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ACRS Metal Components Subcommittee Meeting

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UNITED STATES OF AMERICA

NUCLEAR REGULATORY COMMISSION

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ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

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ACRS METAL COMPONENTS SUBCOMMITTEE MEETING

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Room 1046

1717 H Street, Northwest

Washington, D.C.

Thursday, September 5, 1985

The ACRS Metal Components Subcommittee met, pursuant to notice, at 8:30 o'clock, a.m., Paul G. Shewmon, chairman of the subcommittee, presiding.

APPEARANCES:

PAUL G. SHEWMON, Chairman of the Subcommittee,

Member, ACRS

DAVID A. WARD,

Member, ACRS

A. IGNE

ACRS Staff member

R. DILLON

ACRS Consultant

PRESENTERS:

M. VAGINS

C. SERPAN

M. MAYFIELD

P R O C E E D I N G S

MR. SHEWMON: Good morning, gentlemen.

We continue our review of the research program, and we hear about the HSST for a bunch of the morning, and then later we will hear about piping.

[Slide]

MR. VAGINS: For the record, my name is Milton Vagins. I am a senior metallurgical engineer with the Materials Engineering Branch, Division of Engineering Technology, Office of Research.

Today we are going to review a few elements of the pressure vessel research program of our branch, and I notice that, Paul, you said the HSST program. I want you to realize that the program is much bigger than the HSST program. I will point that out as we go.

[Slide]

The MEBR -- and that, of course, stands for Materials Engineering Branch Research -- addresses issues concerning the integrity of light-water reactor pressure vessels. The primary objective of the program, of course, is to evaluate the effects of flaws, variations in material properties, including environmental effects.

Environmental effects means not only chemistry, temperature, but also radiation impingement, stress risers, residual stress on the integrity of reactor pressure vessels

under normal or accident conditions. In other words, we cover the entire gamut.

We take the design of the pressure vessels as given to us by the vessel manufacturers and we make sure that it maintains its integrity throughout life.

MR. SHEWMON: How much of this ties over into the secondary system? Can you do anything on secondaries?

MR. VAGINS: No, sir, believe it or not. This particular element of the program that I am addressing today is, pure and simple, pressure vessel.

MR. SHEWMON: So the world is divided into pressure vessels and piping?

MR. VAGINS: And steam generators and NDE, as far as operations is concerned, yes, sir. Secondary systems are nice, and if we had the money, we would look at them, but we don't. Basically what our branch does is try to assure the integrity of the primary pressure boundary, and with BWRs, of course, it's a little bit different. But that is all. The primary pressure boundary circuit. We just don't have the money to do all the neat things that we would like to do in the secondary, turbines and whatnot.

MR. SHEWMON: Okay. Thanks.

MR. VAGINS: Of course, let me point out again that the pressure vessel is the only system of a light-water reactor for which there is no redundancy. If it fails, the

system goes. Meltdown is assured. As far as source term, that's something else. Then the containment building itself becomes your final defense line. So we want to ensure pressure vessels don't fail.

We do all this research not for research value but to improve our regulatory process, ASME codes, ASTM standards, regulatory guides, Federal regulations, and particularly important in the day-to-day conduct of the licensing activities. In other words, we -- me, Dr. Muscara, Mr. Mayfield you will see later -- are integrated into the NRR process. We send them SERs and continually feed this data to them.

[Slide]

Just to give you a feel again. Paul, you said HSST program. The HSST program, of course, is just one element, the biggest element but, nevertheless, one element of our pressure vessel program. As you see, here are the list of pin numbers -- I won't read them out -- and here are the basic elements of the pressure vessel program, HSST program at Oak Ridge, pressure vessel simulation.

This is part of the dosimetry program. This is the MEA program, structural integrity of light-water reactor components. This is integrated totally with the HSST program, National Bureau of Standards direct contract on dosimetry, Hanford also on dosimetry, and Pacific Northwest on code

development.

I am going to chug along. Please stop me if I go too fast if you have any questions.

[Slide]

Now I want to make a very strong point. This is no mystery to the world. The pressure vessel research program is described in detail in three documents. The overall program description is in NUREG 1155, Volume I, which was just published, and this is reactor vessels. There are four of these. One is reactor vessels, one is piping, one is steam generators and one is NDE.

The HSST program plan description is in NUREG CR 4275, heavy section steel technology program, five-year program, 1984-1985. That is the second edition. The first one was 1983-1987, and that is this book. It has been out.

And the final one is the MEA program description in NUREG CR 3788, structural integrity of light-water reactor pressure boundary components, four-year plan, 1984-1988, and that is this document. So we have a program plan in some detail in pressure vessels laid out for five years and have had it.

That reminds me. The other descriptions are found in 189s and what we call the Research Program Control System, which are computer outputs you can get.

This whole presentation reminds me of a

wedding. What you are going to see is something old, something new, something borrowed and something blue. What is old are some of these Vu-graphs you have seen before but I am going to show you again for progress, to show the progress made; the new is self-evident; the borrowed is some data from the Japanese and some Vu-graphs from my contractors; and the blue, unfortunately, is the prospect of continuing and finishing this program in the face of the congressional attitude towards budget cutting.

MR. SHEWMON: I thought you were going to say the blue is the wonderful reports you put out.

MR. VAGINS: It is, but right now it's my morale because I don't see any sense in making five-year plans and creating all this long-term research and having Congress play games with my future, which they are going to do anyway. Right now it doesn't look too good, by the way.

[Slide]

Again, the reports are there and you can get them, and if you really want to know what I plan and what we plan, you certainly can have it.

Just to show you the depth of these programs, I am going to talk about two elements here. The Heavy Section Steel Technology Program is broken into ten main tasks, and they are described here. You can see them in your handout. We are going to talk today a little bit about Task

H2, H3, heavily about Task H5, crack arrest, cladding evaluation, H7, radiation effects, H6, and pressurized thermal shock tests, H10.

[Slide]

To give you a feel for the fact that not all the money stays in Oak Ridge and the diversity of the people working on it.

[Slide]

Here are the subcontractors and consultants involved in the HSST Program. If you look at the bottom line, for instance, in 1984 we spent $1.33 million on these consultants and subcontracts. In 1985 it is $991,000, and projected in 1986 is $1.271 million. That is just for consultants and subcontractors.

This item here, NBS, as you will see in the future -- as we go on, rather, today -- NBS -- this is a relatively small amount -- is cofunding some of our research efforts, and they are putting in more than we are, and I will talk about that a little bit later.

MR. SHEWMON: You have a separate contract with them on dosimetry in addition to this?

MR. VAGINS: Yes, sir. The dosimetry program is separate. This is subcontract for HSST on crack arrest.

MR. SHEWMON: What is the consultants?

MR. VAGINS: Ed Wessel, Ed Rodabaugh, who I think

you know, people of that sort.

MR. SHEWMON: They come in for reviews?

MR. VAGINS: Yes, sir, and for tie-in with ASTM. For instance, Ed Wessel is Chairman of E2408, of which I am an adviser, and we support that activity and review. Rodabaugh works on paper, just putting out a paper on leak before break, which I am supporting. At one time I had all the piping, too. Mr. Mayfield just came on board. They come in and out as we need them.

[Slide]

That is HSST, and I want to make a point at this time. Everbody thinks HSST exists in a vacuum and they do all the work. Well, they don't. The structural integrity of light-water reactor boundary components is almost a $2 million a year program. It is integrated extremely well with the HSST program, and they do work which cannot be done at Oak Ridge.

This is the program, by the way, which picks up where NRL left off. We had work with NRL, Naval Research Laboratory, since the sixties, and they kicked us out, literally. So we issued a competitive contract. It was won by Materials Engineering Associates, and there are three main tasks: fracture mechanics criteria, environmentally-assisted crack growth, and radiation sensitivity and postirradiation properties recovery.

This is the area, of course, that deals with the parametric studies, levels of copper, nickel, and phosphor, et cetera, annealing. Those three main tasks.

Again, to give you an example of the field we cover, in the MEA Program --

[Slide]

Those three main tasks are broken into 21 subtasks. Fracture analysis, fracture criteria has six tasks, seven, et cetera. I won't go through that. But you can see the depth. This is Remington. They have been doing some of the work at Remington. They do testing. HSST fourth irradiation. This is the fifth irradiation.

MR. SHEWMON: Is annealing part of that program?

MR. VAGINS: Yes.

MR. SHEWMON: What bullet does that come under?

MR. VAGINS: High temperature annealing, composition effects on annealing, mechanism model of irradiation damage. We are supporting Odette, not directly. EPRI is supporting Odette, and I am supporting Hawthorne, and we are sponsoring that mechanism workshop next week in Monterey. That is an example.

MR. SHEWMON: Hawthorne doesn't do mechanistic work, does he?

MR. VAGINS: We are sponsoring Hren down at the University of Florida and his group.

MR. SHEWMON: John Hren? I have never seen a report --

MR. VAGINS: He does good work but he doesn't publish much. He is getting into the swing. What they are basically doing is -- they went to iron ore models. They are doing SEM transmission model study. But we are working with EPRI and Odette and with the entire international community. We can't work in a vacuum.

MR. SHEWMON: EPRI is backing that event. You might talk with Odette about what he is going to do in the future.

MR. VAGINS: As usual, we will pick it up. EPRI continually backs out before the job is done. They seem to have more money problems than we do. Nevertheless, if we have money -- by the way, if I sound a little blue, I am.

MR. WARD: You sounded optimistic when you said that if EPRI backs out, you will pick it up.

MR. VAGINS: That is what we have done in the past. We fill the gap. That is what our job is. If nobody else does it, we do it. If industry will do it --

MR. SHEWMON: Professors come cheap. That doesn't take much money.

MR. VAGINS: The trouble is -- I will give you a good example of what is happening. The budget -- just the HSST budget in 1980 was $1.8 million. I came here in 1979 with the onset of the pressurized thermal shock issue, which

we identified and we forced and we analyzed. We developed this hump in order to meet this issue and finally get some answers out of the HSST Program. We have been doing it. 1986 is supposed to be the big year, 6.3, then it was supposed to tail down in 1988 to $3 million.

MR. WARD: The sort of the point is that in planning the research, it's a reality your budget is going to be cut.

MR. VAGINS: No, it hasn't been.

MR. WARD: But in future years you expect it. So the pressure should be put on EPRI not to drop things.

MR. VAGINS: We do. We have done that. You will see in piping they dropped out prematurely and we are fired up now. We tried to --

MR. WARD: You are fired up? You are getting EPRI to pick it back up, you say?

MR. VAGINS: We are fired up to do major piping, but we are getting EPRI to cooperate, putting money into our international program that you will hear about later. You know, you say put pressure on. There is very little that we can do at our level to force EPRI to do anything. You have to remember that their entire nuclear budget last year, entire nuclear budget was less than $60 million, and that covers the gamut. So materials have gotten short shrift lately in EPRI, for whatever reason.

Materials has increased our budget over the years in

declining budgets. The main cuts have come in the area of thermal hydraulics and code development. But our turn is now. We have now reached the point where the HSST Program is probably the single largest remaining program in the Office of Research, which makes us, of course, a prime target. And as I said, that is going to be cut.

I am carrying one-thirteenth of the entire office budget right now. The likelihood of my maintaining this level is very small. If we were allowed the money and we were allowed to continue our planned research program -- you will find this in the back of our program plan. This is slightly obsolete, slightly because we have had some slippages.

[Slide]

Nevertheless, this shows the flow path of the planned research and the integration of all the pressure vessel research with the end objectives out here at the end of fiscal 1987, 1988. We still have ongoing, continual support in material characterization, et cetera, but basically we should have most of our answers out here, and the HSST Program goes down to what I consider a sustaining level, just carrying out material characterization tests, radiation tests, et cetera.

So again, you have that in the handout and you can look at it. We have a lot of material to cover.

[Slide]

Today I would like to cover, by your request, actually, the pressurized thermal shock experiments, results and plans, wide plate crack arrest experiments, cladding effect studies, the HSST fifth irradiation, this fracture toughness, this curve shift verification, the HSST sixth irradiation, irradiated crack arrest, and if I thought Mr. Etherington would be here, he has some concerns about low upper shelf material and I would be prepared to address that, although I have nothing formal on that.

[Slide]

This is an old Vu-graph. This is a Vu-graph which was first presented in 1982 and has been presented every year since. This is the research which is directed toward defining the uncertainties in pressurized thermal shock, and there were very classic ones. Paul has seen this every year since 1982, and he will continue until I am finished.

But there are 14 elements which we define had to be clarified and resolved before we had the total pressure in pressurized thermal shock. Applicability of linear elastic fracture mechanics. I think we pretty well demonstrated that on several issues, and as you will see, extremely well, and it is extremely applicable.

Effectiveness of warm prestress. We demonstrated that and are still working on it.

Vessel failure under nonpressurized thermal shock

conditions. In other words, just thermal shock. We demonstrated through our thermal shock experiments 1 through 7 that you cannot fail a vessel just through thermal shock if the vessel is depressurized. This addresses the problem of LOCA, large LOCA coolant accident, large break. If you depressurize the vessel, the probability of that vessel cracking are totally practically nil, self-limiting.

The behavior of small finite flaws when subject to pressurized thermal shock conditions. Remember we are talking about very small flaws, indeed. I think we have demonstrated that small flaws will grow long and then grow deep, so that you can treat this with modeling long flaws.

Cladding-flaw interaction, bimetallic effects. We are still working on that. Of course, the cladding will affect the behavior of small flaws and is quite critical, but from a conservative viewpoint, we ignore the cladding in all our analysis except for the thermal part of it, and we take the worst effects. We put the stresses in that it causes, but we don't take any credit for the ability for the cladding to limit flaws. That is what we are working on now, but it is really trying to define our margins on our present analysis.

Irradiated cladding. You can't really tell what cladding is, either end of life or during or somewhere during the middle of life when you have a PTS scenario unless you really understand what happens to the cladding during

irradiation, and we are doing that.

Arrest on the upper shelf. As you can see, we have done that. We will do it some more.

Post-arrest performance. What happens when a crack runs into the vessel and stops and the pressurized thermal shock scenario goes on? What happens? Does the vessel blow up, splinter, or just open up and leak? We are also analyzing that.

Definition of margin when using the RT/NDT to set the fracture toughness curves. You will see we have done a lot on that.

Variation of through-wall fracture toughness degradation. This was done in dosimetry work in the PSF, which was described slightly yesterday. It is being done in Gundremmingen. Hopefully, when we finish we will have a pretty good handle on what the toughness is as we go through the wall. In otherwords, the attenuation of fluence and its effect on toughness.

Validation of fracture toughness degradation as a function of fluence for ferritic welds. Again, this is a question of just irradiating and testing, and you will see that.

This is again the parametric studies on the effect of trace elements, copper nickel. I noticed yesterday the word "phosphorous" never came up, and I was sitting there

itching to ask Odette about phosphorous. I think the answer he would have given is that phosphorous in our -- the effects that phosphorous has on the irradiation embrittlement on our pressure reactor vessels is blended in with copper. It is linked. You cannot separate it. But there are vessels where copper is relatively low, phosphorous is high, and the embrittlement is very large. If you will remember, Reg Guide 199, Revision 1, had an element for phosphorous. You know, you have got the curve at .008 percent phosphorous. If you varied from that, you had to change the curve.

Louvissa-1 is a Russian reactor in Finland. It's a chrome molymetal, different from ours, it is relatively low in copper, but it is high in phosphorous.

The thing is embrittled so fast that the Finns had to downgrade it, the pullout elements. They have dummy elements on the outside, and they had to downgrade it, actually.

So phosphorous is a problem and I think Rev. 2 will talk about it, but in our reactors they are linked.

MR. WARD: There are a lot of other reactors that Louvissa designed throughout the Soviet Union and in other countries. Do you know what is going on there?

MR. VAGINS: No, but the Russians first didn't believe. This problem was identified by the personnel --

MR. WARD: Omatron Voyma Oy. The utility. They

went to them and told the Russians. The Russians said, we don't believe you. Then they came and went through it all, and finally the Russians do. And I think the Russians are doing something about all the reactors. The new reactors, the new Russian ones, are different, I mean the material.. I don't know. They don't confide in me. We don't have any international agreements with the Russians.

MR. SHEWMON: I want to get up near the top of that slide. Part of this business is "Don't tell me what you have done, tell me what you are going to do for me next." In a sense one could say why are you doing anything on those first three. You have answered questions.

MR. VAGINS: Statistical anomaly. You run tests. Is that definitive or is that --

MR. SHEWMON: There has certainly been more than one test on the linear elastic fracture mechanics.

MR. VAGINS: No, sir.

MR. SHEWMON: They may not be what you think. With that attitude, you can go on forever and try to.

MR. VAGINS: We are not. I will lay out the plan. As you saw, the initial plan was to end it by 1988.

MR. SHEWMON: Effectiveness of warm prestress is something people have suspected and have so-so evidence for, and you have gotten better evidence for. How long are you going to work on that?

MR. VAGINS: Till 1988.

MR. SHEWMON: Which happens to be five years -- no, not even five years from now. It's three years.

MR. VAGINS: That's right. Actually, 1987 we finish the answers. 1988 is our phase-down year. It is all laid out in the plans. The effectiveness of warm prestress was argued about, et cetera. We have shown the effectiveness. What we are trying to show now is what is anti-warm prestress. We know that it will work, but when do you mitigate or obviate the effects? When you repressurize, how far up do you have to come? That has never been defined.

As far as applicability of linear elastic fracture mechanics for pressure vessels, before the HSST Program in recent years it was never done on pressure vessels and has never been done for a combined pressure and thermal shock environment. That is the first time ever.

MR. SHEWMON: I didn't say the program hadn't done good things. I am just saying don't tell me what you did yesterday. I asked what is the justification for going on with it.

MR. VAGINS: I am going to get into that. You only had one test. I will admit it is a million dollar test.

MR. SHEWMON: One test done here by us.

MR. VAGINS: One test done by anyone.

MR. SHEWMON: It is on what you consider. Now, the

Navy never worked on it?

MR. VAGINS: No, sir.

MR. SHEWMON: I see. That is one way of defining what happened in the world in the past.

MR. VAGINS: In fact, the Navy now is going to Oak Ridge to repeat some of our thermal shock tests on clad vessels and clad cylinder, but as far as I know -- they may have had a secret program they don't tell me about. No one has ever done this. The Germans have run what they call a pressurized thermal shock test, and the British are --

MR. SHEWMON: I'm talking LEFM. I'm not talking thermal shock.

MR. VAGINS: LEFM, no. I will be very definitive. That is the first test of this nature ever done.

MR. SHEWMON: Of this nature.

MR. VAGINS: Pressure and temperature together.

MR. SHEWMON: Go ahead.

MR. VAGINS: Also, not only of this nature, but where it involves initiation, arrest and reinitation. Prediction tests have never done been done. You have blown up some vessels and done a post-test analysis, but no one has ever run a predictive test.

