QUANTITATIVE FAILURE PREDICTION: ARE ALL THE WICKETS COVERED?

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Panel Members: Nancy Mann from Rockwell International Science Center (an expert in statistics, especially extreme value statistics), Ed Lenoe from Army Mechanics and Materials Research Center (with expertise in reliability and ceramic turbine development), Tom Demacks of TMH (he's been using ultrasonics to detect defects in ceramics), Roy Rice from the Naval Research Lab (an expert on fracture expertise in reliability and ceramic turbine development), Tom Demacks of TMH (he's been using ultrasonics to detect defects in ceramics), Tom Demacks of TMH (he's been using ultrasonics to detect defects in ceramics), Norm Tallan from the Air Force Materials Laboratory (with a major interest in ceramics for structural applications), and John Schuldies from Aresearch (the NDE expert at Aresearch with a lot of experience using current NDE techniques).

A. G. Evans, Moderator (Rockwell International Science Center): To initiate the proceedings, I shall pose the questions that this evening's discussion is intended to address.

As indicated at the outset of the session today, we want to find out: (a) where are we with the use of NDE techniques to predict failure in ceramics, (b) what do we have to do to quantify those techniques, and (c) what approaches are on the horizon for improving our capability for failure prediction. More specifically, is the failure prediction sequence I described in my talk a complete one, or are there some features in the failure prediction process that we are missing? What are the optimum NDE techniques, recognizing they can be material or component specific? I'd like those who had posters, and who have special techniques, to feel free to come up and discuss their techniques, in order to address how well the techniques can really answer the questions--how big is the defect, what type of defect is it, and so on. Finally, we must recognize that when you get involved with programs of this character they don't have infinite numbers of dollars, therefore a limited number of tests have to be performed and hence, what sort of statistical planning should we use in designing our tests to maximize the pertinent information. Those, then, are the questions we will be asking. Before we get into specifics, Norm Tallan has volunteered to give a very short description of the program the Air Force is about to start in ceramic turbines and put a perspective on some of the questions we just raised.

Norm Tallan, Panelist (AFML): The Air Force is extremely interested in ceramic components for turbine engines, particularly for small limited life applications and we've been looking very carefully at the work that ARPA has been doing in the past both in the Ford/Westinghouse program and more recently in the Garrett program, and we are about to launch our own manufacturing methods program which will pick up on the technology that has evolved from those programs and try to address, particularly, the questions of productivity, cost, and reliability. I emphasize, particularly for this meeting, the question of reliability because the current Garrett program, for example, has demonstrated that as far as designing with brittle ceramic materials concerned, we can accurately predict the temperatures and stresses in components, and rig tests have borne out that those designs are reasonable. We have ample evidence that the materials that we need both for the vanes and blades are probably good enough, in fact I'd say are almost certainly good enough for at least the limited life applications we have in mind for many military systems (where the lifetimes would probably be under 100 hours). But even though we are talking about these relatively short life applications where perhaps we don't have to worry about very slow stable crack growth rates, we do want to know that first of all the components will not fail under initial loading, and also that they will not fail by any unexpected failure mechanisms that we haven't considered. In terms of reliability in our program, I think it very important that we consider all the aspects--the system requirements, the materials that we would use, the kinds of components we have in mind, and what the likely costs are going to be. As an example of some of these factors, consider the inlet guide vanes that we would use in the first stage turbine. The material that's most likely to be used is reaction bonded silicon nitride which, as we know, is a porous material that may dictate some of the techniques we would use. But, furthermore, one of the reasons we are specifically interested in reaction bonded silicon nitride is that we can make it to shape, and if we are going to test that by NDE, we are going to have to test it on a complex shaped surface. On the other hand, the vane itself is probably one of the inexpensive components to make and even if we are talking about a real engine application two or three years from now, we could probably predict that we could buy vanes for, say, $30 a piece and if we have a 30-vane starter, we're dealing with about $1,000 component and we can afford to do some tests in a case like that to throw many of those away, if we do the NDE and there is any uncertainty at all about the quality, we could probably throw them away. On the other hand, if the material does not have slow crack growth (as it appears right now), then perhaps we can proof test those components: one of the normal reasons for hesitancy about proof testing being that we may damage the part. Also, since the stresses will largely be thermal in origin we can probably proof test them easily by a rig test. So, I think there are really
some cost and potential damage tradeoffs to be made in reaction bonded silicon nitride. These would be entirely different from the blade material, which is likely to be hot-pressed. Here we would probably start with a hot-pressed ingot, which could easily have smooth surfaces that could be inspectable; in fact, the ingot form is still relatively inexpensive compared to the machined component. Each blade at the moment is probably going to cost somewhere on the order of $500-$1,000, so if we have a 30-blade rotor, we are considering $15,000-$30,000 for the components. It's really critical, therefore, that we have some good assurance technique, particularly before we put that rotor together. And maybe it's feasible to really do the nondestructive inspection on the ingot before we do the machining, to look for the volume flaws. Then, after we've got the complex surface, which is hard to inspect, inspect only for machining damage. In any event, I think whatever we do in our program we are going to be most concerned that we not only have consideration of the materials that we are going to use, and as many good techniques that we can apply to these, but that we in fact have some reasonable program for actually making a decision - a go/no-go decision - on these components before we put them in an engine. And I think that the position that Tony took this morning is one that we would be very interested in; essentially, a probabilistic approach where perhaps you could use the NDE techniques available in the near term to at least reject those components which we know are bad enough that they will not make the application and not bother to proof test these. Perhaps we can, in the NDE initial screening, decide that there are some components which are so likely to be good that we wouldn't subject them to the potential damage of the proof test; and only proof test those in the uncertain region. In any event, I would say that the program that we are undertaking in manufacturing ought to be an ideal proving ground for many of the NDE techniques that would be developed under the ARPA program. I would certainly hope that we could apply those and get some real experience in the manufacturing program to see how well they work.

