ACOUSTIC EMISSION; A SUMMARY OF CURRENT UNDERSTANDING

Anthony G. Evans
National Bureau of Standards
Washington, D.C.

Gentlemen, I want to talk in fairly general terms about the acoustic emission technique, which I think you will find is rather different from the other techniques we have heard about thus far in the meeting.

The first question you ask when trying to assess a nondestructive inspection technique is, "What in principle can the technique do for you"; and the second question you ask fairly soon after the first question is, "What are the practical constraints in a quantitative sense?"

I want to spend the first part of the talk answering the first question and the second part describing approaches that are or can be used to minimize the practical constraints for effective nondestructive inspection using acoustic emission.

A. Principals of Acoustic Emission for NDE

What you want to address when trying to decide what a technique can achieve is the NDE requirement itself. When fracture is determined by the propagation of a pre-existing crack, which it is in most of the materials we are concerned with here, the quantity we really want is the stress intensity factor at the critical macrocrack at any instant in time. The reason that we want the stress intensity factor is that it is uniquely related to the slow crack growth rate: in the simple quasi-static stress condition, the crack velocity is a function of the stress intensity factor; in the rather more complex cyclic stress case, the crack growth per cycle (da/dn) is a function of the stress intensity factor amplitude, the average stress intensity factor, the frequency and the shape of the cycle.

Once you have obtained the flaw crack growth functions using fracture mechanics techniques, and you have a value for the stress intensity factor at the critical macrocrack, you can use these in combination to deduce either the number of cycles to failure or the time to failure. For example, in the simple steady state stress case;

$$K_I = \sigma Y \sqrt{a} \tag{1}$$

where K_I is the stress intensity factor, σ is the stress, a is the crack length and Y is a geometric parameter. Differentiating with respect to time;

$$\frac{d K_I}{dt} = \frac{\sigma^2 Y^2}{2K_I} \left(\frac{da}{dt} \right) . \tag{2}$$

Separating the variables and integrating gives;

$$t_f = \frac{2}{\sigma^2 Y^2} \int_{K_{Ii}}^{K_{Ic}} \frac{K_I}{(da/dt)} dK_I \tag{3}$$

where K_{Ic} is the critical stress intensity factor and t_f is the failure time. K_{Ii} is the initial stress intensity factor at the most deleterious flaw which is the quantity that must be determined by the nondestructive inspection technique. The lower the K_{Ii} value that we can detect nondestructively, the longer will the survival period be that we can guarantee for that component.

Having stated that it is really the stress intensity factor we are after, let's now have a look at the nondestructive inspection techniques to see what information they really give us. If we examine all of them, we find that there are only two which give K_I directly; these are overload proof-testing and acoustic emission. All other known techniques give the defect size and configuration, and from these you have to calibrate the stress intensity factor, a procedure which contains several pitfalls.

The relation of acoustic emission to the stress intensity factor was first determined empirically (for a wide range of materials), where it was noted that the acoustic emission rate was a function of the stress intensity factor. This empirical result has subsequently been substantiated by phenomenological analysis. Interestingly enough, for many brittle materials, the functional relationship between the stress intensity factor and the acoustic emission rate and the stress intensity factor and the crack growth rate are identical, i.e., the acoustic emission rate is directly proportional to the crack growth rate. This is illustrated by some data obtained on silicon nitride in Fig. 1.

B. Practical Limitations on the Use of Acoustic Emission

The primary problem in the application of acoustic emission to NDE is that acoustic emission is not only obtained from the critical macrocrack, but also from a wide range of the potential sources. An inventory of the potential acoustic emission sources in structural components is presented in Table I, separated into internal sources (those occurring within the component itself), and external sources (those occurring outside or at the interface of the component). The first internal source is crack propagation. Unfortunately, acoustic emission from the critical macrocrack is not the only source. If there are second phases in the material (or the material is anisotropic in other ways), acoustic emission can be obtained from microcracking, debonding and hole formation which might in no way be related to the onset of rapid fracture. Acoustic emission due to plastic deformation may also occur, especially if dislocation motion is in the form of very rapidly moving glide packets. Another profuse source of emission is twinning, and we will hear about this in rather more detail in the next talk. If we assume that the spatial resolution is completely effective, the only external emission comes from sources very near the critical macrocrack, e.g., interface frictional effects.