[Slide]

What we are trying to do is develop methodology which is predictive so that my colleagues in NRR can say this

is what is going to happen and, indeed, it will happen. So what we are going to talk about now is exactly the issue you raised, pressurized thermal shock experiment PTSE1, and why we are going to do PTSE2.

[Slide]

These are some issues still to be finalized in the pressurized thermal shock. Warm prestressing effect on crack initiation, crack propagation from brittle to ductile regions, transient crack stabilization in ductile regions, crack shape changes in bimetallic zones of clad vessels.

[Slide]

The criteria for these series of experiments was the scale must be large enough to provide full-scale restraint on the flaw. Small scale testing, even large specimen testing 8 inches thick in compact form do not provide the triaxial constraint you will see in a real pressure vessel, so we decided to have a real pressure vessel with large enough scale to do this.

Test condtions must have realistic PWR stress fields and gradients, must have realistic fracture toughness in the zone of action, attainable fracture conditions, cleavage initiation with arrest below and/or on the upper shelf. I will get to that and what I mean by that in a little while. Arrest in a high K gradient. In a real pressure vessel, once the crack starts, it goes right up to the roof, goes right

straight up.

Progressive ductile tearing with intervention of instability and restabilization. What happens when the crack gets to the back of the wall, the pressure vessel is hot and the material is still ductile. And then, of course --

MR. SHEWMON: What does full-scale restraint of flaw mean?

MR. VAGINS: Thick section. The whole philosophy of HSST, thick section, 6 inches. So we have triaxial plane strain at the crack tip. Even an AT conpact gives you pseudo plane strain at the crack tip. That is not -- you do not have triaxial stresses.

MR. SHEWMON: This has nothing to do with whether or not you develop a full hinge in a crack in terms of a leak before break or in piping.

MR. VAGINS: No, sir. Piping is fully ductile, fully plastic hinged.

MR. SHEWMON: If it is fully ductile, and one of the things we have out there as part of the question.

MR. VAGINS: Some of the ferritic piping might not get to be fully ductile before it breaks, and that will be discussed by Mike later today.

[Slide]

So we have all those neat things. The pressurized thermal shock experiment utilizes HSST in intermediate

vessels. We recycle our old intermediate vessels. We recycle the heads. What we do is put a new cylinder in here for material. These are the old series of HSST vessels which we started testing in 1969 and 1970.

But the interesting thing about this is that with this setup, we can now independently control the temperature and the pressure. This is not an easy thing to arrive at, by the way. We are talking about extremely high pressures and temperatures.

[Slide]

What we have in this experiment, for those of you not familiar with it -- by now there shouldn't be too many -- you have the intermediate test vessel. You have a crack emplaced on the outside surface. The inside surface is pressurzied. It is ballasted and pressurized separately. We have put this inside a shroud. There is a quarter-inch annulus all the way around that we can pump. We pump a mixture of ethanol and water on the outside.

On the outside of the shroud vessel is a heater. The vessel is heated to 550 degrees Fahrenheit as initial condition. It is pressurized and the temperature controlled independently. So we get any combination of thermal shock and pressure loading.

The placement of the crack on the outside instead of the inside allows us to separate this pressure from

temperature. You can visualize the kind of pumps we have to have. The design pressure of the ITVs are 10,000 psi. In order to get decent flow, you can imagine the kind of pumps you would have to have if you had the crack on the inside. Pump against 10,000 psi at a flow high enough to get the proper thermal conditions.

So this is a compromise, but nevertheless it allows us to do what we have to do, and there isn't that much difference in the behavior. The flaw is very shallow. It is 11 millimeters deep -- that's what we did on the first one -- and a meter long in the test section.

[Slide]

The experiments we are doing, which is only 1 and 2, are unique because we can provide the constraints, we can provide the combined stresses, exactly similar to what you get in a real reactor vessel. We can play games with the pressure and play games with the warm prestress and the anti-warm prestress. As I said, we can maintain plain strain conditions for high crack arrest observations and ductile fracture. We really can simulate to a great extent what is going on, and the geometry is nice and simple and we can apply analysis to this situation. It is just not a "build 'em and bust 'em" experiment. We do nothing without a full pretest analysis and materials characterization. That is one of the hallmarks of the HSST program.

[Slide]

So we had originally planned three PTS experiments. Pressurized Thermal Shock Experiment 1 was to address warm prestressing effectiveness and arrest on ductile shelf with a state of the art material. High toughness. PTSE2 was again to address the arrest phenomena at high values but with low upper shelf material. Something like a 50, 40 foot pound, 50 foot pound weld, and a warm prestress effectiveness and antiwarm prestressing.

PTSE3 was intended to study the influence of stainless steel in finite flaws. That has been deleted from the long-range program for cost purposes. We just don't have the money, and we don't think we are going to get the money. So it has been deleted because we think that it is not a safety issue but a margin issue.

MR. WARD: Explain that, please.

MR. VAGINS: What we have done from the regulatory viewpoint is take the bad effects of cladding and take none of the ameliorating effects. PTSE3 was to study how much of a margin --

MR. WARD: To see if you could credit the cladding in any way.

MR. VAGINS: Right. It's not a safety issue, but it's a levels of conservatism issue. If we had the money, it would be nice to do. It is one of the things the Commission

wants us to do. In the letter to Stockman, as you can see, the Commission says if we don't define levels of conservatism, we are going to end up shutting down plants. Nevertheless, that is the philosophy and that is why the program has been cut.

[Slide]

Again, the question of real dollars. PTSE1 --

MR. WARD: Bill, would you go back again? What was the potential for that?

MR. VAGINS: The potential for funding?

MR. WARD: If you could credit the stainless steel cladding in some way.

MR. VAGINS: If a crack won't initiate, we won't have a PTS problem. If it inhibits the initiation of the crack because of the tough -- if the stainless steel cladding, even though it's a quarter-inch thick -- remember, the flaws we are talking about are the same dimensions, a quarter-inch deep. If they inhibit the crack from initiating, then indeed the PTS issue, the levels of safety go way up.

MR. DILLON: Milt, we have heard a lot about international programs. There is no interest in this in Europe?

MR. VAGINS: Yes, there is. For instance, the people who are doing the most, believe it or not, are again my friends from Voyma, Omatron Voyma Oy. They have in reactors

studies now of specimens. They have some clad specimens. They are working on it. But basically Europe has played this issue down.

For instance, Germany first claimed they had no problems and they only have two plants that are high copper and subject to this problem. One is Stadeg and the other is Obrigheim. What they are doing on cladding, as far as I know, is nothing. The traditional method all around the world has been to ignore the cladding, use it as a safety bump, but that is it. Nobody has been working on it.

MR. SHEWMON: The Obrigheim people reconfigured their core and they will cut the plan down fairly --

MR. VAGINS: So did Stadeg and so did the Finns and whoever else has had problems.

MR. VAGINS: I will give you some idea of the size.

[Slide]

I will buzz on through this real quick. This is the test vessel. This is the size of the intermediate test vessel. It's a little over a meter in diameter. It's about, from the top to the bottom, 2 meters. The test section is about 1.3 meters. This is the size of people. That is the intermediate test vessel.

This is what I am talking about, constraints. Here is what you get from small test specimens, and here is what you get from our vessels, full constraint. It's a real

pressure vessel. So you are not really -- you do have problems with simulating constraint, and of all the people in the world, we are the only ones using real pressure vessels like this.

The Japanese have started an $8 million PTS program. They will be at Oak Ridge on October 3rd and 4th. I am going to see them on the 4th. They are not going to use pressure vessels; they are going to use wide, long specimens.

[Slide]

This pressure vessel is instrumented with 161 sensors for measuring internal pressure-temperature profiles and crack mouth opening displacements at the rate of 10,000 points per second. Here is an example of a typical through-wall spools that we use for the thermocouples. We measure temperature through the wall and around the vessel and our crack mouth opening displacements, measure the cracks.

MR. SHEWMON: What is the distance across one of those nuts on top?

MR. VAGINS: Distance cross one of those nuts? You mean the size of that nut?

MR. SHEWMON: Yes.

MR. VAGINS: This is about .8 meter. Those nuts are pretty big. They are about that size, about 5 inches.

MR. SHEWMON: The .8 meter is the diameter of the width?

MR. VAGINS: Remember the reduced section on the head, so it is a meter diameter in the test section.

MR. SHEWMON: Fine.

MR. VAGINS: These heads are old. They have been reused and reused and reused.

MR. WARD: Milt, yesterday we heard about the acoustic emissions program.

MR. VAGINS: We use it on this also.

MR. WARD: You are?

MR. VAGINS: Yes, sir. On every test we try to put acoustic emission on, for two reasons: to give us data and also to assist Joe when we can. It doesn't always work. The timing isn't right. For instance, people have to come in from Pacific Northwest Laboratories. It costs money, but we put our own acoustic emission on at Oak Ridge. A guy named Knauth does it.

Again, this is not a very good picture.

[Slide]

This shows you size instrumentation. This thing is lowered into the outer shroud.

[Slide]

Just quickly. Not a very good picture. There is a crack that runs right through here. These are crack mouth opening displacement gauges. Now, we do an analysis based upon that. Then we control it based upon what we see. In

other words, we get very good correlation. We know how deep a crack goes based upon the CMOD.

[Slide]

Here is the parametric description of the vessel. Inside radius is 343 meters. The wall thickness for this test was 147.6 millimeters. The flaw length was 1000 millimeters or a meter. The flaw depth was 12.2 millimeters.

MR. SHEWMON: Why did you start out with it so long?

MR. VAGINS: Because we are trying to simplify the analysis.

In PTSE2 and PTSE7, we show that a small flaw will grow long, but it grows every which way. It spreads out because the stress section is uniform in our tests so the crack has no particular bias. It grows and bifurcates and bifurcates and bifurcates. This makes ongoing analysis very difficult. We can predict the initiation, but from there on in, we have got a mess. That may be what happens in a real vessel.

But we are trying to keep this within a limited predictive capability. We want this flaw to go on a certain plane. So we make the flaw long and it jumps into the plane, as you will see.

MR. SHEWMON: If it bifurcates in ceramics, it picks up a good deal more -- it absorbs a good deal more energy.

MR. VAGINS: Yes, sir.

MR. SHEWMON: Does that mean it also absorbs more energy, or would it absorb more in the real world than you are giving it credit for here?

MR. VAGINS: Yes, sir.

MR. SHEWMON: Is it a factor of 2, 4, do you know?

MR. VAGINS: I don't think a factor of 4. The initiation will be the same. The trouble with our pressure vessels is that if it initiates, the driving force is so large that we don't really care what follows thereafter. It will probably penetrate the vessel. What is important is that if it initiated arrest, total arrest, then as the transient goes on, how do we predict the next step? We can do it in our tests because we get these simple flaws, but in a real vessel it probably will take a greater load to initiate it because you have this multifracture surface. Your energy is dissipated, not concentrated. So it is on a level of conservatism if it arrests, but in most scenarios we studied it probably would not.

So this long flaw was to let us do a predictive analysis, let us see what would happen.

[Slide]

The whole thing of this thing is these tests are proof of principle test beds and not demonstrations. They are proof of principle of our mathematical approach to the

problem, our mathematical model.

[Slide]

From our small specimen characterization -- this is quite important. I was talking about small specimens. What we try to do is develop a toughness curve. If you look at all these small specimens, these are 1 and 2 Tlatches. This is 1T. There are some 2Ts in here. According to the test procedures we have, ASTM E399 is the only one that describes testing in this region.

We had one valid point, period. All these other points were invalid by our test criteria. So John Merkle has come up with this called beta 1C correction factor. It comes out of Irwin's work. By manipulating data, he has taken his invalid data and reduced it to this range right here. You can see it overlaps known valid data.

So what we did is try to bound this curve. We said our materials should perform like an exponential, and we tried to fit an exponential lower bound to this material because we have seen in our tests with long flaws we tend to get lower bound performance. So we fit this curve called A. The test was run, and in order to really get a really good fit post-test, we developed this Curve B. We had to shift it over just a little bit. I will show you that in a minute.

[Slide]

So we developed a way of taking small data and

making it look pretty good from the viewpoint of the performance of large vessels, and we did the same thing with the crack arrest data. Here is our crack arrest. Now, this time we fit it through the mean instead of through the lower bound. Crack arrest behaves that way.

[Slide]

Very quickly, this is the material parameters of the material. Basically this was A508, Class C type material, which means it was a forging. The heat treatment was a little bit different, but basically it was A508 forging. What we did was heat treat it in order to get the RT/NDT up to 91 degrees Centigrade to simulate some irradiation damage, but unlike a pressure vessel, the RT/NDT is more or less constant to the wall. In a real pressure vessel, the RT/NDT, of course, would be higher in the inside wall and degrade through the wall. It would be a variation.

[Slide]

This is the planned scenario. The original planned scenario for pressure was this one, this curve right here. This is what we planned and this is what we actually got, and nothing happened. The crack did not initiate. The temperature was -- the sink temperature was minus 30 degrees Centigrade. In other words, we got the full thermal shock but we did not get initiation. We said, my God, what's wrong, are all our theories wrong? When we looked at the pressure, the

pressure was a little off.

I will come back to this slide.

[Slide]

What happened was the following. Actually, everybody was excited, but I knew what happened. What you see here is the KIC toughness curve and the KIA arrest curve as we developed from our small specimens. The abscissa here --

[Slide]

The abscissa is crack tip temperature. What is happening here, we start here at high temperature. The crack tip temperature is falling. Thermal gradient is on it. Thermal stress exists to the pressure stress we are getting by pumping up the inside of the vessel.

Here is the K. The stress intensity of the crack tip of the standing crack is going up as the temperature drops down, and it crosses the KIC line right there. Right there it should have initiated. It didn't. Wny? If you look at that line, it is flat. It crossed it at zero slope and then started to fall, and the wall prestressed.

All right. We repressurized it. We actually went above by about 4, 5 percent, this level, and it didn't initiate. Look at the difference here. Look at the value of the K resistance to the material. The blood vessel warm prestressed and we could not initiate that crack. Inadvertently. We shouldn't have gotten this dip in here. It

should have gone straight up like that, but we had this dip in the pressure system.

MR. SHEWMON: Is B the time you raise the pressure? Is B a completely different experiment?

MR. VAGINS: B is what happened afterwards. We halted the experiment right here, bang. We didn't know what was going on. We didn't want to blow everything apart. We went back and analyzed it. Two weeks later we ran B. Now, we said we have warm prestressed vessel. We had to overcome that warm prestress.

So what we did was go and take this pressure transient. Instead of starting at zero megapascals, we started at 20 megapascals and went up to almost 60 megapascals. This is the ramp of the pressure. The temperature is more or less the same. In other words, the vessel started at 550 on the outside, uniform through the wall. We hit it with this ethanol-water mixture of minus 40 degrees Centigrade, this time really shocked it and brought the temperature down.

What happened this time was, lo and behold:

[Slide]

And we predicted it beforehand. We were a little bit off, and I will explain what happened. This time we are coming up on B. Notice we are above A. The stress intensity is higher. We crossed the KIC line, and bang, it initiated right

at that point. It jumped to here at a little over 200 megapascal square meters and arrested.

The initiation point was over 150 megapascal square meters. It was high, about 175, actually, quite up high in the transition. It arrested. We repressurized, and we should have gotten initiation at that point. But again, it is very close to that line. If that line is slightly off it won't prestress because we stopped it down here. In other words, we went to peak pressure, then came down. We did not get reinitiation. We halted the test again.

MR. SHEWMON: The drop. You actually have some way of measuring the blunting of the crack?

MR. VAGINS: We looked at our CMODs and we didn't see any motion.

MR. SHEWMON: What drops KIC?

MR. VAGINS: Pressure. We dump the pressure at that point. We didn't get initiation, so we said, so far, so good, let's dump it, because we still were quite insecure. Our predictions were there, but nobody has ever run a test like this before. We didn't want to blow a $1.5 million facility up on the first test. Remember the crack is going from the outside into the inside. It is even worse than a crack going from the inside -- it is going into a more steeply rising K field than if it was going the other way.

So what we did again, we stopped it, and then two

weeks later we ran the test again, same thermal gradient but higher pressure this time. We could have done this in one shot. We tried the first time.

[Slide]

Let me explain again. This first time we were supposed to get it to warm prestress here, overcome warm prestress, then make a jump peak. Well, what we did, we warm prestressed it, couldn't overcome it. We overcame it here, and then in order to overcome it again, since it was warm prestressed at this point, we came up here. Notice this is above that, plus, and we went up here.

We got the pressure up to 90 megapascal square meters, and lo and behold:

[Slide]

Instead of one test, we ran three and got the same results. Now, we got this thing to initiate at 250 megapascal square meters, and I will show you what that means with the viewpoint of upper shelf and upper transition. It jumped and arrested at close to 300 megapascal square meters. It arrested right on that line and we started to repressurize then dumped it. It was getting too high.

So instead of one experiment with three steps, we got three experiments and demonstrated the same thing. Again, a little timid. A little timid. Didn't want to blow the facility into kingdom come.

[Slide]

This next one will be a little different, just to give you some examples. These are the three maximum excursions on the first one where nothing happened, and we got at the crack tip temperatures. We had 105 Centigrade. This is crack tip 7857. The KIA was up to 150 to 154, 139. This is the driving force.

The interesting thing here -- this is IB and IC -- the point that should be made very clearly is that the temperatures at the crack tip are exactly what you see in a real vessel when -- in other words, undergoing a PTS. These are not liquid nitrogen temperatures; 104 degrees Centigrade at the crack tip initiated; arrested at 164 degrees Centigrade. And the second test initiated at 125 degrees Centigrade and arrested at 179 degrees Centigrade.

And look at these values. Initiation at 254 megapascals, arrest at 340. Nobody has ever done that, and they certainly haven't done that in a pressure vessel. It answers a lot of questions about what happens in constraint.

[Slide]

This is the type of pretest predictions we make. They are called football curves. These little boxes here are the initiation curve. What you have down here is time. The beginning of the transient. Here is crack depth. We start with crack depth right there. As time goes in, this is the

initiation curve. We proceed along in time until the lines intersect, initiation curve initiates, and these curves are the crack arrest curves. It should arrest there. And time proceeds along and it should have initiated here. This is Test 1B now.

Notice that this spot -- here is the warm prestress line. When it hits that, no initiation will take place. So we are a little off on the materials or some other factor. What you see here are various plastic instability curves. This is so-called -- this dotted line says the temperature is at its upper shelf temperature at that point. In other words, as time goes on, everything above this is an upper shelf temperature.

[Slide]

This is for 1C. This was the prediction and the actual test, predicted initiated, arrested. Now, as you notice, the initiation curve is below. It should never initiate again, and it didn't during the test.

[Slide]

So our results were well predicted and the initiation-arrest events were extremely well predicted. Here are initiation events, here are arrest events. Here is the KIA and KIC lines derived from small specimen data. This line here theoretically is the onset of ductile thresholds, 100 percent shear on the Charpys. You can see our arrest is well

to the right of that point, and from this point on -- this was almost pure cleavage. This was mixed mode, but still predominantly cleavage, fracture surface.