A.G. Evans: I think that gives a nice perspective that we should keep in mind when discussing techniques and their use in actual components. Does anyone have any specific comments based on Norm's brief discussion? In that event, what we'll do now is throw open the question that I asked firstly. Is the failure prediction sequence that I presented a complete one? The sequence was: (a) we first infom something about the defect size (b) then we break samples containing defects to measure the fracture strength under fairly well defined boundary conditions (like a constant stress rate experiment), then (c) combine those two behaviors, in a probabilistic fashion, to obtain a relationship which is a fracture probability vs inspection size and a rejection probability vs inspection size and then use those graphs for a final comparison of NDE techniques. Also, add in (when necessary) that the cracks will grow slowly in the environment of the turbine (or whatever other component we are interested in) to the critical size.

Roy Rice, Panelist (Naval Research Lab): I don't know whether this would be a different approach but one thing that I haven't heard discussed, at least specifically, is an addition to your indirect techniques. For example, if you have a teacup and you want to know whether or not it's in good shape, simply hold it on your finger or a piece of wood and ring it. If it doesn't have a high enough pitch, you know it's got a defect in it - you don't know the size and you don't know where. I think this is indicative of class of inspection that may be feasible. For example, on a complex shaped part, if you ultrasonically excite it, it is possible by its modes of vibration to tell whether or not that part is outside the normal spectrum. It's an indirect technique but I don't think it was specifically mentioned and I'm wondering what opportunities there are for this.