C. Source Separation

There are two principal approaches that one can utilize to achieve source separation. The first approach is a first principle's approach which entails the calculation of the acoustic emission expected from each source;

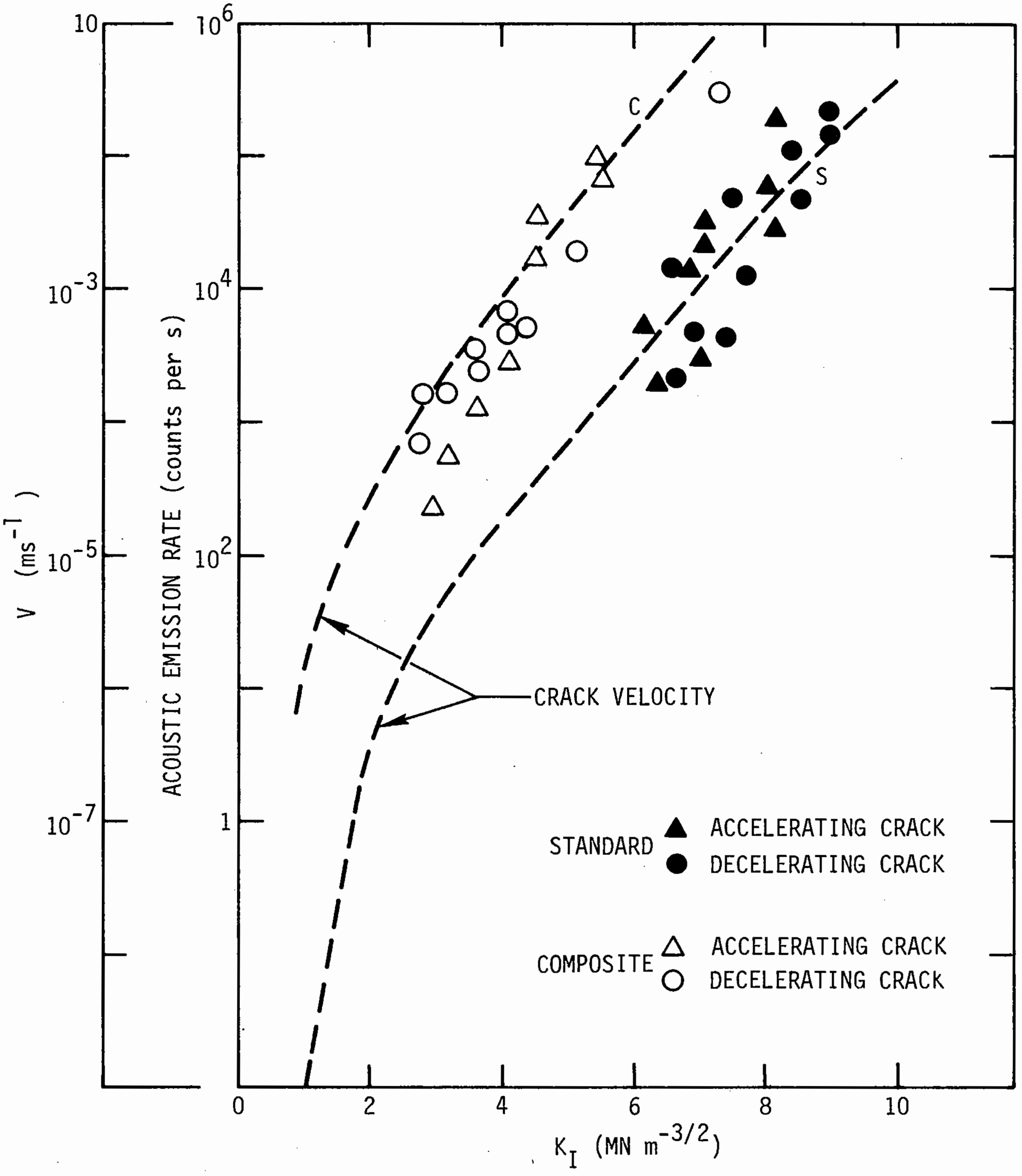

Fig. 1 Crack velocity and acoustic emission rate as function of stress intensity factor.

TABLE 1

Some possible sources of acoustic emission during the structural testing of components.

Acoustic Emission Sources

Internal

- Crack propagation (including debonding and hole formation)
- Plastic deformation
- Twinning
- Phase transformations

External

- Frictional Effects
- Bubble formation (At liquid interface)