[Slide]

Now, one of the things was to compare this to the Code. If we did a Code analysis, we would have to use this curve. These are the curves for the Code. Here is our actual results in our curves. This shows the level of conservatism in the Code. Now notice, if this thing -- this whole area here says the vessel failed. Our PTS scenario says we can't demonstrate arrest before KI reaches that point, 220 megapascal square meters. The vessel failed. But look what we got here, arrest at 300 megapascals.

MR. SHEWMON: The lateral shift horizontally is no comparison to the Code. It is what happens at about 200.

MR. VAGINS: They are both comparisons to the Code.

MR. SHEWMON: Why does the Code talk about one temperature dependence curve? It would seem to me the whole point of 199 is that that thing can shift.

MR. VAGINS: It does. I'm sorry. We converted this to parameters of the test. This should be T minus RT/NDT, this abscissa. We shifted this to put in the parameters of the test rather than the nondimensionalized parameters, so that -- if you took the T minus RT/NDT, put the actual values in, did it by Code, you would use that curve. If you did it

the way we did it --

MR. SHEWMON: The Code establishes it from the Charpy data?

MR. VAGINS: The Code has a general value. It's the lower bound value of raw material we have ever done. Only the shift is developed from Charpy data.

MR. SHEWMON: So the Charpy data establishes some temperature on that Code KIA curve.

MR. VAGINS: There are no Charpy values in this curve at all. No Charpy values have anything to do with the KIC and KIA.

MR. SHEWMON: Some way of fixing the temperature on that dashed line, because you can shift that dashed line up and down any temperature you want.

MR. VAGINS: Yes, sir. The temperature is fixed. Let me get this curve in here.

[Slide]

Here is the KIR line from the curve. This is Section 3. The abcissa is T minus RT/NDT. The RT/NDT, the material is established in one of two ways, either with a drop weight tear test or, in lieu of that -- you run a drop weight tear test, and then for nuclear vessels you have to run three Charpys. You have to group three Charpys at 50 foot bounds. If you can do that, then the RT/NDT is a drop weight. If it, it is a Charpy dominated. Most of our RT/NDT values in the field are

Charpy dominated, which we think is high, if that is what you mean.

MR. SHEWMON: That's what I'm trying to get at.

MR. VAGINS: That is what that curve is. What we did is take that in terms of our material and convert it back to temperature for that previous slide.

MR. SHEWMON: The conservatism, then, is given that procedure, what it would be.

MR. VAGINS: Yes, sir. The conservatism is a difference --

MR. SHEWMON: So for that steel --

MR. VAGINS: We are saying we have got about a 50 degree conservatism in the Code.

MR. SHEWMON: In this case it is Centigrade degrees you are talking about.

MR. VAGINS: Yes, sir. The difference between here and here.

[Slide.]

This was determined by charpy, right where we put that curve was determined by charpy, because it could group three charpies at 50 footpounds. I am mixing apples and oranges. Footpounds and megapascals.

[Slide.]

Very quickly, this is the way the surface looked in the crack. Here was the outside surface, here is the initial

flaw. A lot of material was chopped off.

Here is the original flaw, which is 12.2 millimeters. The first jump was down to here. Notice it's fairly uniform, left a couple of islands of unbroken ligaments.

The second jump went down to here. The difference in color was just we want to call it effective heat temperature or corrosion.

Remember, we ran a test. This was the original flaw. We put the fluid on it. Nothing happened. We waited two weeks. We ran this test. There was fluid on this surface at high temperatures, and then we ran here.

So the difference in surface color is basically the corrosion, but also this flaw here, this crack jump, is mixed mode, but still cleavage, this is almost predominantly cleavage here.

The thing to notice is the relatively straight front, and in the third jump where we get more mixed mode, we get a lot of unbroken ligaments remaining.

But, nevertheless, the crack just went straight down and stopped dead where it's supposed to.

[Slide.]

PTSE-1 accomplishments:

Demonstrated Section III and Section XI flaw evaluations to be conservative.

Demonstrated effectiveness of warm prestress effect.

Demonstrated accuracy of developed methodology and computer codes.

Demonstrated reality of crack arrest in a steeply rising K field. You saw the K field going up and it still arrested, steeply rising.

Demonstrated applicability of LEFM for thick sections, high in the transition zone.

One of my colleagues critized this several years ago, saying we could not use LEFM because by the time the crack penetrated one third of the way in the wall, we'd be in ductile material and we had to use elastic plastic fracture mechanics. I said that was wrong, and I think I have been shown to be correct. LEFM is totally correct.

What this shows is that you could use LEFM up to the point the crack arrests. Then what you do is the temperature is high, you do a static ductile fracture analysis, as we did in A-11, lower upper shelf toughness approach. We have the elastic-plastic procedures, we can do it. So it's two ways of looking at it now.

If you initiate a crack in a frangible zone, if the crack initiates a cleavage, it will run and stain cleavage until it arrests. Once it arrests, it will then -- you may go to ductile fracture. This will be shown further on the wide plate tests I have to show you.

MR. SHEWMON: You have taken about half of your time now. Have you covered about half your materials?

MR. VAGINS: Yes. The rest is -- this is most important. I wanted to cover it.

MR. SHEWMON: While you are there on that first point up there about the conservatism, I was looking at Reg Guide 1.99 and not finding it very well. Maybe I am looking at the wrong place. The old end of the way you'd get a reference NDT of some sort of shift down from whatever is the best line for the charpy vs. temperature,' or whatever you want to use as an indication of toughness, is 50 degrees what they aim for, for that?

MR. VAGINS: I'm sorry --

MR. SHEWMON: If you had a charpy curve, if you had a good charpy curve -- sorry. If I was a regulatory and I had a bunch of charpy data and I then wanted to set up a procedure for how I would have people determine a reference curve, I would take the mean for that and the scatter and probably put 2 sigma down below that and say, "This is what you will use for a reference temperature, given this data. I want to be sure I'm on the conservative side."

What you have shown for your point is 50 degrees C in that shift. Is that about what people put in for the 2 sigma values?

MR. VAGINS: The code doesn't tell you to do it that

way. There is a very specific procedure. The specific procedure outlined in Section III is that -- again, as I said before, you run a drop weight test and establish the NDT as the Navy does it.

Then you run a charpy test and you've got to clump three charpies at 50 footpounds. It's those -- or within 60 degrees Fahrenheit of the NDT. Then the RT/NDT -- then the NDT is the RT/NDT. If not, you keep running the test until you get 3 charpies at 50 footpounds, and then you have to add -- that will be the RT/NDT, you add 60 degrees to it. In other words, 60 degrees to the NDT. You keep going up. It's very conservative. And you use basically an eyeball value, you do not use a mean value.

MR. SHEWMON: And that 60 is C or F?

MR. VAGINS: F.

MR. SHEWMON: What you found is C --

MR. VAGINS: All I showed was that in terms -- if you do it that way, you're still not quite sure -- okay. Remember, the drop weight tear test, charpy tests, are not fracture tests. What we are trying to do is determine what a fracture curve looks like in relation to these ways of setting it.

We arbitrarily --

MR. SHEWMON: Those other ways do predict the curves out of the code. You get --

MR. VAGINS: Let me go again. The toughness curve was established by this so-called million dollar curve run by HSST in the late '60s, early '70s. We ran big specimens, all sorts of specimens, got the fracture toughness at various temperatures for all sorts of nuclear grade materials, drew the K-1R line -- the K-1R line is a lower bound curve which bounded that curve. All the data --

[Slide.]

The curve was not established with charpies, with nothing, had nothing to do with it. That's the thing about the RT/NTD. This curve, the K-1R curve, was established as a lower bound curve to all the data we had available in the early '70s, and that included crack arrest and it included rapid initiation, and slow test. This is the K-1R curve.

All right. The RT/NTD was then established as our shifting parameter, came out of 'he Navy work. In order to normalize this, make this for any material we normalized RT/NDT, and the RT/NDT was established the way I just described, your drop weight and charpies.

Remember, all early nuclear vessels had no drop weights, and their charpies were keyholes. We were lucky to get a 30 footpound charpy value out of our early vessels. That's all the data we had. So there's a degree of uncertainty in what RT/NDT is for some of our early vessels, except we go to archives materials and try to get it that way.

MR. SHEWMON: Onward.

MR. VAGINS: Okay.

[Slide.]

We demonstrated a whole bunch of things.

I'm just skipping a few of these things. Let me just get into this.

[Slide.]

This is one I showed last year also. What is the impact of this on NRC regulatory positions. This was a confirmatory test, after all. We had already set our PTS criteria before we ran this test. That's always the case. It takes a long time to run big tests, and we have to make judgments ahead of time.

The analysis techniques used to established the fracture mechanics portion of the PTS position are accurate and slightly conservative. If the loading and material toughness properties are known to big criteria -- in other words, the analysis is right, tell me what my materials and tell me what the load is -- all right, if the loading and materials toughness properties are known, then an accurate evaluation of the structural integrity of the reactor vessel can be predicted. Important.

Warm prestressing is a real factor.

In all the scenarios we analyzed in trying to establish the PTS screening criteria, which is about 14 real

scenarios, in 95 percent of them, warm prestressing would have intervened. In other words, it did intervene. Analytically, in warm prestress the crack would not have initiated.

In our probabilistic approach to the support of the PTS scenario, we ignored warm prestress totally. It was not used as a distributed parameter. It was ignored.

Well, if we treated warm prestresses as a distributed parameter, the screening criteria then really should be an order of magnitude lower. Not the screening criteria, our level of confidence, probability of failure should be an order of magnitude lower than we actually got.

In other words, we ignored one out of 10 events, we ignored nine out of 10 events. The whole order of magnitude of things which would inhibit a cracking of the vessel was ignored.

So, therefore, the PRA that we did to back up our screening criteria said that the probability of vessel failure was something like 10 to the minus 6.

MR. SHEWMON: If you were going to try to translate that into a shift in temperature, what would it be?

MR. VAGINS: One order of magnitude is 60 degrees. Again, we keep coming back to 50 degrees.

MR. SHEWMON: F or C?

MR. VAGINS: In this case it would be C. RT/NDT.

MR. SHEWMON: That's 275 and 300 were also in C?

MR. VAGINS: No, those were F.

MR. SHEWMON: Those were F.

MR. VAGINS: Let's put everything in terms of F, then. Let's say order of magnitude at 60 degrees F.

MR. SHEWMON: 50 converts to 90.

MR. VAGINS: I don't think I was right. I think it was more like 50, 60 degrees F. I'm trying to remember now. I had it all written down somewhere.

MR. WARD: You were about to say the probability of vessel failure was --

MR. VAGINS: Would be 10 to the minus 7th instead of 10 to the minus 6th.

MR. WARD: That's based on confirmatory research?

MR. VAGINS: The fact that out of the real transients, we had 14 real transients around the world, Hecher Wesheim, Rancho Seco, H. P. Robinson, all these, Crystal River, we had these transients, and we analyzed them. In 95 percent of the cases, or about 12 of them, 13, warm prestressing intervened and we ignored it.

MR. WARD: What are you going to do with this new information?

MR. VAGINS: Nothing. I'm just presenting this as hoping -- making everybody feel better. This is defining our levels of conservatism. The regulatory position is that everything done so far is good and conservative, we are good

boys, we wear white hats and the test speaks for itself.

[Slide.]

But there are still some unresolved ' s. We only had these few data points. Unfortunately they are very expensive, so we can't run too many of them. But we would like to know what happens to low upper shelf. Low upper shelf material was addressed in unresolved safety issue 11, but that only addressed it as -- from the viewpoint of tearing on the upper shelf. It never was totally approached -- totality from a total viewpoint, and the biggest test of this upper shelf here will be here in this PTS scenario where you initiate on lower shelf and you drive the crack into the upper shelf. What will happen then?

We know we get high arrest in our standard material. This A-508, it gives you an example of the energies involved. This A508, Class C material had an upper shelf value, charpy upper shelf value of 80 footpounds, not terribly high. We're still getting arrest at 350 megapascal square meters.

So this is part of Etherington's concern, what toughness curve do we use for initiation and what happens at arrest. And this will be done now because we have got some slippage in deliveries at the end of April, beginning of May 1986. That's PTS, the experiments.

Are there any questions?

I covered a lot in that very short time. Some of it you've heard before, some of it is new -- wait a minute. I wanted to show you one other thing here. What is PTSE-1 going to look like? See what we have planned.

[Slide.]

Here is our first schematic plan for PTSE-2. Same procedure. Once we establish our toughness curves, which shouldn't be too much different, we are going to come up, we are going to get a very decided warm prestress, we are going to come up and try to overcome warm prestresses called anti-warm prestresses. Initiation can take place anywhere along here. We think it's going to take place pretty high.

Then we're going to get a tremendous jump and arrested high values.

MR. SHEWMON: How do you determine the magnitude of that jump?

MR. VAGINS: It's a guess, literally. The jump theoretically can occur any place in a rising K field. We already know we have never been able to get an initiation below this point. In other words, we went to a maximum K. We have never been able to get initiation. So what we are going to do is go above it, see how high above it we have to go, this time very carefully control the pressure and see if we can do it the first shot, do it once.

MR. SHEWMON: You're not going to chicken out?

MR. VAGINS: No, sir. In fact, if we blow the facility up, who cares? They cancelled my PTSE-3, so we're going to put the metal to the pedal, or the pedal to the metal, or something like that, and go.

MR. WARD: Just like LOFT.

MR. VAGINS: Yes, except the entire HSFT program history cost since 1967 was not equivalent to one year of maintenance of LOFT, let alone experimentation.

MR. SHEWMON: Much less taping it down.

MR. VAGINS: Do I sound a little bitter? I wonder why.

MR. SHEWMON: When are you going to return to what was Harold Etherington's concern of the low upper shelf?

MR. VAGINS: I was going to talk a little bit more about it.

MR. SHEWMON: If that's about it, let's talk about it a little bit more.

MR. VAGINS: That's out of schedule, but that's fine.

MR. SHEWMON: If you are going to return to it again later --

MR. VAGINS: I can clarify it now. It's really simple. Etherington has a real concern and we are concerned. There is no data. Believe it or not, in all our tests that we have done and everything else that we have done, we never

tested low upper shelf materials in the transition, tested on a lower shelf and on the upper shelf. We have never tested it in the transition.

MR. SHEWMON: Where does that transition come back into regulatory decisions?

MR. VAGINS: It's the K-1C curve and the K-1R curve. I am not concerned about the K-1R curve which we use for normal -- you heard Dr. Randall speaking yesterday about setting PT limits in the normal operation. The K-1R curve is fine, even for low upper shelf. That's really crack arrest curve. It's so far to the right of the K-1C curve. The only concern we now have is whether we are really conservative for low upper shelf material initiation for PTS, pressurized thermal shock, because we always get some ductile tearing.

Etherington is correct, we always get some ductile tearing before we get the onset of cleavage. If this low upper shelf material gives us early tearing, we may get early conversion of cleavage instability and that curve, the K-1C curve that we use now, may be slightly unconservative as we go up in the transients. That's one factor.

The other factor is that for PTS, the flaws are so small and fairly rapid in onset, that the initiation generally occurred about 100 ksi square inches or 120 megapascal square meters. So we don't think it's going to have any significant impact on the screening limit. It is an area of concern. We

have no significant experimental data.

Traditionally people worried about the upper shelf, worried about ductile tearing, and how do you analyze this. To me, Appendix G --

MR. SHEWMON: Let's go back to what Reg Guide 1.99 is used for, to see if I can understand what is going on. That is used to set limits on when somebody can pressurize the vessel, and you feel that those temperatures are high enough that you don't have concern on that, or conservative is greater than that in some other way?

MR. VAGINS: Yes, sir, because what they use is the K-1R curve, not the K-1C curve. The K-1R curve is a crack arrest curve, rapid loading, crack arrest. Believe it or not, that was put in for levels of conservatism.

Also the PT analysis uses a safety factor of 2 on pressure.

When you do that analysis, you have large safety factors and when you use a curve that is based upon rapid loading of crack arrest, in neither condition do you have a normal operating condition.

So for setting the pressure temperature start-up limit curves is perfectly adequate and quite conservative. But in the pressurized thermal shock scenario, we used K-1C, not K-1R, slow initiation curve which is less conservative than the K-1R.

[Slide.]

Let me give you an example. In relationship this would be the K-1R and this is the K-1C. The K-1R is at higher temperatures than the K-1C --

MR. SHEWMON: You use the K-1R in setting the pressure limits on start-up? The K-1R as a conservative substitute for K-1C?

MR. VAGINS: Yes, sir, for initiation. In reality, what you will have is slow initiation, but K-1R will be conservative.

So, therefore, what I'm really saying is we don't have a lot of data to substantiate anything. We will have some this coming year. I'm getting some low upper shelf carbon moly material, not reactor vessel material, about 40 footpounds or about 60 joules, and we are going to be using that in a wide plate test in our pressurized thermal shock experiment.

Later on we will be testing some welds which were low upper shelf. Right now we have really no material worldwide. Nobody has tested this stuff, for some reason. Trino has low upper shelf, the Italian reactor, they're worried about ductile tearing, but nobody has really conducted a significant K-1C --

MR. SHEWMON: Yankee Rowe is the same material.

MR. VAGINS: Yankee Rowe is the same material by the

same vendor in a transverse direction. We are taking the worst direction.

My general answer to Etherington, it's a real concern, we are aware of it, it does not affect normal operation. It may affect some of the conservatism we have built into our screening criteria for low upper shelf materials and that is to be determined.

MR. WARD: That's to be determined where?

MR. VAGINS: PTSE-2 and some material characterization I will do next year, if I get some money. I hate to keep crying money, but my tests cost money.

MR. SHEWMON: He's down to a fast million.

MR. VAGINS: You think that's funny. Well, a test costs a million dollars to run, and a million and a half dollars to build a facility --

MR. SHEWMON: I was thinking about the effect of inflation, when you talked about the million dollar curve. It doesn't sound as impressive now as it did 20 years ago.

MR. VAGINS: That's absolutely right.

My fifth irradiation is a $6 million program, and you will see that in a while. I am off schedule here. Where am I up to?

MR. SHEWMON: You've covered PTS, wide plate arrest --

MR. VAGINS: Unirradiated crack arrest. This is

kind of interesting. I'll try to zoom through this.

This is effectively crack arrest.

[Slide.]

This is the unirradiated crack arrest studies, including wide plate test series.

MR. SHEWMON: Some time in the next 20 minutes I'd like to have a 10-minute break.

MR. VAGINS: Now is a good time. Then I'll zoom through this.

[Recess.]

MR. VAGINS: Let me proceed. I'm talking about crack arrest methods now. This is unirradiated. I'll try to get through this fairly quickly.

The objective of crack arrest is to provide data.

[Slide.]