Ed Lenoe, Panelist (Army Mechanics and Materials Research Center): Well, first of all, I return to the question that was posed; is the formalism adequate, are there any things that are missing from the life prediction? The formalism that has been described is certainly rational but it's fair to say there are alternate approaches. At least in the turbine area, critical demonstration tests are underway precisely to explore the adequacy of these various analytical treatments. There is one major deficiency which hasn't really been thoroughly studied are materials instability, such as oxidation, phase changes, dimensional variations that are introduced by environmental exposure. We have some techniques to understand that and screen that out, but there are certain temperature regimes where this to me will be the critical limitation on a particular component in a turbine environment. Some limited studies suggest that kind of a phenomena may be stress/diffusion controlled. That hasn't really been looked into at all except on a limited basis. If that kind of thing happens, that means the fracture toughness may change in certain ceramic materials and perhaps the creep properties, and so forth. Actually, before I saw your questions, I had written down some feelings with regard to the entire meeting that relate to this session. While during the meeting a number of speakers as well as audience participants have stated that we must know what we are looking for and I would like to explore that notion a little bit from several viewpoints - first from the structures viewpoint and then from the fabrication or processing viewpoint. It's well to recall that the definition of a critical flaw size in any application must be determined by stress analysis techniques. This critical flaw is necessarily related to the structural geometry and the stress states, particularly the NDE techniques applied to the examination of the designated critical areas and volumes of the structure. So far, in much of the work that has been presented here, at least in the ceramics area, nondestructive evaluation has seemed to emphasize simple geometries, and in some cases perhaps irrelevant, defects. Now, in addition to what I said about the structural geometry and stress viewpoints, definition of the flaw or defect is a complicated iterative procedure. It cannot be viewed strictly as a microstructural thing. It cannot be viewed as an impurity. That impurity and the definition of that defect must be related to service requirements in the component that you are dealing with. Actually, the NDE techniques have
to follow in parallel with the fabrication or processing. Often in producing a ceramic part, for instance, we introduce cracks and flaws and voids and so forth, that are controlled more or less predominantly by the process itself. In a number of instances, such flaws and folds will occur in virtually non-stressed areas. Therefore, they are not critical defects even though they look horrendous. Thus, from the process viewpoint, NDE techniques suitable for various sub-steps of the fabrication must also be available. Then, we can also mention just in passing residual stresses.

As far as application of the advanced NDE techniques, I think its interesting to consider the results of a recent study conducted by the Society of Nondestructive Testing. What they were after was to review the qualifications of currently employed technicians in the representative industries. Generally they were appalled by the results. These technicians were found to be relatively poorly trained with only modest understanding of what the kind of measurements were that they were dealing with. Now, if the techniques for sophisticated data interpretation were to actually ever be used by the average technician, we have to develop absolutely fool-proof software, and equipment and transducers that are totally reliable. I don't mean that to downgrade the technicians, they just happen to be ill-trained and doing a job for low wages. So I hope that the talented and highly trained engineers working at the forefront of this quantitative utilization of NDE bears this in mind. In addition, some effort should be made to isolate technologically interesting machine and structural components and subsequently develop specialized transducers and analytical techniques which account for the hardware complexities.

I was talking basically about rotor fabrication. The rotor can be fabricated in a variety of ways. Under the ARPA/Ford program, we started out using a slip casting and injection molding and obviously, as you go through this process, you want to have various controls. Potential defect introduction in the process of making a so-called multi-density rotor - this is where the blade ring and the blades are combined in a composite ceramic wheel occurs: in the process of removing the blade rings from the molds, you can introduce cracks at the base of the blades: in the process of drying out, you can introduce high oxygen content which can have disastrous effects on long-term stability.

A.G. Evans: You are quite right, all of those are real problems that have to be borne in mind, especially the very specific character of the techniques and the knowledge that we don't need to inspect the whole part. I'm glad you emphasized those. Now I think we're at the point that since we have the NDE community with us of trying to acquire the information we need to select techniques that will be most pertinent to ceramics.

I think we're at the stage now where we'd like those people who feel they have something to offer to the ceramics community in terms of quantitative NDE techniques to try and address the questions we raised earlier; that is, how well can you characterize the size of small defects, and can you possibly tell something about their character?

Bob Gilmore, General Electric: I want to address this question to Ms. Mann. We have talked for three days now about characterizing an indication that we have found and I think that one of the things that has been skillfully skirted in every single discussion is "let's talk about the one's that we miss every now and then." We talk about cutting humans out of the loop, but the fact remains that if you perform one test that's a routine scan you may miss a certain percentage of indications that could or couldn't be critical. If you perform a second test (so that your scan lines don't follow the same groove) you'll get a certain number more. And, I think the thing that we haven't discussed in ceramics or anything else is detection probability, and by this I mean if we have a population field of 2,000 defects which could or could not be critical to maybe 20,000 parts, how many parts didn't we take out by the system.