this procedure might elucidate differences that are amenable to practical detection. The first part of the calculation determines the form of the stress wave at emission. Only the simplest possible situation, a step function in inelastic strain, has been treated thus far; no time dependence has yet been incorporated. For this first calculation, the amplitude of the stress wave is found to be directly proportional to the frequency and, of course, a function of the magnitude of the step. This calculation hasn't distinguished in any way between different sources of acoustic emission. This is achieved by introducing the time dependence of the event. The emitted stress wave must be transmitted to a transducer located on the surface of the component, and clearly, the stress wave will be attenuated by the test medium. Fortunately, we know something about the attenuation of stress waves in single-phase materials. For example, at low frequencies (the Raleigh regime), we expect the transmitted amplitude to be proportional to ω^{-N}, with $N \sim 4$. At higher frequencies (the stochastic regime), the transmitted amplitude is proportional to ω^{-2}, and finally, at the highest frequencies (the diffusion regime) there is no frequency dependence. For a single-phase material, therefore, the amplitude of the stress wave when it first reaches the transducer should exhibit a maximum at a certain (low) frequency. However, most structural materials aren't single-phase and substantial developments are needed before it will be entirely feasible to calculate the form of the attenuation for real materials with complex microstructures. The direct wave from the source to the transducer is not the only stress wave that reaches the transducer; deflections occur from the surfaces of the component. Their presence generates peaks in the frequency dependence of the acoustic emission at specimen resonances, and these must also be calculated. Finally, superimposed on this behavior is the characteristic response of the transducer itself. The total calculation is, therefore, a very complex one, especially when attempting to distinguish subtle differences in the frequency spectrum of the acoustic emission due to the various emitting processes.

The second approach is a semi-empirical approach, which is more likely to be successful in the short term. This approach uses signal analysis techniques to examine the signals given off by the processes, and attempts to identify differences that will enable the source event to be distinguished in an in-field application. Several techniques have been utilized, as summarized in Table II. The first technique is amplitude analysis. This technique uses a tuned transducer and the measured 'amplitude' can be the peak height of the output voltage for each event, the number of counts per event (i.e., the number of times that the voltage crosses a pre set threshold), or the area (the integrated voltage, time product). The effect that this technique seeks is a shift to higher amplitudes as the stress intensity factor increases which would permit it to be distinguished from stress independent emission sources, such as frictional emission. An effect of this type has been observed but, unfortunately, it doesn't appear to be general. However, the technique will undoubtedly find application for materials where empirically it is found that there is an amplitude effect due to K. This highlights an important feature of most empirical approaches for signal separation (at their present level of development). They appear to be very specific, specific not only to the material, but specific also, perhaps, to the configuration. Hence, we have to learn something about our material and about our system on an individual basis.

The next technique is frequency analysis. With this technique, each individual burst is examined and the frequency spectrum for that burst is analyzed in detail. The purpose of this analysis is, hopefully, to identify optimum frequency bands where the amplitude of the acoustic emission from macro-crack growth is much larger than that from all the other sources. For example, some work by Graham and Alers[1] suggests a possible frequency range for A-533B steel in which the acoustic emission due to deformation exhibits a much larger amplitude than the acoustic emission due to crack growth.

Another technique is a phenomenological evaluation which entails calculating the event rate as a function of the applied stress and time for each of the processes emitting stress waves. The functional relationships between the acoustic emission rate and stress and time for each of these events can then be compared with the experimentally observed functional relationship.

TABLE II

Some Signal Analysis Techniques

Technique	Objective
Amplitude analysis	Effects of K
Frequency analysis	Optimum frequency bands
Phenomenological evaluation	Event rate as a function of stress

Incidentally, I should interject here by noting that these techniques should be regarded as complementary techniques; all of them may be required to achieve the requisite separation. The acoustic emission rate typically expected as a function of the stress (or the strain) due to dislocation motion is shown in Fig. 2. Most of the activity occurs early in the loading cycle, when the dislocations are moving rather intermittently in glide 'packets'. At larger stresses the dislocations move on a more individual basis and the acoustic emission decays. Then, as failure is approached and macrocrack growth commences, the acoustic emission rate starts to increase again. This acoustic emission rate increases with stress, strain, or stress intensity factor, and is a function of the temperature, environment, etc. This is the acoustic emission that provides the failure indication.

In ceramic systems, profuse acoustic emission is obtained due to microcracking. A phenomenological evaluation of the acoustic emission from microcracking shows that the acoustic emission rate decreases with time at constant stress, primarily because the number of readily activated sources is being reduced. But, as noted above, the acoustic emission due to macrocrack growth increases with time because, as the crack grows, K increases. A typical acoustic emission record for such a material exhibits the general features depicted in Fig. 3. Again, the acoustic emission due to macrocrack growth can be identified from the stress/time characteristics.

There are many other examples of the phenomenological approach, but time limitations prevent me from describing them.