As you can see, crack arrest is a fairly important concept where a crack will stop running, even though it's still being driven. It's the property of the material, and it's one of the hardest things to do.

What we have done in the past, up to now, we have developed a whole concept to obtain reference data for ASME boiler pressure vessel code. It's the HSST data which forms the K-1R curve, K-1C curve, K-1A curve, both Section III and Section XI.

We developed data in support of the HSST program and

we actively participated in the formulation of ASTM standards which will be used to develop data and code support.

[Slide.]

Our current goals on the HSST program is to coordinate and participate in ASTM round-robin testing to develop worldwide ability to get the same data.

We developed specimens. We developed a modified specimen and you will see that soon. We designed plate tests, and we are now working in the area of viscoplasticity to understand the mechanics of crack arrest, and we believe once we understand the mechanics of crack arrest, we understand fracture.

[Slide.]

Right now you have to understand, you have to realize that fracture is still done in terms of far field parameters. We ignore what's really happening at the fracture zone.

[Slide.]

This stands for itself, why we have to understand fracture arrest. As you see, it plays an important part in the pressure vessel integrity, it can stop a running crack, and then we have to know if the crack will arrest at the pressure vessel, how deep it will arrest, and what is its sequence in ductile tearing.

In other words, the arrest of a running crack from

the frangible zone establishes the boundary conditions for the initial conditions for ductile tearing for the rest of the vessel.

[Slide.]

Crack arrest occurs when the driving force, K-1, reaches critical value, and that value, K-1A, is a function of the temperature of the material. It changes the ability to arrest a crack, changes as the temperature of the material changes. We are really talking about a linear fracture behavior, it's a cleavage behavior. Crack arrest is not a defined term in ductile tearing. Ductile tearing is a forced tearing. It will stop when you stop forcing it at a certain value.

Cleavage instability is quite different. Crack will initiate and jump and arrest when it hits a certain value in the cleavage domain.

The crack arrest toughness shifts with irradiation. In other words, it becomes more difficult to establish crack arrest as you irradiate the materials, the same as crack initiation. They both shift to the right and higher temperature.

[Slide.]

The present -- the K-1A is the crack arrest stress intensity. Data do not exist at the present time to high enough values to adequately describe failures in our scenario

in PTS. What we have got is about -- almost all our data is dumped down here in the transition.

As you notice, we were concerned about what happens when you drive the crack and you get stress intensities way up here. As you see in the PTSE-1, we have done that. Indeed, we have got an arrest on this line extended above the so-called upper shelf cut-off.

[Slide.]

Present day testing. The standard we are looking at to establish through ASTM is based upon so-called CCA, compact crack arrest specimen, basically developed by a man called Ripling, and it is really nothing more or less than a flat plate with a hole in it here and a wedge which drives down through, splits it apart, the crack jumps and halts somewhere in the material.

This material is at one temperature because it is wedge driven. The crack extends in a falling K field. In other words, the K is highest when the crack goes in, because we have a displacement governed condition. You open up the mouth until it cracks and the time necessary for the crack to jump the wedge is stationary, so you have a displacement governed condition. The K is falling, it arrests somewhere in the material. That gives us values again only down here.

[Slide.]

Only down here in the lower transition. In other

words, we start a crack, it runs, it arrests down here. It is very difficult to achieve a rising K field outside of doing pressure vessel studies.

[Slide.]

Current small crack arrest specimens yield data, as I pointed out. Here is a sampling of our data down here. Most of the valid data lies about 100 -- at about 150 megapascal square meters or less.

By the way, that is still not a standard test. What we are trying to do is establish an international standard through ASTM.

[Slide.]

MR. SHEWMON: Is K-1A used in the code any place?

MR. VAGINS: Yes, sir. Section 11.

MR. SHEWMON: For what? For this kind of evaluation? Flaw evaluation? How do you evaluate a flaw in Section XI which deals with NDE and flaw evaluation? It's the only place it's used.

Why aren't they primarily understood and what initiates it?

MR. VAGINS: We also use that K-1C and K-1A up here in Section XI. K-1R up here is in Section III.

MR. SHEWMON: That still doesn't answer the question of why the code is concerned about the arrest of a curve. I would think the initiation would be their primary concern.

MR. VAGINS: It does give you an option for arrest. It does tell you how to calculate for arrest. There are some errors in it. I don't like the way they treat the flaws. It's being changed, it's in the process of change. But they tell you if you have a flaw, you detect the flaw with NDE, you have to carry out a full flaw evaluation. You have to say what the flaw will be at the end of life, what the load will be, maximum transients you expect, what it will initiate at, and will it arrest.

Even if it doesn't arrest, then the vessel fails.

In other words, it deals -- Section XI will allow a flaw to initiate.

MR. SHEWMON: Most people would try to say that it wouldn't initiate, but if it does initiate, they can go beyond that and say what it arrests.

MR. VAGINS: Right. And that is a safety issue. Nobody wants a flaw to initiate because that is a catastrophic financial issue. The vessel is sitting there cracked. What do you do with it? You can't repair it well. You can't repair it at all.

MR. SERPAN: The arrest is in Section XI, which is a flaw evaluation section. In Section III, they don't talk about arrest. It's the design, that's sort of the difference.

MR. VAGINS: Section III, you are not allowed to have a flaw, period.

All right. Now what we are doing in all our experiments in these big cylinders and pressurized thermal shock experiments are getting very high values and extending this data up and we are getting more on this wide plate testing, which I will go into in just a moment.

[Slide.]

The wide plate crack arrest tests are being performed to provide K-1A data above the ASME upper limit criteria for prototypical light water reactor pressure vessel steel, provide data from which dynamic fracture models can be verified or developed, and evaluate approaches for dynamic measurements.

In other words, the analysis we have been doing is so-called quasi-static. It is just based upon the initiation, the initial conditions and the end condition. In some conditions we might have dynamic effects and we have to have a full dynamic analysis. Where the inertia of the system is considered and weight propagation is considered. And we cannot run an effective static test until we show that indeed the dynamic effects are second or third order.

[Slide.]

And we have shown that so far for our pressure vessel study. At least for cracks in the beltline away from reflecting surfaces like nozzles, et cetera.

What we are running now in a cooperative program

with NBS is a wide plate crack arrest test. What this is is a wide plate which is almost 10 meters, 30 feet between pins. It is a meter -- a section is a meter wide, and the thicknesses are presently four inches. We are going to six inches thick. 100 millimeters, 150 millimeters thick.

The test section is welded in here. The test section itself is a material, a meter by a meter, and full thickness, four or six inches. The side groove crack is put into one side. We cooled one surface, we heat the other surface to establish a temperature gradient through the material and therefore establish a toughness gradient.

We stretch this material, we stretch the specimen, and the specimen, being this long (indicating), is very compliant.

In other words, if a crack initiates, the wave emanating from the crack tip, the elastic unloading wave, takes -- moving up at the sonic velocities in steel, takes enough time to go up to the top and reflect back, that the entire crack initiation propagation and arrest event is over.

So we eliminate dynamic effect totally. At least most of the dynamic effects.

[Slide.]

Just a picture of it. This is the wide plate test section. This is, as I said, four inches thick. This is a meter by a meter. There are two specimens in here. We

machine a groove which is about .2 of a meter here, and then we put a crack in there, using the hydrogen charging method developed at Oak Ridge.

We put a brittle weld charging with sulfuric acid until it cracks. We have a very sharp crack in the edge of this tip.

MR. SHEWMON: Who is the PI out there? Principal investigator?

MR. VAGINS: Dr. Richard Fields.

Also Roland DeWitt.

Those two scientists are working as the principal investigators out there.

MR. SHEWMON: Is DeWitt full time at NBS?

MR. VAGINS: Yes, sir.

MR. SHEWMON: He's from Texas, isn't he?

MR. VAGINS: Roland DeWitt has been there as long as I can remember. There may be another DeWitt.

[Slide.]

The plate is highly instrumented. This is a side groove to make sure the crack runs are not surface. We have 30 some odd strain gauges along here. We have thermocouples. This is a weld to the pool plates. You can see the size as the gentleman is standing here. So this is meter by meter welded into groups.

[Slide.]

Just to give you an effect of the size, there is the machine. These are people down here. That is again roughly 10 meters. This is in the 6 million pound machine at NBS. We are going to run 18 such tests. We have run four already.

[Slide.]

Here is another picture of it. What happened, here is a pin, here is a pin, this is the test section, and here we have insulation all the way around it. We have heating straps on the back, and we have liquid nitrogen cooling channel in the front edge. We can get a transient, for instance. The front edge will be at minus 110 degrees Centigrade. The back edge will be 250 degrees Centigrade. So we have a gradient across this thing of about 400 degrees Centigrade.

This gives us a fracture toughness difference. We initiate the crack in the cold, it's frangible, it drives way up and it arrests or it doesn't arrest.

[Slide.]

What we have shown is that it will always arrest if we have -- careful of those words, now. If indeed we have a situation where the back path is in a fully ductile domain -- in other words, the temperatures are high enough, the crack will always arrest. It may not be stably arrested, but it will arrest.

For instance, WP-1.1, the first test, we ran the test, we had trouble getting it to intiate. The test ran over

4 million pounds tension. The crack ran and this is again in a normalized scale, the crack ran, it arrested at that point, arrested about halfway through the plate at about 350 megapasacal square meters. This is a static analysis, and then promptly tore apart. The plate -- the arrest was about 900 microseconds.

MR. SHEWMON: That's a long time.

MR. VAGINS: Long time. What happened was the crack started at 900 meters per second, it slowed down as it came to the arrest point, it stopped dead for 900 microseconds, and then tore apart. Visually it looked like one big bang.

MR. SHEWMON: Is that milli or micro?

MR. VAGINS: Micro, less than a millisecond. It stood there while the plastic field formed and then it tore by void coalescence and ductile tearing. Until that time it was pure cleavage. So it went up, bang, stopped, the plastic field was able to form, it tore apart, all within 900 microseconds.

And what we have shown is that a running crack starting in a cleavage dominated domain cannot convert to ductile factor domain until it stops dead. There must be time for a plastic field to form in front of the crack, or else you cannot get void coalescence, which is a dominant tearing mechanism.

So what happens, as you drive it with higher and

higher energy, you're going to keep going up on this curve. How high up, I don't know. But you will always get an arrest on what looks like this curve extended. It is not stable arrest, but it is arrest, and then you have to go back and do a quasi-static ductile tearing, so you can divide in our pressure vessels cleavage from ductile. By this phenomenon, you can do a fully accurate linear elastic-mechanic analysis to the point of arrest. If you see arrest at that point, taking the depth of the crack at arrest, you do a ductile fracture analysis to see if the vessel stayed together, and it is perfectly correct, and we have the means to do both now.

So that answers a big question we have.

[Slide.]

The large specimen data is giving us -- we are getting data way above here. Notice, this is the limit Section XI and the PTS rule says if we can't show crack arrest at this point, the vessel fails.

So now we are looking at quite a bit of conservatism in most of our materials. Again, I will say nothing about low upper shelf materials until next year.

[Slide.]

Now other people have done this wide plate test, but done it a little differently than we have. If you now look at all the data we have been developing, it shows a consistent trend when put into this normalizing T minus RT/NDT value.

This is Japanese material, or thermal shock experiment 455A6 PTSE-1 Japanese data, quench thermal shock experience, and flawwide plate test.

Here are the results. As you can see, it runs consistently. It is consistently above the K-1A line, except for the three French data, which are right on the K-1A.

Now whenever we get results from foreign sources like the French or the Italians, we are a little concerned about whether they calculated or measured the RT/NDT correctly. That is an important parameter. Our results are all consistent. We do it the way we do it for code analysis, and if you look at that stuff, it is very consistent, indeed.

Now we try to explain this curve, this phenomena, and that's why we are doing a viscoplasticity study. We are looking at rate effects, how long it takes a plastic field to form, what is the phenomena of fracture itself. This is the way we measure. We have these strain gauges along the crack path.

[Slide.]

If you look at this, you will see how the crack progresses. A crack starts here, and the minute it goes past the strain gauge, it stops. The strain gauge drops and if you look at this, you can see the progression until you get arrest, and then ductile tearing. The abscissa -- this is in time, this is in strain, the ordinance is in strain. If you

look at the time, that's milliseconds. So we are looking -- the abscissa is in milliseconds, thousandths of a second, and this is the way we measure the velocity of the crack and the crack propagation.

[Slide.]

This is the blow-up of the strain gauge, what happens as the crack comes along. You're sitting over here at nominal elastic strain in the section. As the crack approaches, you start picking up a tremendous amount of strain at the crack tip. And when the crack tip passes the gauge there, these are several gauges, all normalized. The strain drops and you can really identify the position of that crack.

Also you get a full strain history in the plate, which we can then put back into a so-called generation phase in our computer codes and out comes material data.

Later on we put the material data in the application phase, and out comes the velocity of the crack and its position.

[Slide.]

This is some more types of analysis. Here is the analysis of the actual strain gauge. Here is a comparison of the actual strain gauge output at several points compared to a pretest analysis, post-test analysis from a computer, what the computer says it should be. It gives you a dynamic analysis and we get pretty good agreement.

[Slide.]

Basically we are really extending the understanding of crack arrest. We are getting much more data. We are developing data in high toughness regions. We are really beginning to understand this whole concept of viscoplasticity.

Just to give you an example, this is a long plate, a wide plate test. I am just going to show you a little bit.

Here is a test section that's being cooled.

[Film being shown.]

Watch what happens. This is very interesting. It is being pulled on. Bang. This will repeat in a minute.

Remember, we are cooling this side, this liquid hydrogen, and we are heating this side. Watch what happens. Pulling on it, pulling on it. Do you see that? Did you hear a bang? Then you saw it suddenly tear.

Once more. Bang. Some movement and then a tear.

[End of film.]

MR. SHEWMON: The difference is how long it takes for the elastic wave to go up and come back?

MR. VAGINS: Actually in this case, no. In this case we got arrest, we got some bouncing back and forth. It only takes 10 milliseconds for the wave to go up and come back. As you notice for the arrest, for the initial arrest, that is more than enough time. The initial arrest occurred in a few milliseconds. But here we got some stress for sections

back and forth.

What happened, the first bang, it jumped in and arrested, and then it slowly tore apart and stopped. It tore -- it didn't tear completely apart. It arrested -- the whole test ran in a puff. There was about three inches left we had to tear apart. There we had a classic example of cleavage, arrest, conditions necessary for ductile fracture curves, and it tore, ductile. Very important factor there, that you cannot get ductile fracture in a running crack originating in the cleavage domain.

I wanted to show you a fracture surface. There is just one picture and that is the end of it.

[Slide.]

This is typically what you see. This is wide plate test two, what you had here. This one was so high, it did not -- there was no apparent arrest until you looked at the strain gauges. We got a cleavage, here is initiation point, cleavage, jumped in. You had micro arrests, reinitiation, arrest and then tearing. All this light point is cleavage, all this dark area is ductile fracture. That is a typical performance. We keep seeing it over and over again.

And this is important.

[Slide.]

This is one of the tests we have had. This is 1.3. This was this test. What we got was this was the crack arrest

point right here. You got cleavage tearing to this point. Then we got a little bit of ductile tearing, a pop in, then a reinitiation. This is cleavage and that is ductile. Clear as a bell. You just cannot pass that point without arrest. You cannot have a crack proceeding in a cleavage mode, convert to ductile fracture while it is running.

People have been talking about a crack will slow down, change, it will slow down, stop. The conditions for ductile fracture occurs, then it will tear. It is a very important factor from this point of our analysis capabilities.

That's all I have on the wide plate test.

Are there any questions about the crack arrest, unirradiated crack arrest testing and what we are trying to accomplish and what we have accomplished?

MR. SHEWMON: We have got effective cladding K-1C verification irradiated crack arrest here.

MR. VAGINS: Right. The unirradiated crack arrest you have just seen. Now let's talk about cladding a little bit. I think that is next.

[Slide.]

Separate effects, pressure vessel cladding studies.

The reason why we call it separate effects is because we are not going to run our big test on pressure vessels, therefore we are running small specimen tests traditionally called separate effects.

The objective is to assess the effect of stainless steel cladding on initiation fracture of base metals, ductile cladding vs. brittle base metal, metal residual and thermal stresses.

The approach will be -- we have two labs working on this now, fracture tests on surface flawed panels being done by MEA, clad vs. unclad behavior, irradiated vs. unirradiated behavior, evaluated residual and differential thermal expansion stresses, relate the clad specimens to vessel performance via ORNL analysis capability.

In other words, what we are looking for is data to put into our analysis to tell us what -- if cladding indeed does us any good.

[Slide.]

Data for use in assessing the role of cladding in mitigating crack initiation. Initiation due to PTS. This is what MEA is doing, or effects on crack arrest.

Study the effect of radiation-induced strengthening of the cladding on the "cladding effect."

Quantification of residual and thermal expansion stresses.

So we have two conditions. If cladding remains ductile, you have one condition. If cladding does indeed embrittle, you have several other conditions.

[Slide.]

Cladding may keep short flaws from extending into long flaws. If it does, then our screening criteria is indeed very conservative.

[Slide.]

Now, Oak Ridge is looking at it from one viewpoint. They are looking at it from the viewpoint of pinning -- let's say we did get a crack started. Would the cladding slow it up and cause a more rapid crack arrest? MEA indeed is looking at it from the viewpoint does it inhibit crack initiation.

MR. SHEWMON: Who is getting data on what happens, what are the properties of irradiated cladding?

MR. VAGINS: Oak Ridge. And we will get to that a little later.

[Slide.]

This is exactly what is happening here. Here is pre-irradiation. If you look at the fracture toughness of cladding and the base material function of temperature, here is your base material and here is your cladding.

Your cladding is 308, 309 type cladding. It is ferritic. It is not very tough, believe it or not. It is not tough at all compared to most austenitics, and it exhibits a very clear and defined transition.

MR. SHEWMON: What do you mean, it develops a clear transition? Transition of what?

MR. VAGINS: In toughness. It looks very similar to

ferritic steels.

MR. SHEWMON: Either you have misdrawn the curve or I don't understand it.

MR. VAGINS: This is the transition.

MR. SHEWMON: Tha.'s your sharp transition.

MR. VAGINS: It's the way this thing is drawn. I'll show it to you in a minute. This is just for an example.

[Slide.]

It depends upon what scale you are using, and this is what happens in irradiation. The irradiated cladding may shift its toughness, and certainly we know the base material shifts its toughness. So you have to look at the intereffects both for initial conditions.

MR. SHEWMON: What is the ferrite content?

MR. VAGINS: Tyical weld, about 8 or 9 percent.

MR. SHEWMON: It's only the ferrite that has the transition, it goes to cleavage.

MR. VAGINS: Yes, sir. It's enough ferrite, though, to really show a marked reduction in toughness with temperature.

[Slide.]

As an example --

MR. SHEWMON: It's a J-1C that goes up. If you don't believe me, just talk to Hanford.