Nancy Mann, Panelist (Rockwell International Science Center): First, you mentioned another important point; that is, how do you characterize what it is that's the important factor that will cause failure? Here we've talked about size, very conveniently, as if everything else would be held constant; but actually, you're going to get a signal and from that signal you're going to enquire whether there is something about that signal that's important (that will tell something about strength). It's much simpler, of course, if the only thing that you're varying is size. But, if it's the real world, and you're simply looking at a material that has some kind of a defect in it, and you don't know what kind of a defect it is, then there are many things about it that vary from sample to sample. So, that's the first question that I see as an important one. Then, given that, suppose you do decide to manufacture samples and nothing varies. Then we have the kind of problem you spoke about, where there is a probability distribution and there is the probability of not detecting the defect at all. I don't know how to address that problem yet.

John Schuldies, Panelist (Airesearch): I certainly agree with the comments that were made, but let me say something that I think we're all missing. There needs to be more of a working relationship between the fabrication of the ceramic and the NDE. What I mean by that is both types need to be disciplined in the other's area of expertise. Firstly, if you have a working knowledge of what goes on when a part is either injection molded or slip cast or machined, you can second-guess where the major flaws are going to lie. If you are made aware of that problem, you concentrate on it and eliminate it. For example, in the green bodies which Ed Lenoe referred to previously, not enough work has been done in that area.

Roy Rice: I'd like to follow up on some comments that Ed made. He briefly alluded to changes in the population of defects. Even in the short time that Norm was talking about (100 hour lifetime), we have
to consider the possibility of a dynamic population of defects in ceramic materials. Also, to put this in perspective, I’d like to emphasize the importance of surface flaws. We have found, even in direct tension testing of silicon nitride, the predominant source of failure to be machining flaws. Correspondingly, we are now finding in the improved reaction sintered silicon nitrides something like 75% of our failures are from machining flaws rather than processing defects. It also turns out that the stresses in a turbine vane or blade are a maximum on the surface. Now, these surface flaws have had very limited detectability. I am very encouraged by the one talk given here; in fact, I believe it’s the first time that a surface crack has been detected in a ceramic. However, there is a significant population of surface cracks in a ceramic and we have to sort out the worst one, which may be only 5 microns deeper than the remaining 95% of them; and those flaws are typically in a range of 20 to 50 microns in depth. Then, depending upon the character of the material, within a matter of a few ten’s of hours to a few hundreds of hours, the surface that contains those defects has been totally oxidized and essentially disappeared. Now we have a modified population of defects, introduced by the oxidation itself. In addition, as time progresses, the nature of the processing defects will have changed. Some may have become more benign but others may have become significantly more severe. So we have to keep in mind that there is a dynamic situation. Also, one other point that I’d like to make is that many of the defects that we are dealing with are not random. A significant percentage, in fact in many cases, a majority of the defects, both processing and machine defects, have a significant orientation depending upon the nature of the processing we are dealing with. That may be a help and in some cases it may be a problem. Also, many of the defects we are looking for, we’re looking for in areas that are most difficult to inspect. I am encouraged by the progress, but I think we’ve got to keep in perspective some of these additional challenges that we have to meet.

H. Burte: I feel a little bit like Alice in Wonderland. As encouraged as I am by the progress, as enthusiastic as I am with the potential, I have a feeling that we haven’t fully addressed the key issue. The tough problem is not how to find a smaller crack or a smaller flaw in the laboratory. That’s tough enough but that’s not the toughest question. The real problem is the probability of finding a flaw (or some parameter relating to the severity of the flaw) and the probability curve has a sigmoidal shape, where the plateau may or may not be up around 100%. The problem is not to drive this curve down to smaller sizes, but to change the shape of the curve towards a step function. In metals, we’re having problems under production conditions finding flaws which are one or two orders of magnitude larger than the 4 mil flaws you’ve been talking about. Now I’ll be the first to agree that the job should be easier in ceramics than in metals, but I think you should go down the litany of the things that can go wrong and then check off why it won’t go wrong in ceramics; or if it will go wrong, what you have to do to prevent it.