D. An example of the Utility of Acoustic Emission

The example to be discussed, taken from our own experience, relates to the proof-testing of porcelain insulators for radio communications towers. Several of the towers were developing cracks during service, leading to a degradation in their performance. It was hoped, therefore, that an effective overload proof test could be devised, to guarantee that macrocracks would not develop during service. Theory, based on slow crack growth data, indicated that the insulators could be proof-tested in a reversible manner to twice the service load. A guarantee that the component would not macrocrack in

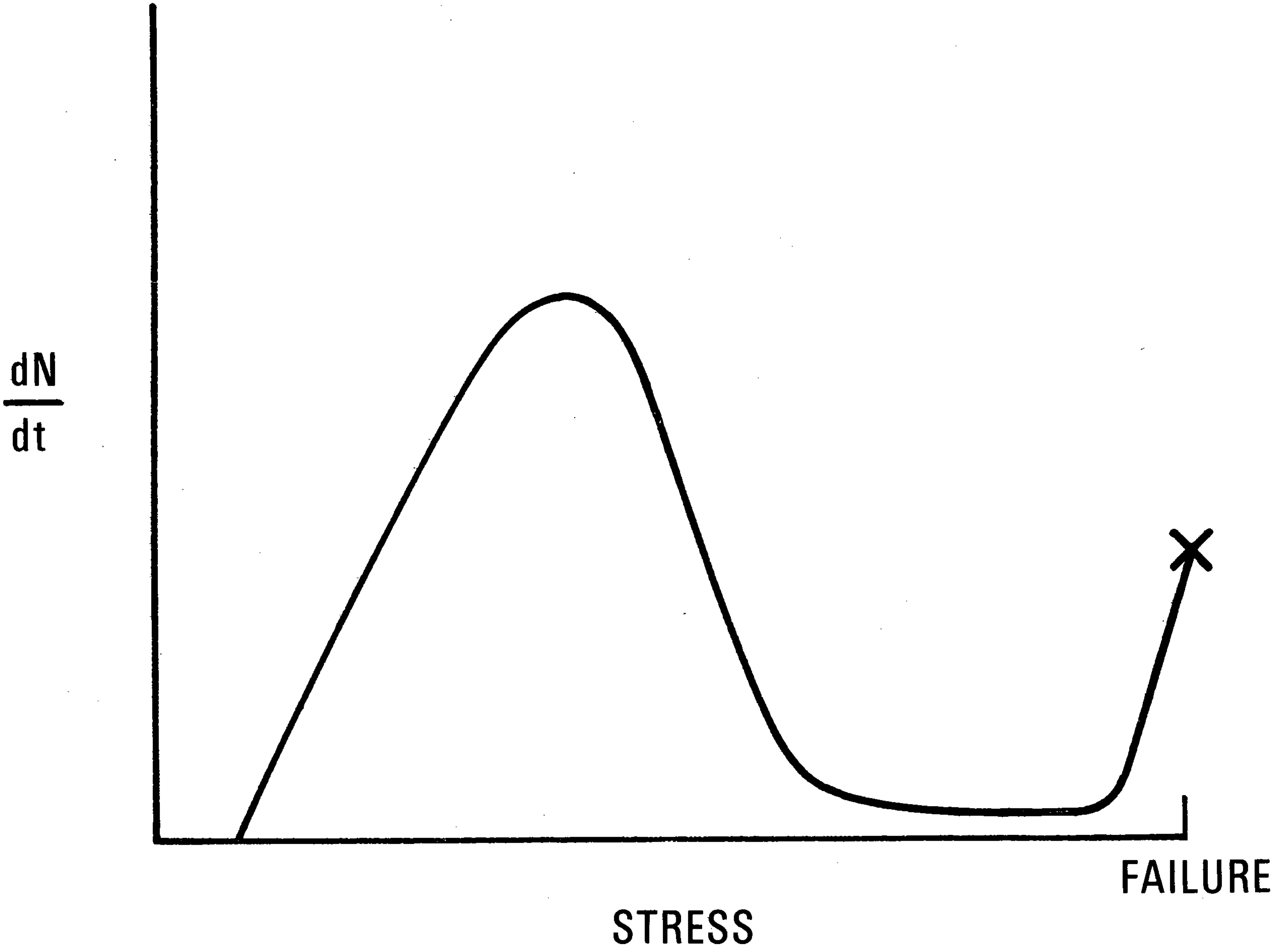

Fig. 2 Acoustic emission rate as function of stress.