MR. VAGINS: For the radiation? It's possible.

This is a specimen that Materials Engineering Associates is using. These are the scales. It's a four inch wide specimen. It's 12 inches long. It's a part-through crack specimen which exists right here in the face, it's clad, et cetera.

The beautiful thing about this specimen that we are going to run several of them, we are going to run specimens without cladding to see what happens on initiation, initiation values for this flaw, then we are going to clad it and test it, go through a stress relief and everything else, go through a determination of cladding and virgin material, what it has on initiation. Then we are going to irradiate this entire clad specimen, take that specimen, just stick in the reactor, irradiate it to 1 or 2 x 10 to the 19th and then see what happens.

MR. SHEWMON: Where are you going to put the crack?

MR. VAGINS: The crack is right there, right at that BB, right here, and it looks like this.

MR. SHEWMON: Okay. Fine.

MR. VAGINS: We are using state of the art clarity on this --

MR. DILLON: Where is the crack with respect to the cladding?

MR. VAGINS: I'm sorry, it's through the cladding, right here.

MR. SHEWMON: Why doesn't it show up in the section that shows the cladding?

MR. VAGINS: It should. It should come right through here.

[Slide.]

As I said, there are two ongoing studies. There is the Oak Ridge study and MEA study. The approaches are slightly different. The early Oak Ridge study was typical of early construction. It is a one wire type cladding done by combustion. They are also doing three-wire. Oak Ridge chemically and heat-treated their materials. MEA will have irradiation. Oak Ridge will not have irradiation. They will simulate by heat treatment. MEA's concentrated initiation, Oak Ridge has concentrated on arrest. MEA's is tension specimen, Oak Ridge's is a four-point bending specimen. MEA is doing both clad and unclad studies, and so is Oak Ridge, but their specimens are quite different. You saw MEA's specimen.

[Slide.]

This is Oak Ridge's specimen. It is a very large specimen and what they have is a plate which is two inches thick. In this area you have a flaw through the cladding, but the cladding is machined away from the edge of the flaw, so the flaw can start and run into the cladding. So it is more of a crack arrest or resistance to running crack type.

[Slide.]

Oak Ridge has tested in this configuration. You've got the four-point bending here, here is the plate. You've got your specimen, the cladding is up here. What we do is load the specimen up, cool it down, load it and then we have a brittle weld in here. We charge it with an acid, sulfuric acid, get it to crack and the crack runs.

[Slide.]

The flaw looks something like this. Here is where the cladding ends and here is where the flaw ends. So it is a little bit different from the MEA.

[Slide.]

Finally, the MEA progress of the program has not run any results yet. They are still in the process of finishing their specimens. Oak Ridge has finished their first phase. All they have really shown is you've got to be very, very careful with the cladding. You get some moderate effects, but nothing to boast about so far.

What they did was the early type cladding was quite brittle, and it did not give us much benefit at all. In other words, we got some slight effect from crack arrest, but not much. That program is well underway and we should have results by next year.

Any questions about that?

That was real quick.

MR. SHEWMON: Yes. I guess in the analysis the PTS has been convenient to act as if the clad wasn't there, since we don't give them credit for it.

MR. VAGINS: Right.

MR. SHEWMON: But the crack, if we go back to where anybody ever sees flaws in real pressure vessels, do they find them under the clad? Do they go through the clad? Do they find any at all?

MR. VAGINS: The answer is no, they found no flaws in operating on old cracks, in operating pressure vessels. The French found, with their big hubbub some years ago about some clad cracking, they determined yes, there were some cracks under the cladding. Due to their welding process --

MR. DILLON: That was a tube sheet or something.

MR. VAGINS: No, that was a pressure vessel, that was their pressure vessel. When they found they had too much heat input during their first welding pass.

MR. DILLON: They had exactly the same phenomenon in a tube sheet.

MR. VAGINS: I wouldn't doubt it. But the thing that got the French all excited was the fact they found these clad cracks, they got all excited about it.

MR. SHEWMON: It wasn't just the French. Prairie -- what's the Minnesota reactor? Prairie Island, I think, was made overseas by the same vendor in Holland or something.

MR. VAGINS: We don't think we have any cracks. We don't know. Every time we have run an inspection, we haven't found any. They found some -- was it Robbins? Chuck, which is the one they found all those indications when they did the L-wave?

MR. SERPAN: I don't remember.

MR. VAGINS: We found indications, but half the time they resolved them by saying some of them were slag, some were inclusions, some were just indications. The only crack we have actually determined is the outside crack at Indian Point 2. That is the only one I know of, other than the crack in the nozzle at Hatch, a BWR. That's from thermal fatigue.

But, no, we haven't found any, and when we do, we just don't know, and we don't know what the status of the cladding is in these vessels. We think they are intact.

MR. WARD: I always thought it was always awful, almost impossible to detect them under the cladding. Now you are talking as if it's very clear --

MR. VAGINS: In the early days we didn't. We gated out the first inch of material, we gated out the cladding, we didn't even look at it. Now we are looking at it with these new techniques and we can see immediately below the cladding, and theoretically they claim they can see in the cladding.

Again, it depends upon the surface of the cladding, how well they get their transducers up against the cladding.

MR. WARD: Okay.

MR. VAGINS: To be precise, we don't really know the status of the cladding in our vessels, to a great level of confidence.

I am just going to briefly talk about the irradiation program.

[Slide.]

This is the ongoing HSST irradiation studies. The purpose of it is pretty obvious. We have to have data for the fracture tou hness on the behavior of the material in its irradiated state, so that we know what can happen during life and end of life.

The HSST irradiation programs provide answers to questions that the NRC needs. It is quite obvious what are the fracture toughness of irradiation pressure vessels. What happens when we have low upper shelf materials that drop below 50 footpounds? If you remember Reg Guide 1.99 Rev. 1 said if you drop below 50 footpounds, your delta RT/NDT shift is infinite.

Also Appendix G required that this is an unresolved safety issue A-11.

The questions obviously pertain to the integrity of the vessel. We have to have the material properties for the vessel.

As you know, the material properties for the vessel

changes the function.

[Slide.]

Neutron fluence, irradiation temperature, chemical composition of steel, microstructure of steel, and neutron energy spectrum. All these affect fracture toughness.

[Slide.]

Typical irradiation shifts for Charpy. This was some actual data from submerged arc welds irradiated one time -- that's 10 to the 19th neutrons per centimeter squared, or 10 to the 23rd neutron per meter squared at 288 C, normalized to unirradiated curve.

Here was your unirradiated curve. Here was a 600 percent copper, .06 copper which irradiated. You see no apparent shift. Here is your .3 copper, tremendous shift and drop in the upper shelf.

Notice one thing about this particular Charpy data. There was no real change in shape. Etherington's concern in this case, if you thought about this for fracture curve, would just be a truncated K-1C.

[Slide.]

There have been -- the HSST -- the irradiation program in the HSST --

MR. SHEWMON: What would the truncated K-1C curve do?

MR. VAGINS: Probably be truncated in the same way.

I don't know. We don't have the data yet. Part of Etherington's concern was that both Charpy curves, when they get irradiated, tend to lean over. This one didn't.

Anyway, I just thought I would mention it.

[Slide.]

The HSST program, one of the most expensive things we do in the HSST program, believe it or not, are these irradiation programs. What we have done is we have completed four irradiation programs over the years, irradiation series 1, 2, 3 and 4, and this gives you the explanation.

This was an upper transition, and here we were trying to again define how the curve shifts, and we did. But we didn't have a lot of specimens. This was completed a long time ago. The type of specimens we used were from .4 inch thick to 4 inches thick. We have used Charpy intensity specimens. We would just see what happens to the irradiation -- to the toughness curve, K-1C, when you irradiate it to end-of-life conditions.

See here, we actually went up to 7 x 10 to the 19th, but we did not have a lot of specimens. The second and third irradiation was the famous low upper shelf irradiations. Everything was done on the upper shelf. We started with low upper shelf weld material supplied by Babcock & Wilcox free, and we tested them. That is complete.

The fourth is state of the art, this is good stuff,

good welds, state of the art. We have just completed testing. That report will be out soon.

MR. SHEWMON: One percent nickel in the weld metal?

MR. VAGINS: In these --

MR. SHEWMON: That stuff you said was current practice, good stuff?

MR. VAGINS: This was current practice, good stuff, about .6 nickel. It varied as current practice, about plate and weld, whatever is there.

MR. SHEWMON: Can you tell me why they tried to raise the nickel in metallurgical terms or fracture mechanics terms?

MR. VAGINS: I can't tell you -- it has nothing to do with fracture mechanics. It has something to do with the alloying process. I don't know why they raised it.

MR. SERPAN: You get better through-thickness hardenability, thicker sections with nickel. That was one of the biggest reasons why they wanted to put more of it in, get more uniform properties through the thickness, and better hardenability through thickness with nickel.

MR. VAGINS: Remember, these were the thickest sections ever made at the time.

MR. SHEWMON: Now they are reevaluating that in view of --

MR. SERPAN: I really don't think so. I don't

understand the big effort to reevaluate that and knock that nickel back.

MR. VAGINS: They can get their --

MR. SERPAN: If the copper is not way down, the nickel is nowhere near as effective.

MR. SHEWMON: There is a synergism down there. It is not just high nickel alone will do it.

MR. SERPAN: No.

MR. VAGINS: Absolutely. It is a synergistic effect, copper to nickel.

MR. SHEWMON: That gives my Japanese friends fits. You answered no, you answered yes, you both meant the same thing.

[Laughter.]

MR. SERPAN: I realize that.

MR. VAGINS: I did?

MR. SHEWMON: Is that right? No. Is that wrong? Yes.

[Laughter.]

MR. VAGINS: What we are showing is the present practice shows very little irradiation effects. The fifth irradiation -- this is the most expensive thing we have ever done -- is a $6 million program. This is where we talk about the K-1C curve shift verification. Indeed, does the K-1C curve and the K-1A curve shift the way the Charpys do? And

indeed, does the curve shape change?

Okay, I will get into more of that in a little while.

The sixth irradiation is going to be a crack arrest irradiation. We are just making specimens, and the seventh irradiation is ongoing. It is a stainless steel irradiation. These are Charpys and the specimens I talked about from MEA.

Remember, there are two different programs here in the HSST and the MEA program.

[Slide.]

This is the first program, first irradiation. This is exactly what we wanted to do, what we are doing now in the fifth. But we didn't have statistically valid data, and here was our unirradiated curve, K-1C. We have specimens up to eight inches thick, and we initiated them with dynamic loads.

This helped form, as I said, the million dollar curve. If you notice, this is the irradiation curve tested, but we only have a few data. The WR and RW is an old curve, or transverse and parallel. Instead of LT, they use the term RW and WR. But if you notice, we did get some high values. I am not quite sure how valid these are. These were static, this was dynamic, this was irradiated 3.7 to 4.2 x 10 to the 19th. This is a 4-T, these are 1.9-Ts. These are obviously invalid curves, but are early indications that the curve did shift. But it is not statistically valid and it is not really

-- these points are open to question.

[Slide.]

So the sixth irradiation will be, as I said -- we will try to get K-1A values, irradiated K-1A values, crack arrest values.

[Slide.]

The fourth irradiation, as I pointed out, was to characterize fracture toughness of current practice, low copper, relatively low nickel, irradiated pressure vessel steel, with emphasis on upper shelf properties.

And what we showed indeed was that the upper shelf -- the Charpys hardly changed at all.

[Slide.]

Here is a good example. Here is a Charpy curve of the current practice materials, fifth hyperbolic sloping tangent of the upper shelf. Here is unirradiated, here is irradiated. Practically no effect whatsoever.

This irradiation was 1.6 3 x 10 to the 19th neutrons per centimeter squared.

[Slide.]

The fracture toughness curves. Now we have a fracture toughness curve which shows some little bit of slope change -- actually, it wouldn't be much. You extend it up. Nothing much on the upper shelf. This small shift in the fracture toughness curve.

These points are all invalid by current standard testing procedures. They are invalid. We corrected them using the beta 1-C correction.

[Slide.]

This is what you get, the comparison between the Charpy, the Charpy at 41 joules, the K-JC in 125 megapascal squared meters, and the K beta C corrected at 90 megapascal squared meters.

The shift, as I said, this is invalid. This is our correction technique that we think makes the material more valid. And if you look at it, you will see that uncorrected, the KJC seems to exceed the Charpy slightly. The corrected more or less the same.

In fact, they are always the same except in one instance. These are three different materials reflecting differences. This is .14 copper, .67 nickel, .12 copper, .10 nickel. This is a plate, this is a weld. .56 copper, .63 nickel. Goes all the way out, and this is .046, et cetera.

In other words, this is our highest nickel and copper combination synergistic effect.

MR. SHEWMON: What is the copper content of the vessels that are now being licensed?

MR. VAGINS: There is no copper in the plate itself. The welds themselves are controlled down to about -- less than .04, .05 percent.

MR. SHEWMON: With that much nickel, .12 -- at least .14 to .04 makes a fair difference.

MR. VAGINS: Here is .046 and here is .04. Here is .63 nickel, here is .13.

MR. SHEWMON: I was comparing that one with the first one. That's plate, though.

MR. VAGINS: This is a weld, that's plate. But you can still compare it. But you see this is .046 copper and this is .14 copper, both about the same nickel. You can compare it. It's the copper that predominates. It's the synergistic effect. Here is the effect of nickel. Look at this. This is .04 copper, .13 nickel, .04 copper, .63 nickel. Basically the same copper. This is higher nickel.

Anyway, this gives us a little confidence about the comparability of the Charpy shift, Charpy and fracture toughness shifts.

[Slide.]

Three conclusions came out of the fourth irradiation:

Reg Guide 1.99, Rev. 1 guidelines were conservative for current practice weldments.

Current practice weldments exhibited no significant drop in Charpy upper shelf energies.

The need for using statistical methods of analysis for Charpy results was demonstrated.

MR. WARD: When you say 1.99 guidelines, is that existing 1.99?

MR. VAGINS: That's Rev. 1, Revision 1.

MR. WARD: What about Revision 2?

MR. VAGINS: That takes this into effect and reduces the levels of conservatism.

MR. WARD: But still conservative?

MR. VAGINS: Oh, yes, I hope.

MR. SHEWMON: How much conservative?

MR. VAGINS: I can't put a number on it.

MR. SHEWMON: What is the current practice, welds exhibit no significant drop in how much irradiation?

MR. VAGINS: These things were irradiated up to 2 x 10 to the 19th neutrons per centimeter squared E greater than 1 MEV, which we are trying to limit our end of life fluence system in all our vessels.

[Slide.]

The fifth irradiation is exactly this --

MR. SHEWMON: Was that any place in the code or the recommendations?

MR. VAGINS: No.

MR. SHEWMON: I remember having Combustion people tell me that their -- it's not Combustion 80 or whatever 80 -- CESSAR 80 was going to get 4 x 10 to the 19th, and that fit the absence of regulations or there was no regulation on it

and they went ahead sad and happy at least a year ago.

MR. VAGINS: There is no regulations on fluences. The only regulation exists on toughness requirements, Appendix G, 10 CFR 50. However, under PTS guidelines, we are trying to get these people to reduce their fluences to keep the fracture toughness up.

MR. SERPAN: The Germans have mandated that no vessel would get above 1 x 10 to the 19th.

MR. SHEWMON: We came at it in Kussmaul saying PTS, what is your problem, why don't you things right, and then you wouldn't have that. Do things like we have.

MR. SERPAN: We have not imposed that kind of a fluence limit.

MR. SHEWMON: That's when I asked the Combustion people that came up. They were surprised there was a factor of four higher for their most modern plant.

[Slide.]

MR. VAGINS: Let me finish up real quick.

Section III, and our whole licensing basis says these are the curves, it's a Section XI. This is also a K-1R curve in Section III.

Everything in our licensing procedures says these curves shift from the irradiation to the right do not change shape, and that is what we are trying to verify with the fifth irradiation.

We are going to run for the first time irradiated drop weight tears.

MR. SHEWMON: They may actually get truncated sooner for low upper shelf. Is that your thesis?

MR. VAGINS: The code limit is 200 KSI square inches.

MR. SHEWMON: Let's come back to Harold Etherington's point. What do you do with those old low upper shelf?

MR. VAGINS: Right now we have no regulatory basis for it, but if it is low toughness, we truncate this curve without changing shape.

MR. SHEWMON: His concern is whether that is conservative.

MR. VAGINS: That's correct, and that is what we are going to have to determine.

MR. SHEWMON: Okay.

MR. VAGINS: What we are really trying to determine now is how accurate is the code specification. The codes just shift as they are, without changing shape, and that's getting to Etherington's concern, the concept, this is it.

[Slide.]

Some of the material, we know the Charpy shifts like this and changes shape. The question is will this curve just shift the same amount of delta T at the fixed point, or will

it indeed do this? Big question.

Etherington's concern is indeed the low upper shelf toughness, will this curve do this. Those have to be resolved.

[Slide.]

I am out of time. I just want to show you how difficult it is to run an irradiated test, by the way.

What you see here is a 4-T -- that's four inches thick here, it's eight inches deep, eight inches long, it's irradiated, it's hot, it has to be done on a hot cell, it has to be mounted in there, it has to be instrumented in there, et cetera. You can see why this rapidly builds up to an expensive proposition. Testing for large irradiated specimens.

We only have one vendor, one contractor who can do this. This is a government-owned machine. It is a 550 kip machine. We have warm cells up at the University of Buffalo. Oak Ridge cannot test large specimens, cannot test large irradiated specimens. MEA is the only one who can do it right now. I am sure Westinghouse can do it also, but they have never been our contractor. So it gets expensive.

MR. SHEWMON: That's probably enough concerns for today.

MR. VAGINS: I think that is enough. The time is about right. I have covered an awful lot. As I said, this is

a lot of money, a lot of effort, covers many, many issues. In no way could I have given you a total picture in the time.

MR. SHEWMON: I think you did a good job. Thank you.

Now we get to meet the new man on the street.

While he is getting set up, would you introduce the man who is going to speak to us. You can tell us a little bit about his background while he is getting set up.

MR. SERPAN: Mike Mayfield came on the Materials Engineering Branch in June, I believe, of this year. He has been employed at MEA for the last couple of years in piping and fracture work.

He was formerly at Battelle Columbus where in fact he worked on some stuff for us back in the late '70s. He did the old cold leg break study.

Mike has come on, as I said, in June. He has been given all the piping work -- the piping fracture work, rather than piping corrosion work. He has been working with MELP and he has been very, very busy.

He will be taking off this weekend with Wilkowski from Battelle Columbus to Japan, where they will be going on a two-week tour there to sell the IPIRG program to the Japanese, or at least hopefully.

MR. SHEWMON: IPIRG?

MR. SERPAN: International Piping Integrity Research

Group. An Mike will talk about that. I mentioned that yesterday in my Foreign Interactions presentation. Mike will talk more about it today.