Ed Van Reuth: I guess I am eminently qualified, because I have lost more nights’ sleep over ceramics, I guarantee you, than anybody in this room. And I’m coming to a conclusion which just frightens me. Let me paint a little bit of background to this. When I first got frightened about ceramics, a pacifier was quickly thrust in my mouth in the form of finite element analysis and “hey, don’t worry about it, we know everything that’s going on in every one of these little cubes in this material!” But there was a gnawing question in the back of my head going, “How do they know that? How do they know that, how are they going to prove it?” Well, it’s quite simple, we’ll do a proof test. Now with ceramics which are non-forgiving materials, of course, you should know the stress in every one of these finite elements to a certain probability and a certain degree of confidence. Now we don’t. We go into something that we think is a proof test (normally in a rig which is supposed to simulate engine conditions and we find out something went wrong with a lot of millions of dollars in rig tests with the final answer being told to me, well, the proof test wasn’t realistic. That’s the problem. A proof test must be very well quantified in ceramics because they are non-forgiving materials and we can’t simply have false hopes based on numbers which are given to us by people who are performing finite element analyses. The numbers may be right, but then we must be careful that the proof test is right.

Tom Derkacs: I have accumulated several comments here which I hope I can relate back to the original question. First of all, I agree that all NDE techniques have a probability curve, and there is no reason to believe that any technique that is developed for ceramics is going to be any different. Secondly, as far as Roy Rice’s comments on surface cracks, we have evidence to indicate we can detect surface cracks down to 40 microns. As far as the comment on reliability, the question that kind of bothers me a little bit is that nobody has said anything about how well we have to characterize the defect. There’s an uncertainty in predicting failure and there is also an uncertainty in characterizing the defect and we ought to have some idea of how good we have to be able to do those things. The other comment I want to make is with respect to reliability, it’s very difficult to determine what the reliability of a technique is when it’s the only technique that’s available to detect the defect. In comparing our inspection results, for instance, with the Air Research microfocus x-rays, we get excellent agreement on the defects that we can both see; but the question is, what about the ones that one of us or both of us can’t see. How do you find those things out. I’d like to suggest that one way might be to work out an arrangement where before any specimen is tested, it’s inspected by the best techniques that are available, so that we can build up a body of data on the reliability of the inspection techniques. I think that’s the only way to do it and it’s going to take a long time and a lot of expense.

Roy Rice: Obviously I’m biased. I think that the only way to test the technique is break the samples afterwards and see if they broke from what you thought you saw in the first place.
Tom Derkacs: The problem with that technique, and that's what we tried to do, is that it's very expensive to make a ceramic specimen. If you make 100 ceramic specimens, how many are going to have detectable defects in the high-stress region? The probability is probably fairly low unless you deliberately seed them, which is not in my experience exactly comparable to looking for natural defects. So, the other alternative you take is to take a billet and inspect it and then make the specimens around the defects. Then, of course, you have the problem of how accurately you can do that, but either way is expensive. I agree that that's the way to do it, if you can afford it; but so far, I haven't seen anybody with enough money that wants to pay for that.

Norm Tallian: Another approach to the same question would be (in the initial phase of the manufacturing method program) to take real components, where we know the processing is often different than test bars, and wherever we get an NDE indication, cut out the test specimen and subject that then to a fracture stress - we don't have to look only at the ones that are in the high-stress region of a component. Then, see that they fracture at the NDE indication, study the origin of the fracture, see what kind of a flaw it was and relate it back to the NDE indication. Then, try to get some idea of what the signatures really mean in terms of effective severity of inclusions.

Roy Rice: Better yet, we need to build up a history of establishing what flaws actually cause failure of components. The worst thing that could happen is for someone to have a failure of a component then throw the pieces away.

C. Jakus: A few months ago I read a news brief in an electro-optical trade journal in which a person stated that optical surface holography is coming to be a serious NDE tool again, with the development of fast films. But the commentator didn't explain what the technique was and what it is used for. But my question to the panel, or to the audience, is that would anybody know whether such a technique would be applicable to ceramics, considering that the surface defects are very crucial?