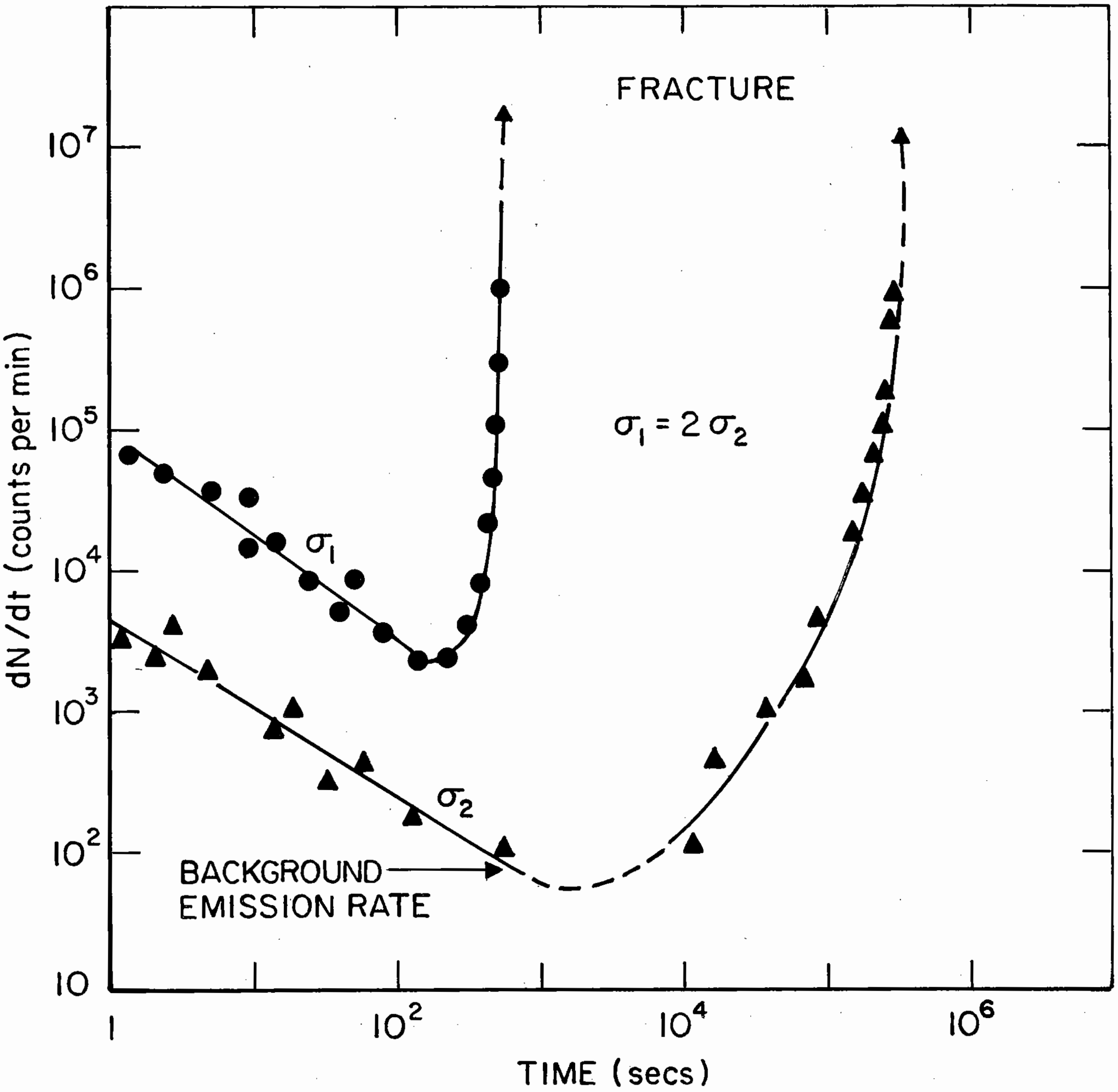

Fig. 3 Acoustic emission rate as function of time at constant stress for typical ceramic system.

service for a 40-year period could then be provided. Independent studies had shown that the major source of acoustic emission in porcelain is the microcracking of the quartz particles which are a primary constituents of the porcelain microstructure. Phenomenological analysis of quartz particle microfracture also indicated that, during the proof test where the load is increased with time at a constant rate then held at the proof load and subsequently decreased at a constant rate, the acoustic emission rate should vary with stress and time as depicted in Fig. 4. However, when the acoustic emission was monitored during the proof tests, some divergence from the predicted behavior became apparent during unloading: the acoustic emission rate did not decay as rapidly with time as the predicted rate (Fig.5). This indicated that some irreversibility was occurring during the proof-test cycle. The irreversibility was due to slippage between the porcelain and the steel end caps, and generated residual tensile stress during unloading. This effect largeley invalidated overload proof testing as an effective evaluation technique. The acoustic emission thus provided some very vital information about the proof testing procedure for the procelain insulators.

E. Material Tailoring

One final approach that might be utilized to enhance the acoustic emission from macrocrack growth compared to that from other sources of acoustic emission is material tailoring. Normally, in a single phase polycrystal, for example, the crack only moves forward incrementally from one grain to the next. But, if second-phase particles are incorporated, then the crack length increments can be increased to a value comparable to the particle spacing, thereby increasing the level of each event. Also, particle microfracture may occur (e.g., porcelain) which can increase the total amount of growth emission. A judicious choice of second phase material chosen to minimize strength degradation can thus substantially enhance the utilities of growth emission as a nondestructive evaluation technique.