Japan will be the last overseas contact we will make in this, and then we hope to have the organization meeting the end of October, first of November, in Columbus in order to try to get everybody in that program and get them signed up.

MR. SHEWMON: Let me know when, will you? I may not make it --

MR. SERPAN: October 31st and November 1st.

MR. MAYFIELD: As you know by now, my name is Mike Mayfield.

(Slide)

I am in Chuck Serpan's Materials Engineering Branch.

(Slide)

I am here this morning to talk principally about piping degradation research. I want to touch on three aspects of that in our piping fracture experiments, the IDWB3640 paragraph in Section XI and in general the leak before break topic.

(Slide)

I wanted to briefly describe the three major programs we have in the piping fracture research area.

The first was degraded piping program. It is in its second phase being conducted by Battelle's Columbus

laboratories. This is largely an analytical and experimental effort.

We are looking to generate significant pipe fracture experiment data base for the analyst to use to benchmark the analyses that they developed.

We are also looking to assess the degree of conservatism in the analyses that currently exist. And along that line, where we find deficiencies in those analyses, we are looking to revise existing analyses or develop new ones as appropriate.

MR. SHEWMON: Will you get into whether that is stainless, and what is an overlay weld? Is that part of it?

MR. MAYFIELD: Yes.

MR. SHEWMON: Good.

(Slide)

MR. MAYFIELD: The second program, the degraded piping program is the largest program we have going in this area. The second one has kind of a long title, Elastic-Plastic Fracture of Pressure Vessel and Piping Steels being conducted by the Naval Research and Development Center at Annapolis. It is predominantly an experimental effort.

We are looking to characterize fracture behavior of piping and piping materials. We do this with both pipe fracture experiments and standard laboratory specimens.

Within that program we are looking to evaluate the

effective crack morphology on effective behavior, we are looking at sharp machine notches, fatigue cracks as well as stress corrosion. One element of crack morphology is to indeed generate stress corrosion cracks and develop a technology for doing that quickly so we can use them in our laboratory studies.

Finally, we are looking to develop and evaluate fracture property measurement techniques, specimen designs, test methods and so on.

(Slide)

The third program that is important to us here this morning is the program being conducted at Materials Engineering Associates, their Task 1E. And in particular, they are looking to establish a numeric data base of pipe fracture properties; tensile properties, J resistance curves, chemistries and so on.

They are tasked specifically to collect existing data, data that has been collected by other laboratories. Where they find deficiencies or lacks, holes in the existing data, they are tasked to test materials, pertinent materials as necessary so that we end up with a comprehensive fracture toughness data base.

And finally, they are tasked to implement that data base on computer. Will be accessible to the outside world over phone links.

(Slide)

We have several related programs and we periodically hold review group meetings so that we can ensure that contractors are working with one another.

Related programs. We have an aging of cast stainless steel program. Bill Shack and company are taking care of that at Argonne.

We have environmentally assisted cracking work going on both at Argonne and Materials Engineering Associates.

There is a study going on at PNL, looking at the susceptibility of weld repairs to stress corrosion cracking.

And of course, the NDE work going on at PNL that Joe Muscara talked about yesterday.

(Slide)

The piping fracture topic, we are looking at the fracture behavior of flawed pipe. We are doing, as I said, experiments to generate a good experimental data base. Data base experiments for characterizing, benchmarking the various analyses.

We are also looking at the various analysis methods. We are also looking at generating representative material, property data, so that indeed we can analyze cracked pipes in plants as appropriate.

(Slide)

Along the lines of the material property data, we

are looking at tensile testing. Indeed, we will talk a minute or two about the strength of materials approaches. The IDBW3640 kind of approach that is essentially a strengthened materials approach to piping analysis.

For that we are looking at generating true-stress, true-strain tensile data. Research is looking at the test methods and how we analyze it.

It would seem a tensile test is a nice straightforward test to run.

(Slide)

I have here a photograph showing -- these are broken tensile specimens from piping material.

This piece is from an axially oriented tensile specimen on a seamless 304 pipe. You can see the specimen has stayed reasonably round. And we have a nice, fine-grained appearance.

This specimen is a piece of cast stainless steel piping. Same type of orientation relative to the pipe. Notice the extreme ovalization of the fracture point and the significant amount of surface roughening. This is important in terms of our test methods, because indeed, if you are using an extensometer that measures changes in the diameter of the specimen, it will be all right here. This one you can get fooled significantly.

Now, why is that important in terms of the data?

(Slide)

We have here stress versus strain plot for -- I believe this is a stainless steel specimen. The data points are shown along here.

If we do a Ramberg-Osgood type of parallel fit to the stress-strain curve, we fit up in the high stress region, we can do a reasonably good job. We don't do very good down here.

If we fit in the low-strain region, we don't do a very good job at the high end.

We looked at just putting a linear regression fit through the whole mess. So, we can't fit this tensile data very well. But,is that ultimately very important?

(Slide)

I show here J versus crack growth plot. These are predictions from one of our pipe tests. This is in particular 16-inch diameter, one-inch thick piece of pipe. These don't show very well here, but this -- we mentioned true stress to strain. Out of test we can get true stress to strain. We also by default get engineering stress strain.

So we are looking at how to fit both the true stress-strain data and the engineering stress-strain data.

These are the same analysis scheme, just using different ways of fitting the tensile data. You can see indeed you get substantial variation in the result.

It turns out, using the true stress-strain data with a simple linear regression -- remember didn't do a real good job of fitting either end of the data -- but that does the best job of any of them of fitting our pipe test results.

(Slide)

So, something as simple as running a tensile test has turned out to be kind of important to us.

As we go on into the elastic plastic fracture mechanics type analyses, we need to get a decent way of measuring material toughness without having to actually do a pipe test.

We are looking at being able to apply specimen data to pipe analyses. That involves predicting large amounts of crack growth from relatively small specimens.

Now we are looking at a couple of different specimen types. Right now we are looking at a compact tension specimen in a thing called a full-width face-notch tension specimen. Within the compact tension specimen testing, we are looking at standard type specimens where there is a particular ratio to the specimen width to thickness.

We are also looking at what we are calling large plan form specimens.

(Slide)

To illustrate that, the piece this fellow has in his hands is a standard one-inch thick compact tension specimen.

We have here a three T plan form specimen, but it is only one-inch thick. In the background we have a ten T plan form specimen. That, again, is only one-inch thick.

We have performed tests to see if, indeed, we can predict what is going to happen, where the large amounts of crack growth you can get from this kind of specimen would be representative of the amount of crack growth you might see in a large diameter pipe.

This thing is not very practical to test, so we are looking, can we extrapolate data that you get from a one T size specimen to the amounts of crack growth you get from a ten T, or that size specimen. The answer appears to be at this stage, yes, with some caution we can make that extrapolation.

(Slide)

Now the full-width face-notch tension specimen, these compact tensions specimens as you can see from the size of them, are not particularly well suited to getting through thickness properties. This would be --this one with one T plan form specimen, one-inch thick, this dimension is about two and a half inches.

So if you are wanting to get crack growth in the radial direction with pipe, this specimen is not particularly well suited to it.

(Slide)

Battelle worked up specimen -- like I say they are calling full-width face-notch tension specimen. It works, in fact, quite well for a through thickness property. You can see they are a compact specimen, a standard bin bar would do nicely for getting crack growth around pipe circumference.

(Slide)

You can orient them so indeed you can do a reasonable job getting crack growth properties along the pipe length. Through thickness is another problem and this full-width face-notch tension specimen does a reasonably good job.

(Slide)

Just a quick photograph here to show you this thing. Looks like a flat plate. The notch -- there is a machine notch right across here. There is quite a bit of instrumentation. We are using a DC potential drop technique for getting crack growth as well as clip gauge right across the notch. And then a clip gauge right out here to get far field deformation.

(Slide)

The specimen works very nicely for getting through thickness properties and has been used for getting weld properties.

Compact tension specimen. Sometimes it is hard to get the notch right where you want it. With this style

specimen it is very easy to etch the sides of the specimen, identify the weld zone, and place your machine flaw right where you want it.

So we have some properties from welds that are indeed showing substantial toughness drop.

Now they told me this morning that you were interested in weld toughness.

MR. SHEWMON: I would be interested in knowing where the heat effective zone and fusion zone is worse.

MR. MAYFIELD: The answer seems to be it is a weld metal, although I don't have fusion and heat effective zone properties to show you this morning.

(Slide)

This is a table just briefly showing the 304 stainless steel. These are J1C, J at initiation, terminology and the like.

For base metal you can see we are getting range from 23,600 to 25,100. An average of about 24,400 pounds per inch. In the sub arc welds -- let me point out these are sub arc welds -- you can see a significant drop in toughness.

For the A516 ferritic steel, we see a similar thing. Notice the base metal, we drop from an average toughness in the stainless steel average of 24,400, we drop for the base metal ferritic, 14,700 in the welds. Again there is a significant drop.

So we go sub arc, stainless steel weld, 2650 down to the sub arc weld in ferritic to 1670.

MR. SHEWMON: In the ferritic, is there a post-weld heat treatment given to that stuff or not?

MR. MAYFIELD: I guess I don't know on this one. There was not on the stainless. I don't know.

MR. SHEWMON: The Code wouldn't allow it or request it in the 304. But I think it would in the A516.

MR. MAYFIELD: You say the Code doesn't force it in the 304. That's very true. Indeed, we are picking up some feedback now from people that suggest that some of the sub arc welds in the field have indeed been, after welding solution annealed, the affect that it appears to have is to lower the strength of the weld. It doesn't elevate the fracture toughness appreciably.

We are looking at that. We still have some sub arc weld material left, both in the pipes we will talk about a little bit later, and in the plate specimens. We are going to look at that starting with the plate specimen. If it looks promising, we will pursue it with pipe specimens.

MR. SHEWMON: Before you leave that, let me ask -- the reason I am concerned about it gets back to properties of weld overlays for now.

Answer that question, and I will come back to you on castings. But, I think that is a longer-term problem. Maybe

less of a problem, too.

Will we come back to the properties of the 304 in sections, or how you do tests?

MR. MAYFIELD: I have some pipe test results from the weld overlay experiments that Battelle has conducted. Those are in the presentation a little bit later.

MR. SHEWMON: Okay. Thanks.

MR. MAYFIELD: Did you get what you need off this?

MR. SHEWMON: Yes.

(Slide)

MR. MAYFIELD: Just very quickly to show you what it looks like from a full-width face-notch tension specimen.

This would be base metal load versus load line displacement response. You can see we get substantial amount of load line displacement when we look at the submerged metal arc weld and this adjusted.

What they have done is normalize the load detection trace for thickness. So the base metal specimen was thicker than the weld specimen. So, they have simply normalized this to the base metal thickness.

As you can see it brings it up. It is significantly less load line displacement.

(Slide)

That is typical also of the ferritic steels. You can see here the 516 base metal and the 516 weld. Now we have

got a small -- once we have gotten well past maximum load we get a small instability in this specimen, so the crack jumps ahead slightly. And then the load came back up and we continued --

MR. SHEWMON: That's a single-pass weld?

MR. MAYFIELD: Multi-pass welds.

MR. SHEWMON: In that respect they reflect reasonably well what would be in thick sections, or at least to some degree?

MR. MAYFIELD: Yes.

(Slide)

I would like to turn now to our pipe fracture experiment.

We have funded a total as of now --

MR. SHEWMON: Let me stay with that.

Is your training as a mechanical engineer or metallurgist?

MR. MAYFIELD: Mechanical engineer.

MR. SHEWMON: If somebody does fractography on those things, why was the toughness so low? Was there any -- there wouldn't be any cleavage in the 304 and probably not in the 516. Were there inclusions, voids?

MR. MAYFIELD: I'm told it is essentially inclusions from the flux.

MR. SHEWMON: And that is true with the 304 and the

516?

MR. MAYFIELD: Yes.

MR. SHEWMON: One thing, Dave, the utilities in this case of Commonwealth and Quad Cities have come back in and asked the Staff how they feel about putting -- leaving these weld overlay pipes with hydrogen treatment in permanently. There is good news and bad. That's why I'm particularly interested in what they find there.

MR. MAYFIELD: Okay?

MR. SHEWMON: Go ahead.

MR. MAYFIELD: Turning to our pipe fracture experiments, we have funded a total of 49 pipe fracture experiments; 30 of them at Battelle Columbus, and 19 at NSRDC.

Our current work plans include an additional 45 experiments; 30 of those will be at Battelle, 15 of them are planned where we are looking at plants for NSRDC right now. I'll come back to that.

Beyond these experiments, Battelle has recommended an additional 39 experiments conducted at other laboratories in different programs.

All of this information is being pulled together and put in what we call a Pipe Fracture Data Record Book. That record book will be available to the NRC Staff and other people.

(Slide)

Our fracture experiments have dealt with a range of sizes. We run from 4-inch to 42-inch. You will see some of this data in a moment.

We have two pieces of pipe that we are real pleased to have. This is the cold leg from a cancelled Combustion Engineering plant. Battelle picked it up not too long ago. It is 37-inch OD by 3 1/4 wall. It is A516 grade 70. It does have the stainless cladding inside. It has the nozzles, welds, elbows, everything you could possibly want from a brand new cold leg, this thing has.

We have, I believe it is from the Monticello recirc loop, a piece of 28 by 7/8 stainless steel. This pipe has a weld in it that at one point we thought had cracks in it. It turns out it does not. So, they are going to decontaminate this thing and we will be using that in some of our upcoming pipe-fracture experiments.

MR. SHEWMON: The Monticello pipe has seen service? That was taken out in the pipe-replacement program?

MR. MAYFIELD: Yes.

In terms of our materials we have looked at and are looking at -- we had stainless steel and welds in stainless steel. We have both the TIG welds non-flux and flux welds using the IDWB3640 terminology. We have cast stainless steels and welds in that. From the same cancelled Combustion

Engineering plant we picked up the surge line 12-inch schedule 160. It is cast stainless steel. It has elbows in it and welds between the straight section and the elbows.

Now part of this material, there is a two-foot long piece with a weld in it that has already been sent off to Bill Shack at Argonne and will be aged. The weld is aged such that out of that one piece we will be able to get, effectively, two pipe fracture experiments; one on the weld, one on the base metal.

We have tested some six-inch diameter Inconel. We are looking at carbon steel and welds in the carbon steel.

The cold leg offers us an excellent opportunity to look at welds in thick section, relatively large diameter pipe.

Our loading type is particularly important from the analysis point. We are looking at tension loadings, bending loadings, combination of tension and bending, and then the effect of system compliance. This is particularly important in terms of being able to predict unstable fractures.

(Slide)

Our analysis methods center on elastic plastic fracture mechanics, the JT type analyses, and what I am calling the strength of materials approach.

(Slide)

Looking first at the elastic plastic fracture

mechanics, you have to start by having a valid formulation for the J integral. There are two types of analyses that have come about. First is a predictive type, and second is non-predictive.

Under the non-predictive heading, this is an ADA factor type approach that Battelle developed under the phase I degraded piping study. The disadvantage to this is that you must have the load deflection trace from the test to be able to make any sort of J prediction or J computation. So it is not particularly useful in predicting pipe fracture behavior.

The predictive analyses, we have the GE estimation scheme; have an analysis by Paris and Tada and what we are calling an NRC/NRR analysis. This is essentially an extension of the Paris and Tada analysis where the NRR people had included strain hardening behavior.

Of course you can always do finite element analyses.

(Slide)

Looking at how well the analyses do, the GE estimation scheme generally gives us conservative predictions for both stainless steel and carbon steel. Sometimes they are very conservative predictions. But in all of the cases we have looked at they are at least conservative.

Interesting, they are more conservative for stainless steels than they are for carbon steels. So, there is a bias in the stainless steel analyses, they are more

conservative.

Looking at the NRC/NRR scheme --

MR. SHEWMON: Will you tell me what question you are trying to address here, that these things are conservative or unconservative about?

MR. MAYFIELD: The prediction of pipe fracture welding. Indeed, the prediction of the loads that the pipe can withstand.

MR. SHEWMON: This is leak before break?

MR. MAYFIELD: It would be pertinent to leak before break. It would be -- let me give you an example.

(Slide)

This is a GE estimation scheme. We have a piece of cracked pipe. We are doing an analysis. For some reason we are not using an IDWB3640 type analysis. We want to be able to predict the maximum load that the piping can withstand, and that would be compared to the maximum load you might anticipate in service.

MR. SHEWMON: If it's a flawed pipe, then it will fish mouth?

MR. MAYFIELD: Yes.

MR. SHEWMON: And the question is when it will go -- what press''e it will go unstable at.

MR. MAYFIELD: Well first of all, if you have a surface flaw, the question will be what kinds of combination

of bending, applied bending as well as internal pressure, at what point will the crack initiate and grow through the wall.

And secondly, how will it behave once it comes through the wall?

So that is what all of these analyses --

MR. SHEWMON: And what GE has, when you talk about the GE estimation scheme, estimates when it will go through or how it will propagate?

MR. MAYFIELD: The GE estimation scheme is a way of calculating J for pipe specimen.

MR. SHEWMON: Is this simple as a code equation, or is it a computer code?

MR. MAYFIELD: At this state it is an equation with a series of factors that must be determined using finite element analyses. Those factors have been tabulated and are published along with this scheme in an EPRI document.

I guess the answer to your question is, indeed, it is an equation of a series of parameters, where you must pick those parameters from a graph or a table.

MR. SHEWMON: Okay. Go ahead.

MR. MAYFIELD: So, by conservative the point here is using this computational technique can we predict the maximum load or the initiation load from a test?

By conservative, what I mean is that we consistently -- the prediction for measured maximum load divided by the

predicted maximum load. If we are predicting that the pipe can withstand loads larger than it can actually withstand, then our analysis is not all that good.

You can see here, if we are conservative, at best we will be dead on consistently for the stainless steels. We are above, so that our measured maximum loads are above the predicted maximum loads. And the range here is looking at the various ways of fitting the stress-strain data.

You can see just from these it has a significant variation or significant effect.

MR. SHEWMON: Fine.

MR. MAYFIELD: (Slide)

The second scheme -- again, this is a way of calculating J to be used in a piping, pipe fracture analysis. This is an extension of the Paris and Tada formulation where strain hardening has been accounted for.

We are conservative in the sense that our predicted maximum loads are smaller than the measured maximum loads. The conservative for stainless steel --

MR. SHEWMON: Is the main question of conservatism or non-conservative come into work hardening and --

MR. MAYFIELD: I don't understand.

MR. SHEWMON: There is a difference in the amount of conservatism. I'm trying to find out what the origin of that is.

MR. MAYFIELD: I believe it has to do with the way strain hardening is accounted for. Yes. Definitions of load stress and that sort of thing.

We are slightly non-conservative in the predictions for carbon steel. This is not a surprise to NRR. They knew this going in, and indeed, at their request, Battelle is working with them to document and benchmark their code to see just where it is conservative, where it is non-conservative and by how much, looking at improvements in that code.