Dave Kuppeman: We have a small program at Argonne to look at various nondestructive testing techniques for silicon nitride for the vehicle program with Ford. One of the techniques that we are looking at is holographic interferometry. We make a hologram, and the film is developed in place so that we can see the interference pattern generated. We can see flaws by this technique which cannot be detected by x-rays or a microscope. The hardest flaw to see is one at the root of the blade and right now, although we've only done some preliminary work, we can see blade cracks as small as 250 microns. That's our present state of the art. One other technique that we find very interesting is a technique where we use a dye which absorbs x-rays much more strongly than does the ceramic, and by analysis through neutron radiography, we can again see surface cracks of flaws. They are quite clear.

Roy Rice: Also there was a Navy-funded program a few years ago which was, in part, the basis of one of my earlier comments. At TRW a holographic technique was applied to ceramic materials and they could, for example, put a surface scratch in a piece of glass and while they could not detect the specific location, they could detect the general location. They could tell the difference between a scratched and unscratched plate holographically by the difference in deflection under very low stress levels and that, as I said, I think is an example of a class of inspection techniques that don't tell you specifically what the flaw is, but you can indirectly correlate it with being a bad part.

R. Gilmore: I'm like a broken record, as usual, but I guess if I looked at NOT, I'd call it "detection, characterization, and analysis." The detection problem, I think, is going to have to receive just as serious, just as long-term, and just as much money as quantitative interpretation of something that you've found. Although ceramics is relatively new, believe me you are going to encounter every problem that any other material has encountered; they may be a little different, but they're all going to be there, residual stress on down.

Gordon Kino: Somebody mentioned the subject of looking at green ceramics and it seems like a very good idea to try and get at these materials at as early stage as possible in the production process. But I was just wondering if anybody has done any measurements on green ceramics, acoustically or otherwise, so some of the parameters are known. It would be very useful to know whether its worth even to try.

John Schudles: While I was at Ford, conventional radiography was employed. Ultrasonics was employed on a limited basis. Velocity measurements were made on green silicon nitride, injection molded silicon test coupons. As I remember it, the velocity was on the order of maybe something like graphite and it was extremely attenuative; very difficult to get a signal into and out of. So, when you start talking about those kinds of problems and that kind of application, then we compound the material aspects all that much more, and it makes the inspection much more rigorous. But I still feel that with a good knowledge of how you form that part you can second-guess the orientation and the type of defect.

Roy Rice: A few follow-up comments on that. First of all, I think there's very serious danger in that type of inspection doing as much or more damage, if you're not careful in the handling of the green parts. The other thing, of course, is that I recall that a number of the processing techniques that we are using or that we may potentially use are not really amenable to that. For example, when we hot-press materials, we start with powder, put it in a dye and pull it out a solid piece. There is very limited inspection that I think you could do on the powder fill in the dye. Also, I think we're
A.G. Evans: If the ceramic is fairly anisotropic and prone to microcracking, yes, it does happen; acoustic
fatigue is the official title for it. However, it doesn't happen in the sorts of materials we are
considering here.

Jerry Hilbrick: I'd like to give some scope to this thing, something I deal with every day in the
metals area and composites area. If I'm looking for 20 and 40 and 50 micron internal type cracks
or defects, undefined at this point, and I call that a needle, then the size of the thing that
I'm looking in is about the size of this building (and that's one heck of a haystack). And the
cost of looking through that haystack, needles width by needles width, is expensive and I can see
a 30u costing me a thousand dollars to inspect when I've got everything worked out. Also, we
do an awful lot of rig testing, and traditionally this is the response of the builder of the rig
leaving a nut inside the rig when he's all finished, or a washer, or one end of his wrench. But
evend more so, from the standpoint of if we have one out of thirty blades that is below test, you
miss the defect in it and it fails. What do you destroy? Well, you'll destroy all of the 29
blades, which I did. You'll destroy the disc and you'll probably destroy the rig which costs you
ten to twenty thousand dollars and six months to rebuild. You'll actually tear up the whole sys-
tem and again, this is an economic thing.

A.G. Evans: I think the sorts of things you were describing go into that cost quantification that I tried
to indicate in my talk and they are important parameters.