This interesting materials development approach has been applied to silicon nitride by incorporating silicon carbide particles. During high temperature slow crack growth, the presence of the silicon carbide particles

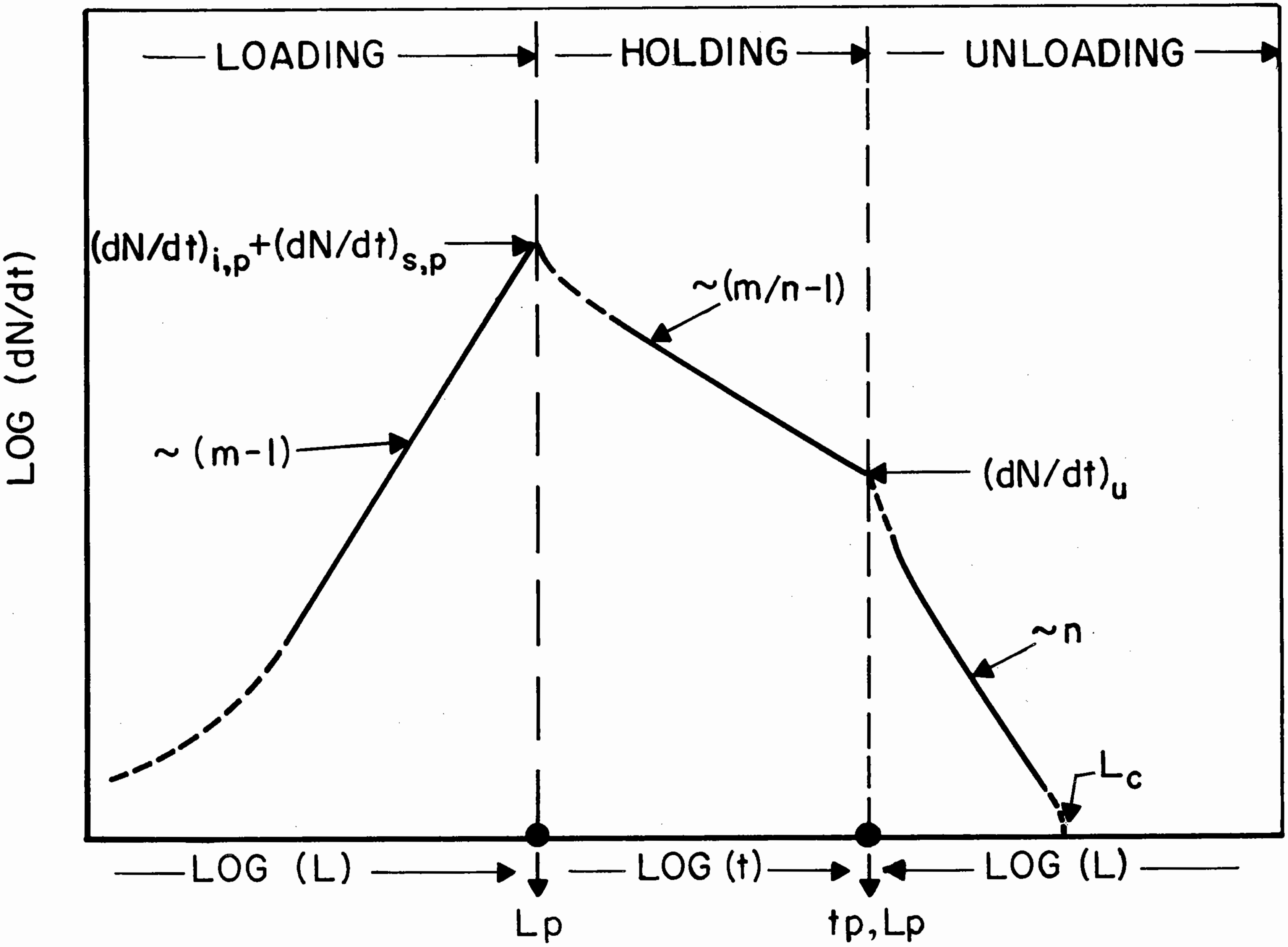

Fig. 4 Acoustic emission rate as function of stress loading, holding, and unloading for quartz particles.

