Radius a_C (cm)	fa=0.16 Hz cm Tungsten Carbide Radius a_{WC} (cm)
2.5	0.160	0.064
4.0	0.100	0.040
7.5	0.053	0.021
10.0	0.040	0.016

C. Data sheet for standard giving propagation loss P_ℓ(dB).

Figure 7. Required equipment and information.
A) Substitution Bridge.
B) Reference table for choice of Standard.
C. Data sheet for standard giving propagation loss P_ℓ(dB).

Now, one needs a reference table so that one can decide what standard to choose. The reference table shown in Fig. 7 is based on our scattering studies and gives a good dynamic range and a simple angular dependence for the scattered power, both for the cavity and the tungsten carbide sphere. Finally, one needs a data sheet giving the propagation loss for the particular standard.

Figure 8 is a photo of our goniometer that might be used with the standard. The goniometer allows you to vary the scattering angle by moving a receiving transducer along about 14 faces. The block is shown in cross section in Fig. 9. It is a polygon with 14 faces which are arranged in such a way that none of the faces corresponds to the same angle giving you, therefore, a maximum number of probing points in the angular dependence of the scattered radiation pattern.

Figure 10 gives a sample calibration at 4 MHz with the aid of a WC sphere of radius .04 cm. The solid line is the theoretical scattering function and the data points are those obtained by a combination of the experimental measurements and the use of the characteristic equation.

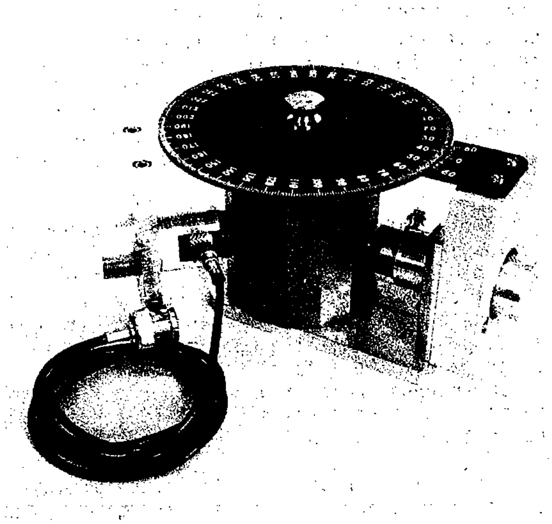


Figure 8. Photograph of measurement fixture including a polygon sample and a pair of commercial transducers.

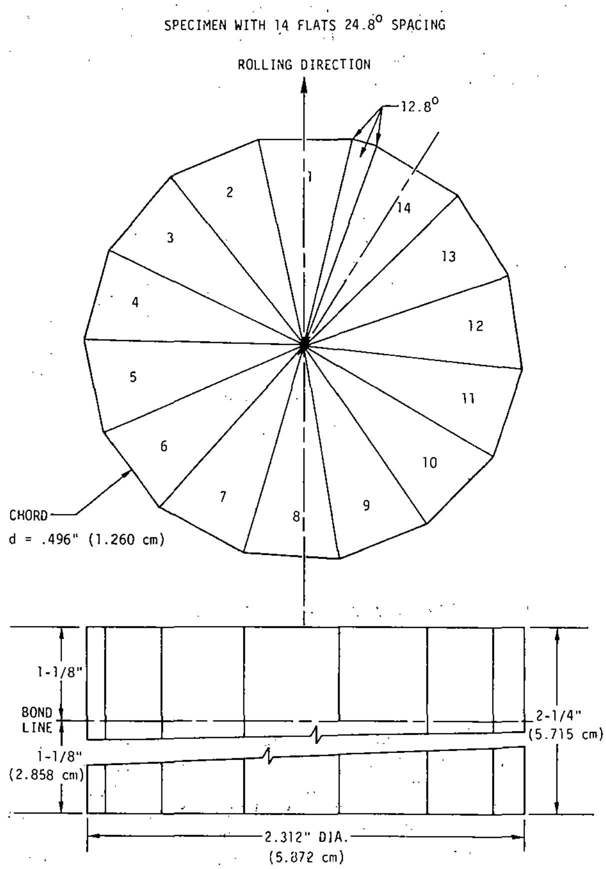


Figure 9. Cross section of diffusion bonded blocks of Ti-alloy machined into the shape of a polygon with 14 faces.