So this didn't come as any surprise to anyone. Perhaps the surprise is it is better than they thought.

(Slide)

I'd like to turn now to the strength of materials type of approach, as to predicting pipe fracture. These are all based on the concept of plastic collapse at the cracked cross-section as being the primary failure mode.

(Slide)

I put together a little plot here showing all -- not even all -- most of our pipe fracture experiments to date. There are some experiments that are not on here that are currently being analyzed. So, if you count the number of points, it won't agree with the number that I told you we have funded.

Measured maximum load divided by predicted maximum load. Again this is a simple strength of materials approach.

You can see the circles are stainless steel specimens, squares are carbon steel, and we have two Inconel tests.

These specimens out here, these are 42-inch diameter pipes. This is a piece of lined pipe steel that Battelle used. It is 42-inch diameter by, I think about 5/8-inch wall. Certainly not representative of nuclear grade material.

This was a piece of stainless steel that again they, Battelle, used in evaluating their test system. Again this thing is 42-inch diameter by about a half-inch wall. Not representative of nuclear grade material.

So, these two are not particularly an issue.

This is a piece of 28-inch diameter pipe we obtained, I believe, from TVA -- either from TVA or one of the cancelled WPPS plants. This would be typical of a carbon steel pipe which would go in a plant. They have one stainless steel point that is indeed below our limit load line.

This is a piece of six-inch diameter schedule 120 pipe that Battelle bought from a pipe yard. It meets the SA106 grade B specifications, but it is not particularly representative.

This is a piece of six-inch pipe we obtained from cancelled WPPS plant. The Inconel, I'm not entirely sure -- I guess that came from the cancelled WPPS plant as well.

The rest of these came from a variety of sources.

MR. SHEWMON: Is there a report out that shows what

black box these numbers are being stuffed into?

MR. MAYFIELD: Yes. Battelle has published now their second semi-annual report.

MR. SHEWMON: So if I look for the second semi-annual report -- I find this rather frustrating, because I have no idea what you are talking about, except the points lie above or below the line.

MR. MAYFIELD: Net section --

MR. SHEWMON: I'm familiar with net section collapse. I've heard of fracture mechanics. But it is still a black box, the way it is shown up.

Go ahead.

MR. MAYFIELD: The Battelle report does, indeed, lay out the equations that are used and the technology behind this sort of plot.

(Slide)

Looking at the IDWB3640 paragraph saying -- it is entitled Evaluation Procedures and Acceptance Criteria for Austenitic Piping. It is a method in the Code, Section XI, for determining acceptable flaw sizes and piping.

MR. SHEWMON: This is a relatively new one that was controversial for a while and now is less controversial?

MR. MAYFIELD: Yes.

MR. SHEWMON: Have Rodabaugh signed off on it?

MR. MAYFIELD: I believe so. I have some of our

pipe fracture experiments.

This method does assume the cracked cross section will achieve a plastic collapse. The Code limits application of this paragraph to austenitic pipe greater than four-inch nominal pipe size. We can use it for austenitic pipe fittings --

MR. SHEWMON: What is nominal pipe size?

MR. MAYFIELD: Four-inch diameter nominal pipe size is actually 4 1/2-inch outside diameter.

MR. SHEWMON: It is not four times good.

MR. MAYFIELD: We can apply it to austenitic weld materials, we can apply it to cast austenitic materials where the ferrite number is less than 20. The specified minimum yield strength for the materials must be less than 45 KSI, and these must be Code-accepted materials. By that it means it has got to appear in Section III appendices as an accepted material.

(Slide)

Battelle has conducted a number of pipe fracture experiments. These are for surface flawed pipes.

It is important to remember IDWB3640 is pertinent only to surface flawed pipe. If you have a through wall crack you are going to take it out. So, we have heard a number of times, seen in the literature, we have done a through wall crack experiment and analyzed it under IDWB3640. What they

are trying to tell you is that they have analyzed their tests using a net section collapse analysis in the spirit of IDWB3640. Those paragraphs are pertinent only to surface flawed pipes.

So what we have here, we are plotting again the measured maximum load divided by the predictive limit load. And, according to IDWB3640, all of our points should lie above the value of one.

The filled symbols are 550-degree tests conducted under the degraded piping program. The open symbols are room temperature stainless steel tests. All of these are stainless steel tests. The open symbols are room temperature stainless steel tests conducted under previous EPRI work.

You can see generally we do pretty good now. Battelle is normalizing --

MR. SHEWMON: That doesn't impress one as having a lot of conservatism to it. The approach is to try to predict behavior and then put a factor of two or something in it?

MR. MAYFIELD: Yes. The Code has built into it -- they assume net section collapse. Then, depending on for their normal conditions or faulted conditions, there are factors. For normal conditions there is a factor of 2.78. For faulted conditions the factor is 1.39.

So they derate below this line.

Battelle is normalizing again essentially the pipe

radius divided by the wall thickness. They believe indeed, if we correctly account for the R over T ratio from these pipes, that these points will move above the line. As you can see, we are not off by much now. But, this is something that they continue to evaluate.

(Slide)

Now you mentioned earlier that early on there was controversy concerning the IDWB3640 approach. One of the big issues concerned these low toughness welds, the so-called flux welds.

The task group charged with IDWB3640 has evolved a scheme for handling flux welds. In fact, what they have done is include load multipliers. They have specified those multipliers should be included for flux welds. There is no multiplier included for non-flux or TIG welds.

We have Research addressing both the flux and the non-flux welds.

(Slide)

And these are weld tests I have shown here. This is the test data, and this would be an analysis in the spirit of IDWB3640. These are pipe fracture experiments using through wall cracks. So, this would be just the net section collapse line.

So if indeed the crack cross section achieved net section collapse, our data point would be up here. It did

not, which was not a surprise. We didn't expect it to.

The Code analysis says -- would have predicted pipe failure here. So, in that sense the Code is conservative. it predicted a lower load than we actually achieved.

Now this data point, yesterday when we made this VuGraph Battelle told me that preliminary analysis indicated that the experimental data was right on top of the IDWB3640 type prediction. This morning they tell me that is not true. That indeed the number is up at .87. So, it is going to be -- the experimental data will be up in this region, which certainly went in the direction that we wanted to be.

(Slide)

Now the Code section -- you mentioned a number of times, is it weld overlay repair business -- this IDWB3640 section is used to analyze the weld overlay repairs.

The weld overlay repairs are mentioned in the Code section, but there are no explicit rules given as to how to analyze them. So we use the concept that indeed the pipe will achieve the limit load. But, we don't have any real rules as to how we do that analysis.

So, we at Battelle have conducted three weld overlay experiments. The IDWB3640 type analysis, depending on how you perform the analysis, ranges from 9 percent non-conservative -- that being that our specimens failed at less than the limit load by 9 percent.

If you used the full weld overlay repair thickness and if you use only the nominal pipe wall thickness, we find that we are 36 percent conservative.

Now, what does that mean?

MR. SHEWMON: Yes.

MR. MAYFIELD: (Slide)

This is kind of a difficult plot to follow. We have here the bending stress divided by the material flow stress. And on the bottom we have the membrane stress from the test divided by the flow stress. And these represent the IDWB3640 analysis. That analysis includes both membrane stress and bending stress independently. So we could just exercise that analysis and get these kinds of lines.

This would be the net section collapse with no safety factor.

This line would be the IDWB3640 analysis for emergency and faulted conditions. There is a safety factor of 1.39.

The bottom line here is the IDWB3640 analysis for normal operating conditions. Safety factor of 2.78.

If we are to be conservative, our data points must lie above this line. Otherwise we are eroding the Code safety factor.

The data points you see plotted here use the full weld overlay repair thickness. So, if we make this a

worst-case analysis, if you will, and use the largest remaining cross section in our analysis, we get test data that fall below the net section collapse line.

On the other hand, if we use just the nominal pipe wall thickness, our data points move up and off the page.

MR. SHEWMON: But the ratio of the total weld to nominal pipe wall thickness depends on who made the weld?

MR MAYFIELD: That's correct. There are essentially three ways of doing these.

These particular weld overlays were made by a commercial vendor that does this as part of their business.

MR. SHEWMON: But what they submit -- I am not sure we are saying the same thing.

As I understand it, when the weld repair business started, you all agreed -- I'm not sure who agreed -- that they would put enough weld metal on there so that it would bear taking no credit for the pipe, remaining pipe ligament at all, or pipe wall thickness.

MR. MAYFIELD: That's right.

MR. SHEWMON: And then they decided that was hot and expensive, and so they started paring it back.

And which of those three modes are you talking about?

MR. MAYFIELD: These tests are from the middle one. You have the very heavy, the full thickness kind of overlay;

you have what they are calling a standard weld overlay that is somewhat thinner, as I understand it is replacing the cracked cross section as opposed to the full pipe wall thickness; and an engineered weld overlay where they go in and do some analysis and decide what minimum thickness to make the overlay.

These are what they are calling a standard weld overlay.

MR. SHEWMON: Which?

MR. MAYFIELD: These test results.

MR. SHEWMON: You said these three. The first was no credit for the pipe; the second was credit for the remaining ligament of pipe; and the third was unstandard in some ways.

MR. MAYFIELD: Was unstandard. They are going through doing an analysis deciding what minimum thickness they must put on those. They are done on a case-by-case basis.

MR. SHEWMON: Since these are standard, tell me again what you told me.

MR. MAYFIELD: In our analysis if we use the nominal pipe wall, let's say a six-inch schedule 80 pipe, there is a defined thickness for schedule 80 in the analysis. We would use that thickness.

MR. SHEWMON: For how deep a crack, how deep a crack or flaw?

MR. MAYFIELD: Not an issue.

MR. SHEWMON: Then I don't know what you are talking about. This is the flawed pipe you are testing here?

MR. MAYFIELD: These are weld overlay -- you asked me how thick? Sorry, that's the flaw geometry they are using.

MR. SHEWMON: So they are flawed?

MR. MAYFIELD: They are flawed.

MR. SHEWMON: I misunderstood you.

MR. MAYFIELD: I misstated. I didn't give you the right answer to your question.

MR. SHEWMON: And the flaw is .65 of the thickness of the wall?

MR. MAYFIELD: Yes.

MR. SHEWMON: What does that other number mean?

MR. MAYFIELD: This is percent of circumference. It is halfway around the pipe.

MR. SHEWMON: Now then tell me, in terms of those numbers, what you are calculating on these points and lines again.

MR. MAYFIELD: This line would represent the plastic collapse of the remaining cross section.

MR. SHEWMON: That is .45 of the wall thickness plus the weld?

MR. MAYFIELD: Yes.

MR. SHEWMON: Okay.

MR. WARD: It is .35.

MR. SHEWMON: Thank you.

So, if you take credit for the weld plus the remaining wall thickness, it is not conservative?

MR. MAYFIELD: That's correct.

MR. SHEWMON: Under what conditions was it conservative?

MR. MAYFIELD: If you just use the remaining pipe wall. You go in, you repair, and you just use nominal pipe wall thickness in your analysis as opposed to accounting for the thickness of the weld.

MR. SHEWMON: You are telling me if I've got a flaw and I've repaired it, the analysis is not conservative on the behavior of it?

MR. MAYFIELD: Depending on how you do the analysis for that repair.

If you take credit for the full thickness of your weld overlay repair --

MR. SHEWMON: And part of the wall.

MR. MAYFIELD: -- and part of the wall, then the pipe does not withstand that amount of load.

MR. SHEWMON: Okay.

MR. MAYFIELD: If you do the repair and do your analysis based on just pipe wall --

MR. SHEWMON: You assume the flaw has disappeared.

MR. MAYFIELD: That's correct, you assume the flaw

has disappeared. You have replaced that cracked area.

MR. SHEWMON: But we haven't replaced it in practice in the field. We never replaced it. If we replace the pipe we don't put a weld overlay on it. If we put a weld overlay on it it is because it is flawed.

MR. MAYFIELD: That's correct.

(Mr. Mayfield drawing diagram)

We start with a pipe that has a surface flaw that is 65 percent of the way through the wall. It is halfway around the circumference. We are now going to add to that a weld repair. So this would be weld repair.

If in our analysis of this we ignore, effectively ignore the weld overlay repair, and we work only on the nominal pipe wall thickness, then indeed we predict a load that has less than the achieved load, the test load, by some 36 percent.

In that sense, we are conservative.

If we include now all of this material in our analysis, we can be non-conservative based on these three test results by 9 percent. This is using the 3-S-sub-M -- of defining flow stress as 3-S-sub-M value for the base metal.

MR. SHEWMON: Let's go on. Thank you.

MR. VAGINS: Basically, what we are saying in this approach, you don't even worry about the crack. You develop the overlay based upon the crack dimensions. Then forget

about the crack.

If you use just the nominal thickness of the pipe, forgetting about the repair, forgetting about the crack, then you find that you would predict a lower load than you actually achieved to be conservative

But now,if you take the full thickness of the pipe, forget about the crack and the overlay, and then use that as your nominal wall thickness, you are going to predict loads greater than you achieve. You will be unconservative.

So the concept of the strength of materials approach is, once the repair is made you analyze the pipe as if the crack were not there.

MR. SHEWMON: But since the crack is there, I don't see why you want to do it that way.

MR. VAGINS: That's the approach of the code. That's all. It is a simple way of doing it. That's all.

MR. SHEWMON: Let's talk about it later. Ward has to catch an airplane.

MR. WARD: Yes.

Well, you are basing the repair, the weld overlay repair, on the characteristics of the crack.

MR. SHEWMON: Yes.

MR. WARD: Then after you have done that, then you pretend the crack isn't there. You pretend as if it has restored the pipe to its non-cracked configuration. And if

you base the analysis on that, it is conservative.

MR. DILLON: What is the ground rule for figuring the thickness of the overlay when you are making this repair?

MR. SHEWMON: IDWB3640.

MR. MAYFIELD: IDWB3640 doesn't give you any hard and fast rules. In engineered weld overlay repair, they need to look at this kind of analysis and decide how thick should we make it. Beyond that it is the nominal thickness from the weld pass, so we make one pass or two passes.

MR. DILLON: That is based on characteristic of flaw thickness, this overlay?

MR. MAYFIELD: Yes.

MR. SHEWMON: Onward.

MR. MAYFIELD: (Slide)

I just very briefly wanted to show you, indeed to get failure in the specimens, this is the data point that is labeled as number one on the plot. The weld overlay is in the middle.

You can see that we have achieved significant plastic deformation in this pipe. This is from the second test.

(Slide)

See the crack right here in the middle. And again there is significant plastic deformation of the pipe specimen.

(Slide)

Now, I wanted to look briefly at where our research is going from here.

The degraded piping program will continue for another one and a half years. We have two one-year options that we can exercise on that program. The work over the next one and a half years will look at larger and larger diameter and thickness materials. This cold leg is an example.

We are going to look at more welds and more materials; a wider variety of stainlesses, the cast materials, aged cast materials, the NSRDC program -- we are currently defining a new program for them. The welds are certainly going to play a key role in that. They are analyzing TIG welds, doing pipe fracture experiments as well as laboratory specimen development on TIG welds. This is a non-flux type of weld.

We are looking at a cooperative effort with Jim Joyce from the Naval Academy to do something about modeling dynamic loading effects.

MR. SHEWMON: People would rather use fluxed welds because they can lay down a lot more material per pass?

MR. MAYFIELD: Flux welds that come out of the shop are typically the shop welds. I don't know why. Presumably it is more cost effective.

MR. SHEWMON: We are talking about repairs right now.

MR. MAYFIELD: Repairs as I know it, are TIG welds. Weld overlay repairs are TIG welds.

MR. SHEWMON: Okay.

MR. MAYFIELD: (Slide)

Chuck mentioned earlier this International Piping Integrity Research Group, calling it IPIRG. This program is essentially a consortium of free world countries formed for the purpose of conducting research on the integrity of cracked piping.

We are looking to this program to allow us a way of funding the large-scale high-energy release dangerous-type experiments, ways of funding seismic experiments, waterhammer experiments.

Moving to the extremes of operational conditions; pressure, temperature, loading rates and so on. The efforts that we anticipate under IPIRG will generally be those kinds of efforts that are too complex, too expensive for one organization to undertake alone.

MR. SHEWMON: Will these all be done here, or some of them done overseas?

MR. MAYFIELD: Some will be done overseas. Potentially, some will be done at other labs in the United States. Some will be done at Battelle. We are anticipating at this point that Battelle will be the prime contractor on this work.

(Slide)

The general objective of our IPIRG program is to develop, improve and verify engineering methods for assessing the integrity of nuclear power plant piping containing defects. That is the starting point.

We are looking to build in the degraded piping program and our other NRC research programs. The intent is to supplement and strengthen the basis for current regulatory actions and to eventually provide input to the leak before break technology as a replacement for the double-ended guillotine brake as the design basis accident.

That is where we hope to go in the future to provide the technological basis for a replacement piping fracture criteria.

MR. SHEWMON: What size range of pipes are you going to be looking at?

MR. MAYFIELD: Again these will run prototypical. So, six-inch up to 38-, 40-inch.

Hot legs will run -- I guess the largest one I have heard of is something on the order of 60-inch.

MR. SHEWMON: Something that we didn't get at this meeting, but I guess will come up in a couple of weeks, is a presentation from Dr. Cloud -- I can't remember his first name -- Bob Cloud, who is doing a project for Beaver Valley, I think. Somebody that is looking for a license to do a

disciplined engineering study of the balance of plant. Meaning, they would like to push this to other things than the Staff has come in for on the original leak before break program for only the primary piping and only above six inches.

I don't know what he has in mind, but obviously there is some interest there, too.

MR. MAYFIELD: NRR has expressed an interest several times in moving the degraded piping program into larger diameters. We certainly had that in the program --

MR. SHEWMON: Larger than 30 inches?

MR. MAYFIELD: Larger than the 16. I guess we have one piece out to 28, prototypical pipe. So they are interested in getting out into the cold leg size, hot leg size, and indeed that is in the program plan. But we had to start with a smaller diameter pipe to make sure that we were --

MR. WARD: Mike, would you put up your last chart again, the previous one.

MR. MAYFIELD: This one?

(Slide)

MR. WARD: Yes. Replacement for the DEGB, is it design basis or what?

MR. MAYFIELD: ECCS, environmental qualifications. That sort of thing.

Those right now -- the leak before break business

applies only to the primary piping. There has been some interest, or at least question raised about extending that technology to other areas.

Right now it is not in there and there are no particular plans to include it at this time. To do that, we must have some replacement to the double ended guillotine break. That is where we are looking to move into that area.

MR. WARD: So this is explicitly to address the basis for ECCS.

MR. MAYFIELD: No. It is looking at pipe fracture. Out of those sort --

MR. WARD: With the expectation that you could apply the leak before break approach to systems other than just pipewhip constraints.

MR. MAYFIELD: Yes. I think that is where it is headed. And what we are trying to do is provide the technological basis for making such a decision.