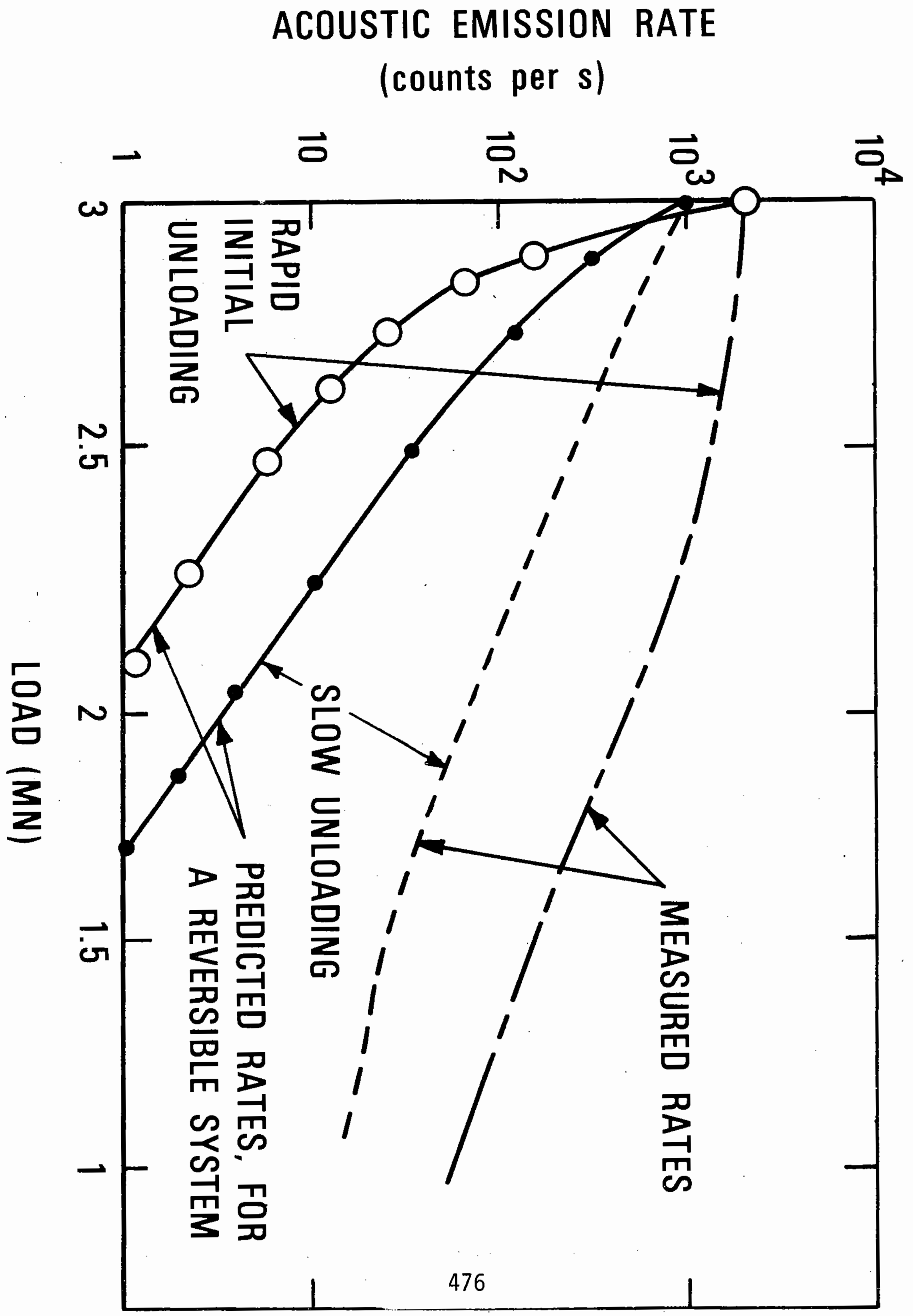

Fig. 5 Acoustic emission rate as function of load during unloading cycle for porcelain insulators

enabled acoustic emission to be detected at substantially lower velocities than in the matrix material (see Fig. 1).

I think my time is up. In conclusion, I would like to emphasize that acoustic emission techniques are at present specifically related both to materials and configuration. One has to think about each situation in a separate way. The best short-term approach in being able to use acoustic emission effectively is an empirical approach in which you try to look at things like the amplitude effects, frequency effects, and sensible phenomenological evaluations. It is a very complex but important NDE subject.

DISCUSSION

DR. DON THOMPSON (Science Center, Rockwell International): How close an analogy exists between the crack movement between particles concept and the dislocation breakaway concept?

DR. EVANS: The treatment is conceptually similar but analytically quite different. A crack doesn't have a line tension in the same way that a dislocation has and one has to approach it in a different way.

DR. DON THOMPSON: Have you worked this out analytically for the crack growth?

DR. EVANS: People are trying to do that. We have tried but our calculations have been very approximate.

DR. THOMPSON: Do these precipitates have to be incoherent with respect to the lattice in order to get a blocking effect?

DR. EVANS: I'm not sure how important coherency is per se. I think there are two controlling criteria. The precipitates must have a higher toughness than the lattice, otherwise they are not going to block the crack, and they must have a reasonably strong interface to prevent separation.

PROF. H. TIERSTEN (Renseller Polytechnic Institute): In the acoustic emission, there would be different waves, longitudinal and shear waves. Do you separate them out and detect them and is there any difference?