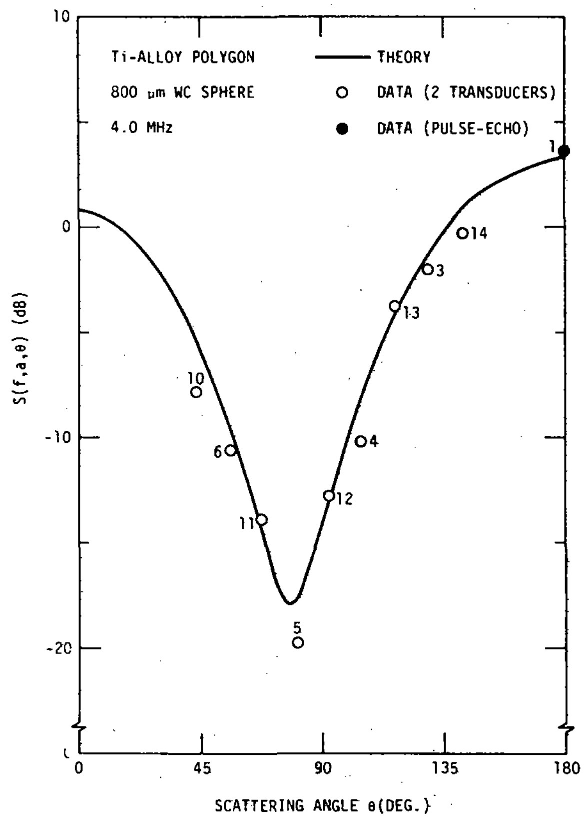


Figure 10. Graph showing S(f,a,θ), for an 800 micrometer diameter (a = 0.04 cm) tungsten carbide (WC) sphere embedded in Ti-6% Al -4% V by diffusion bonding. The theoretical curve and experimental points have been determined in an absolute way.

You see that most of the points (open circles) were obtained in the pitch-catch mode with two transducers, but one point (the solid dot) was obtained by the pulse-echo mode in the back scattering direction. The fact that both of these sets of points appear on the same graph shows that we were able to take into account the differences between the two sets of measurements and demonstrates the power of the characteristic equation.

In summary, the calibration described here involves a "kit" consisting of a guide to a choice of standards; an assortment of standards in the shape of polygons; a data sheet for each standard giving the propagation loss including attenuation, bond losses, and diffraction losses; a data sheet giving the theoretical power scattered versus scattering angle for each standard at selected frequencies; the G factor values for each transducer to be used; and a measurement fixture, such as shown before, to be used as a calibration goniometer.

What are the new features incorporated into the calibration procedure proposed here? First of all, we have a standard defect that is rather well and quantitatively characterized by an exact theory. Secondly, we have introduced a new figure-of-merit for the transducer, the G factor. Instead of having to use a number of standards for the calibration, we can - taking advantage of the angular dependence - accomplish the calibration with a single sample. We have achieved a dynamic range anywhere from 22 dB for the WC sphere to 35 dB for the spherical void.

The advantages of this system are that we have determined a method for the self-consistent calibration of an ultrasonic system. We have a way to get the required dynamic range variation independent of the gain control and using the same ultrasonic standard. We know quantitatively what the dynamic range should be so that a quantitative calibration is feasible with no additional degrees of freedom, and we have allowed for an absolute comparison of pulse echo and the through transmission mode.

There is still a lot of work to be done. For example, we have to learn to take into account broad band characteristics of transducers, i.e., operate in the pulse mode rather than the tone burst mode as was done so far. We also have to develop an analysis procedure for the calibration error. And finally, we also need some statistics on the quality of fabrication of the standards by the diffusion bonding process.

DISCUSSION

DR. EMMANUEL PAPADAKIS (Ford Motor Company): Questions?

DR. JERRY TIEMANN (General Electric): Sort of a comment. I also suggest that you consider how to take into account transducers of different focal lengths, and you should also take into account the transducer in the context of a water coupling medium instead of a direct metal contact.

DR. TITTMANN: That's a good suggestion.

DR. EYTAN DOMANY (University of Washington): If I understand you correctly, the sphere was used because the exact solution exists.

DR. TITTMANN: That's one of the reasons.

DR. DOMANY: I think that the exact solutions also exist for long elliptical cylinders if you hit them from the side, and it seems that there's a simpler geometry to use because you could drill a hole instead of diffusion bonding.

DR. TITTMANN: Yes.

DR. PAPADAKIS: Well, it isn't necessarily easy to drill a long, skinny hole.

DR. TIEMANN: It's a lot easier than making a sphere down the middle of something.

DR. PAPADAKIS: Not the way they're doing it.

PROF. R.E. GREEN (John Hopkins): How do you plan to take account the coupling loss? You have different types of couplers; are you going to make a table of all possible couplings?

DR. TITTMANN: No, before you make your measurement and calibration, you decide what coupling agent you are going to use for the rest of the experiment. And then you use that coupling agent to obtain the G factors that you need for the calibration.

DR. ALFRED BAHR (Stanford Research Institute): In all these measurements, though, you either need the G factors or the total attenuation.