Gordon Kino: I grant you the problem of looking at the 50 micron flaws over a large piece is horrific,
but I don't think it's quite as bad as you paint. The scanning is not done on a 50 micron scale.
What you're doing is using a millimeter diameter beam and are scanning the whole centimeter in
a couple of microseconds, if you are prepared to do things electronically. Then, if you find a flaw,
you've got to examine it more closely.

Tom Derkacs: The point I'd like to make is really two-fold. One is that in scanning the parts that we
have looked at to date, we have looked at 6" square billets of silicon nitride, for instance. As
I said before, we can't guarantee 100% reliability but based on what we've done, both by making repeated
scans of the same billet and also by scanning seeded billets, it appears that we have fairly high
reliability as far as covering the whole material and detecting the defects. Now, the second comment
I'd like to make is that I envision an inspection system for ceramic parts to be nothing at all like
the common C-scan tank and instrument; but rather, a computerized system, possibly using several
different transducers at the same time. And then, compare those defects and their locations with a
pre-programmed stress field based on how the part is going to be used. I think that kind of inspec-
tion of a whole blade, for instance, could be done in maybe 20 minutes or something like that, which
is not very expensive. Now, you might pay $250,000 or a half a million dollars for the system but
once you've bought that, the time and the man-hours to inspect the part is not going to be very great.

Norm Tallan: I think the question of proof testing was brought up by Ed. I think it's true that a proof
test has to be designed every bit as carefully as the original stress analysis of the component, and
we have to design it in such a way that in fact we know that the proof stress is reached at the
critical parts of the components. But with regard to the question again of where we put our emphasis
in the components, a point I was trying to make earlier with regard to the $30 vane is that here is
a component which is probably eminently suited to a proof test. We can probably do it by some kind
of a standard burner rig test with a thermal stress imposed and reasonably well assure that we're not
going to harm the component during the proof test. In fact, the thermal exposure may even be ben-
eficial in some ways in terms of healing some of the surface. We can afford to throw away a lot of
parts, we can weed out some of the ones perhaps by microfocus x-ray before we pass them on, all that
sort of thing. The thing we would be concerned about again is the blade, which is likely to be much
more damaging to mission accomplishment than a vane failure. We're worried about tearing up a rig,
we're even worried about putting it in a small test engine and tearing up the whole engine. But
that's still a relatively small investment (whether it be a $20,000 turbo-jet engine or a $100,000
small turbo-fan engine) compared to the risk of actually either tearing up a whole system (whether
it be a cruise missile or anything else) or having that missile not perform its mission. And, I
think we ought to focus on the whole system, not only the cost but the application we have in mind.
What is the most critical component, the most critical problem, overall. And keep in mind that it's
not only an NDE problem but also a material problem and a design problem and get all these people
together to solve this.
Roy Rice: Ed briefly touched on it and I want to bring up the point again. Of course we are focusing legitimately here on NOE. I think a lot of this ultimately rests on the processing capability in ceramics and I think we can do a great deal there. I think what we really want are the NDE techniques that allow us to help feedback to improve our processing. If we can improve our processing sufficiently, then it's not necessarily a question of inspecting every single component; but to assure us that we are repeating from batch to batch, the same quality that we had in previous successes. So I think let's not lose sight of the possibilities of taking care of a lot of our problems by process improvement, not just inspection and throwing away components.

A.G. Evans: I'll make a summarizing statement if I'm able to; if anybody objects vehemently, say so. The essence I got from the discussion was that NDE should be viewed as a fairly comprehensive process which iterates back to fabrication. We should recognize that NDE can be used in various stages in the fabrication and a different technique might be pertinent to a different stage in the making of a part. We must keep our eyes open for the comprehensive nature of NDE and be aware of any new techniques that will be emerging, to use the available techniques to the best of our capabilities, and to use them quantitatively.

R. Crane: One thing that you should recognize is again what Harris pointed out. That is, each one of those techniques has a curve associated with its ability to detect flaws. A very important concept.

A.G. Evans: I'm glad that you re-emphasized that point. I think we have cleaner systems than metals---I think we can do a better job, but that remains to be seen.