DR. EVANS: We have not at this stage, but others may have investigated this.

PROF. TIERSTEN: From an anisotropic situation you may pick up more than in an isotropic situation because you get three waves, and this is something you haven't addressed in the talk. I am trying to find out what you would be looking at by putting a different collection of transducers on the sample and taking the output from all of them and trying to collate what type of wave might be sent out so you could separate the different things you would detect.

DR. GERALD GARDNER (Southwest Research Institute): Let me just ask this; isn't it true that the monostructure of these stress wave packets has been looked at to a certain extent by the people at Battelle Northwest? The monostructure of the wave packet should provide considerable information, i.e., how much plate wave, how much compressional wave, what are the shear wave components, etc. Because the packet is tremendously dispersive, and if you time it right, you can deduce this composition.

PROF. TIERSTEN: It is coming through an infinite medium in a sense.

DR. GARDNER: But it never is. It is always coming through something that obstructs.

PROF. TIERSTEN: A lot of the components of the pulse act as if it is an infinite beam. If the wave length associated with it is much smaller than the small size of the thing you are looking at, it wouldn't be dispersive unless the waves were on the order of the plate thickness, for example.

DR. GEORGE ALERS (Science Center, Rockwell International): In very thick walls of pressure reactor vessels, 16 inches to 8 inches, you might expect to get a detectable difference in the shear wave and the longitudinal wave transit time, but the pulse duration of most of these things is much longer than that, so they are all tangled up together even for very thick things.

PROF. TIERSTEN: Yes, but they have different displacement components associated with them, and different transducer arrangements would pick up different information. That's what I am talking about.

DR. ALERS: Now, we have made use of these effects in a lot of the aerospace materials which are thin sheets and big fuselages, and in those cases, you do get a separation between the compressional and the flexural modes. You can use the separation to detect both of them and you can work back to where the wave came from due to the dispersion, geometric dispersion of the parts.

DR. GORDON KINO (Stanford University): I have a couple of questions. First of all, do the basic frequencies that come out have to do with the crystallite sizes in the material, or the sizes of some other macroscopic or microscopic quantities?

DR. EVANS: Take the case of a crack. The amplitude is determined by how far the crack moves which is indirectly determined by the microstructure. But, I don't think that the frequency is related to the microstructure.

DR. KINO: Is there a basic frequency which has to do with the grain size?

DR. EVANS: No, not in that sense. One tends to get emission over a wide range of frequencies, not a basic, single frequency.

DR. KINO: Doesn't that mean it is essentially a delta function with a higher frequency than the grain size?

DR. MEL LINZER (National Bureau of Standards): Well, some of the frequency content would be just based on the time scale and the event.

DR. KINO: Yes. Secondly, has anything been done on stimulating an emission by putting one frequency in to produce a sinusoidal stress wave and seeing what that produces in the way of emission?

DR. EVANS: I am not aware of anything. Somebody else?

DR. LINZER: Are you talking about the peak?

DR. KINO: Yes, essentially.

DR. LINZER: Well, people have looked at acoustic emission under cyclic loading.

DR. KINO: Well, I really meant a higher frequency.

DR. MARCUS (Science Center, Rockwell International): I am confused whether or not you can measure the stress intensity factor through acoustic emission. You started out discussing that and then you seemed to imply that the amplitude was not apropos.

DR. EVANS: There is a problem here. I said one can in princple get K from the acoustic emission rates. The problem is that the proportionality between K and acoustic emission rates depends upon the transducer itself, the coupling of the transducer to the component, and how far your wave has to go from the event to the transducer. All those things come into that proportionality factor, and a priori, one doesn't know what that proportionality is going to be. Hence, in a service situation, unless you have a well-controlled system that you understand beforehand, the acoustic emission rate is not going to give you an absolute value for K. What can give you an absolute value for K is the event rate, i.e., the separation of events, because now this doesn't depend on how the wave is attenuated before it gets to the transducer, etc. The implication I was trying to make there is that amplitudes by themselves might not give you an absolute K, but the event rates have a potential to give you an absolute K.

DR. MARCUS: That was the second question. Will that still hold true when the component has been cycled with variable amplitude loading? During the proof test, the history would influence what you would get from a given crack.

DR. EVANS: No, I don't think so. It is the value of K at that particular peak stress in the proof test. I don't think it depends in any way on the prior history of the component. It certainly has not for the ceramic materials that we have looked at.

DR. HENDRIKUS VANDERVELDT (Naval Ship Research & Development Center): I would like to make one comment on that last statement. Some cases have been found where past history does make a difference, specifically, in terms of the peak loads that it has seen, but there is a time factor involved. If the relaxation has been long enough, it tends to recover.