DR. TITTMANN: Attenuation in the material?

DR. BAHR: Well, a total loss including all that you have lumped into P_ℓ.

DR. TITTMANN: P_ℓ does not include the transducers.

DR. BAHR: Right. But what's your feeling about the accuracy to which you can obtain P_ℓ or other quantities in the equation?

DR. TITTMANN: P_ℓ contains the bond losses, the attenuation in the material, and the diffraction losses. There is a standard way to get diffraction losses, and I think Papadakis has pioneered in that field. And the attenuation in polycrystalline media is also obtainable. It's not an easy process, but it certainly can be done, and it should be done by the individual, perhaps, or it can be done by the maker of the standard and provided to the individual if the individual feels that he doesn't have the equipment to do it.

DR. PAPADAKIS: It's probably good to a few tenths of a dB.

DR. TITTMANN: I would think so. With a dynamic range of 30 dB approximately, that's pretty good.

DR. C. C. MOW (RAND): All the papers I have heard so far have tried to look at the overall signature of the spectrum. Have you tried to correlate the peak and valleys with the normal modes of the inclusion shape? We have recently done a lot of calibrations with Prof. Pao from Cornell. We have found that the information lies in the wave number between the peak and valley. You can correlate that with the actual mode, the normal mode of the crack or sphere or cylinder, and from that you can correlate it by the shape that you are really dealing with or what kind of inclusion you have really got.

DR. TITTMANN: I'm well acquainted with that work. It's very beautiful work. I think it's a very viable technique. I haven't seen any such work for a sphere; it's mostly been done for cylinders.

DR. MOW: We did the cylinder with fluid in the cavity.

DR. TITTMANN: I see.

DR. MOW: I think the sphere cavity is also contained in a monograph that was published several years ago. If you want it, I'll send it.

DR. TITTMANN: Yes, I'd like to see it.

DR. JOSEPH HEYMAN (NASA, Langley): I'd like to make one point about this. This is a calibrator. It also calibrates the operator, for if he does not have the proper application technique, this would be easily determined by the non-agreement with the standard.

MR. CHARLES K. BERBERICH (Alcoa Tech Center): How do you intend to implement this procedure as a replacement for normal reference blocks?

DR. TITTMANN: As a replacement for what, please?

MR. BERBERICH: Normal reference blocks.

DR. TITTMANN: I guess I don't know exactly what you mean by implement. I have tried to describe the standards kit with X items and how to use each item.

MR. BERBERICH: I guess I'm referring more to the specification field. How do you intend to influence specifications to incorporate this procedure in lieu of the current procedures?

DR. TITTMANN: Oh, that's a totally different question. It is an important problem which we haven't addressed here. I think we will need a lot of help from people that are doing the implementation of the current standards to accomplish that.

DR. SY FRIEDMAN (Naval Ship R and D): How do you regard the reproducibility of this calibration standard as compared to the current standard? Now, that's a rhetorical question because prior to this talk and also earlier presentations, it was pointed out that the current standards are unreproducible. You have an 800 percent difference, I think I heard mentioned earlier today. What percent difference do you anticipate with this proposed standard?

DR. TITTMANN: Well, to answer that question takes a lot of time. Let me just say a few of the features where I think this procedure has some advantages. First of all, we're dealing here with a thoroughly theoretically characterized defect. The other standard, for example, the flat bottom hole, has not been described theoretically in terms of elastic theory. So, you don't really know what the scattering radiation pattern of that flat bottom hole should look like, even if you ideally could measure it.

DR. PAPADAKIS: And they haven't measured the attenuation in any of those blocks, although there may be 100,000 out in the field.

DR. TIEMANN: There's another problem in that your calculations essentially assume a rather good transducer, one with a uniform field pattern because you're calculating in your G factor the power transmitted per unit solid angle at zero degrees ; actually, practical transducers can be very non-uniform and their beams can be skewed off in various angles, and your G factor in that case won't correspond to the actual transmission down the actual beam direction. Now, when a person tries to apply that transducer in an NDE environment, he's not really going to know which direction the beam is, he's just going to shoot it into the part and get an echo back. So, I think your G factor isn't quite adequate.

DR. TITTMANN: Yes, it is; I have taken that into account. Consider the following: suppose you are looking for a certain size of defect, a certain range of sizes. Then you pick a standard defect that is in that range of sizes of defect. Now, suppose the operator takes a poor transducer that has hot spots in it, whose beam is cocked off the normal to the transducer. When he measures that G factor, that G factor will be very, very low and would accurately reflect in his calibration the use of that transducer in his measurement with the unknown defect. I think this is an important question, and I think that's why this definition is so valuable, because it takes these problems into account explicitly. The operator quantitatively measures the quality of the transducer as a figure of merit just as he will be using it in the actual operation.