MR. WARD: Where is the thrust for that program coming from? Who is asking you to do this?

MR. MAYFIELD: This is essentially an extension of the degraded piping program. When we got into that program we discovered we couldn't fund a lot of the kinds of experiments that were asked for under the original NRR User's Request. They were simply too expensive.

So the motivation for it comes from the original NRR

User's Request and the --

MR. SHEWMON: You are talking about IPIRG and I think he is talking about who in NRR was arguing for extending this beyond pipewhip restraint on primary piping.

MR. WARD: Yes, is there a User's Request letter?

MR. MAYFIELD: To extend it beyond that, no. There is not.

MR. SERPAN: There is not any specific User's Request for that replacement criterion. But we have taken it as an article of faith, and it has been talked about between NRR and within our office in such a way that there is no question that we are going to do that.

It has been woven within the fabric of the Piping Review Committee as well, but there is no specific piece of paper that says it.

MR. SHEWMON: My guess is if you don't talk about ECCS systems and do talk about secondary and smaller pipe or other things, you might raise fewer flags. But, I don't know.

Okay, is that all?

MR. MAYFIELD: I have one last one here.

(Slide)

I was asked to talk about leak before break. Essentially, all of our piping research looks at leak before break technology. The research results that we have today completely supports that. We found no surprises, nothing that

would tend to invalidate the regulatory positions. Essentially, they brought both the limited scope and broad scope modifications to GE C4.

Again, our future research will seek to provide a basis for the selection of a replacement to the double-ended guillotine break to the design basis.

That is all I have.

Questions?

MR. SHEWMON: I don't think there are any more.

I am glad to have that last slide. it is a good conclusion.

Thank you.

We are adjourned.

(Whereupon, at 12:05 p.m., the meeting was adjourned.)

# CERTIFICATE OF OFFICIAL REPORTER

This is to certify that the attached proceedings before the United States Nuclear Regulatory Commission in the matter of: ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

Name of Proceeding: ACRS Metal Components Subcommittee Meeting

Docket No.:

Place: Washington, D. C.

Date: Thursday, September 5, 1985

were held as herein appears and that this is the original transcript thereof for the file of the United States Nuclear Regulatory Commission.

(Signature) Mimie Meltzer

(Typed Name of Reporter) Mimie Meltzer

Ann Riley & Associates, Ltd.

# A REVIEW OF PROGRAM ELEMENTS
# OF THE
# MEBR PRESSURE VESSEL RESEARCH PROGRAM

SEPTEMBER 5,1985

PRESENTED TO

THE ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

BY

MILTON VAGINS
MATERIALS ENGINEERING BRANCH
DIVISION OF ENGINEERING TECHNOLOGY

## THE MEBR PRESSURE VESSEL RESEARCH PROGRAM ADDRESSES ISSUES CONCERNING THE INTEGRITY OF LIGHT-WATER REACTOR PRESSURE VESSELS

- THE PRIMARY OBJECTIVE OF THE PROGRAM IS TO EVALUATE THE EFFECTS OF FLAWS, VARIATIONS IN MATERIAL PROPERTIES (INCLUDING ENVIRONMENTAL EFFECTS), STRESS RISERS AND RESIDUAL STRESS ON THE INTEGRITY OF RPV'S UNDER NORMAL AND UPSET OR ACCIDENT CONDITIONS.

- THE PROGRAM RESULTS ARE UTILIZED TO IMPROVE ASME CODES, ASTM STANDARDS, REGULATORY GUIDES, FEDERAL REGULATIONS, AND THE SUPPORT OF THE NRC STAFF IN ITS LICENSING AND SAFETY EVALUATION PROCESS.

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## PRIME CONTRACTORS

| | |
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| 1) DOSIMETRY MEASUREMENT DATA BASE | B6244 |
| O HANFORD ENGINEERING LABORATORIES | |
| 1) SURVEILLANCE DOSIMETRY | B5988 |
| O PACIFIC NORTHWEST LABORATORIES | |
| 1) VISA CODE DEVELOPMENT | B2853 |

## MEBR PRESSURE VESSEL RESEACH PROGRAM DESCRIPTIONS

- OVERALL PROGRAM DESCRIPTION IN NUREG-1155, VOL.1 "RESEARCH PROGRAM PLAN, REACTOR VESSELS"

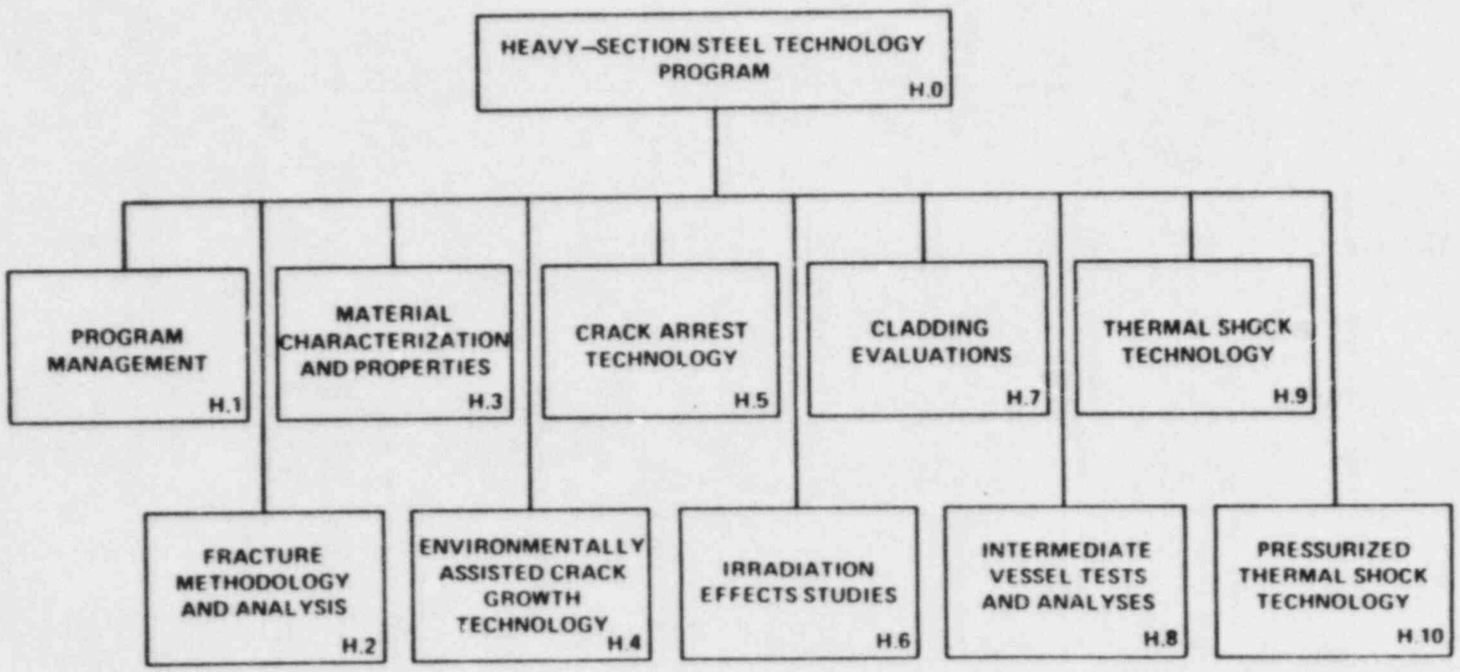
- HSST PROGRAM PLAN DESCRIPTION IN NUREG/CR-4275, "HEAVY SECTION STEEL TECHNOLOGY PROGRAM, FIVE YEAR PLAN, FY 1984-1988"

- MEA PROGRAM DESCRIPTION IN NUREG/CR-3788, "STRUCTURAL INTEGRITY OF LIGHT WATER REACTOR PRESSURE BOUNDARY COMPONENETS - FOUR YEAR PLAN, 1984 -1988"

- FURTHER PROGRAM DESCRIPTIONS FOUND IN 189'S AND RES RESEARCH PROGRAM CONTROL SYSTEM (RCPS)

ORNL-DWG 83-5011 ETD

# THE HEAVY–SECTION STEEL TECHNOLOGY PROGRAM IS COMPOSED OF NINE TECHNICAL TASKS AND A PROGRAM MANAGEMENT FUNCTION

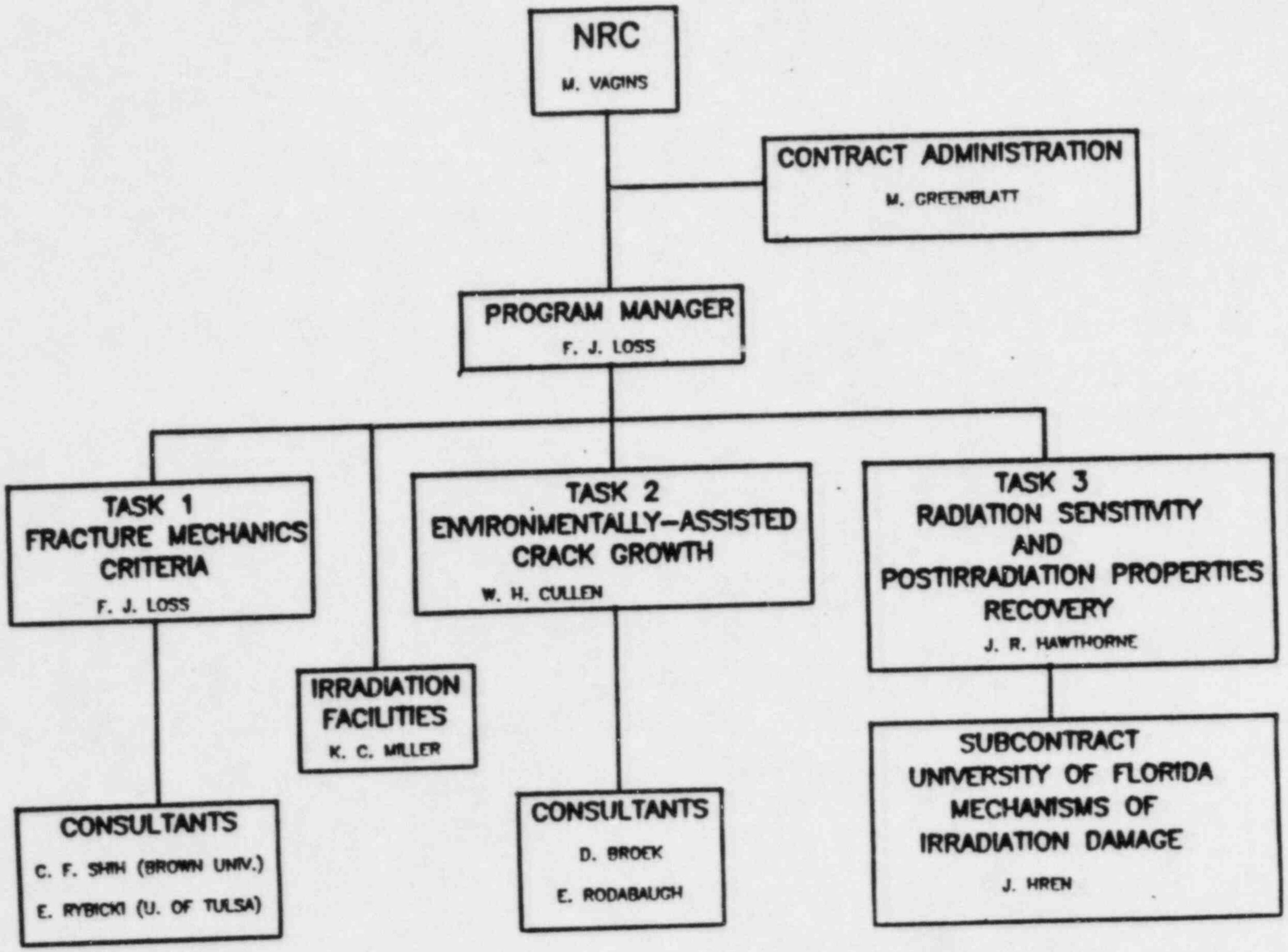


# THE HSST PROGRAM MAKES USE OF EXPERTISE OUTSIDE OF ORNL THROUGH SUBCONTRACTS

| TASK | SUBCONTRACTOR | 1984 | 1985 | 1986 | 1987 | 1988 |
|---|---|---|---|---|---|---|
| H.1 | CONSULTANTS | 60 | 55 | 36 | 38 | 36 |
| H.2 | U. OF MD. | 137 | 135 | 146 | 140 | 120 |
| H.2 | SwRI | 140 | 188 | 275 | 200 | 100 |
| H.4 | W-PED | 224 | 294 | 75 | 0 | 0 |
| H.5 | BCL | 158 | 61 | 25 | 30 | 0 |
| H.5 | NBS | 83 | 150 | 230 | 200 | 100 |
| H.6 | MEA* | 5 | 30 | 90 | 70 | 0 |
| H.6 | CE* | 177 | 78 | 0 | 0 | 0 |
| H.10 | B&W* | 149 | 0 | 344 | 0 | 0 |
| TOTAL | | 1133 | 991 | 1271 | 728 | 356 |

*SERVICES OBTAINED THROUGH PURCHASE ORDERS

STRUCTURAL INTEGRITY OF LWR BOUNDARY COMBONENTS



## STRUCTURAL INTEGRITY OF WATER REACTOR PRESSURE BOUNDARY COMPONENTS

TASK 1 FRACTURE ANALYSIS

- A. FRACTURE OF IRRADIATED CLAD VESSEL STEEL
- B. TEST METHODS CORRELATION
- C. WARM PRESTRESS: MODEL AND VALIDATION
- D. IRRADIATION-INDUCED $K_{Ic}$ CURVE SHIFT
- E. PIPING FRACTURE MECHANICS DATA BASE
- F. HSST 4TH IRRADIATION FRACTURE TOUGHNESS
- G. GUNDREMMINGEN VESSEL EMBRITTLEMENT

TASK 2 ENVIRONMENTALLY-ASSISTED CRACK GROWTH

- A. S-N CURVES FOR NUCLEAR STEELS
- B. ENVIRONMENTALLY-ASSISTED FATIGUE CRACK GROWTH (EAFCG)
- C. EFFECT OF GEOMETRY ON EAFCG
- D. EFFECT OF CLADDING ON EAFCG
- E. MECHANISM MODELS FOR EAFCG
- F. TOTAL FATIGUE PROCESS IN PWR ENVIRONMENTS
- G. CUMULATIVE DAMAGE FOR EAFCG
- H. ICCGR

TASK 3 RADIATION SENSITIVITY AND POSTIRRADIATION PROPERTIES RECOVERY

- A. HIGH TEMPERATURE ANNEALING
- B. COMPOSITION EFFECTS ON ANNEALING
- C. MECHANISM MODEL OF IRRADIATION DAMAGE
- D. IAR PHASE 2
- E. DOSE RATE EFFECTS
- F. VARIABLE RADIATION SENSITIVITY

ORNL-DWG 84-6361A ETD

# THE HSST PROGRAM BUDGET HAS INCREASED IN RECENT YEARS TO ACCOMMODATE MORE COMPLEX EXPERIMENTS AND INCREASED IRRADIATION WORK

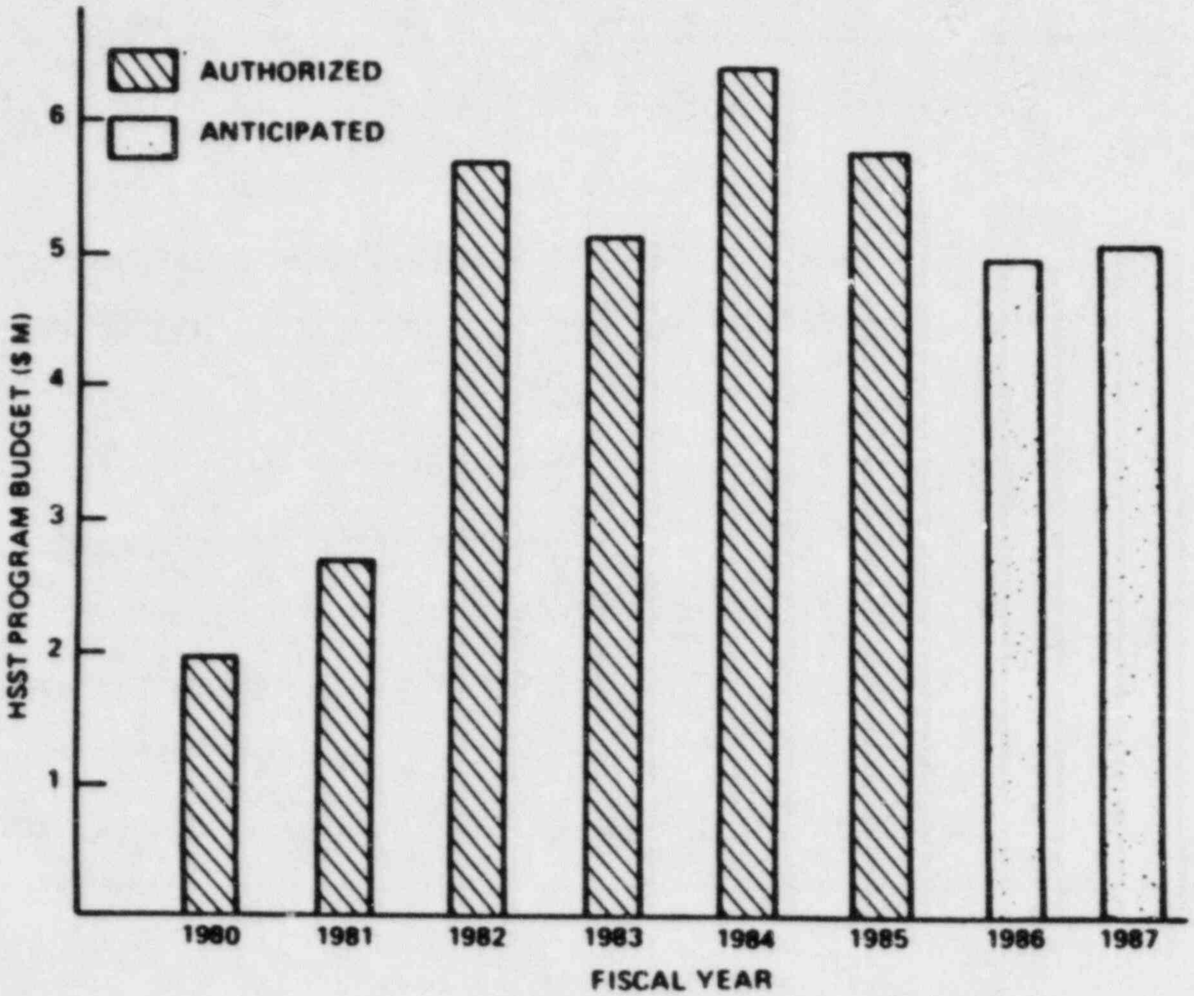
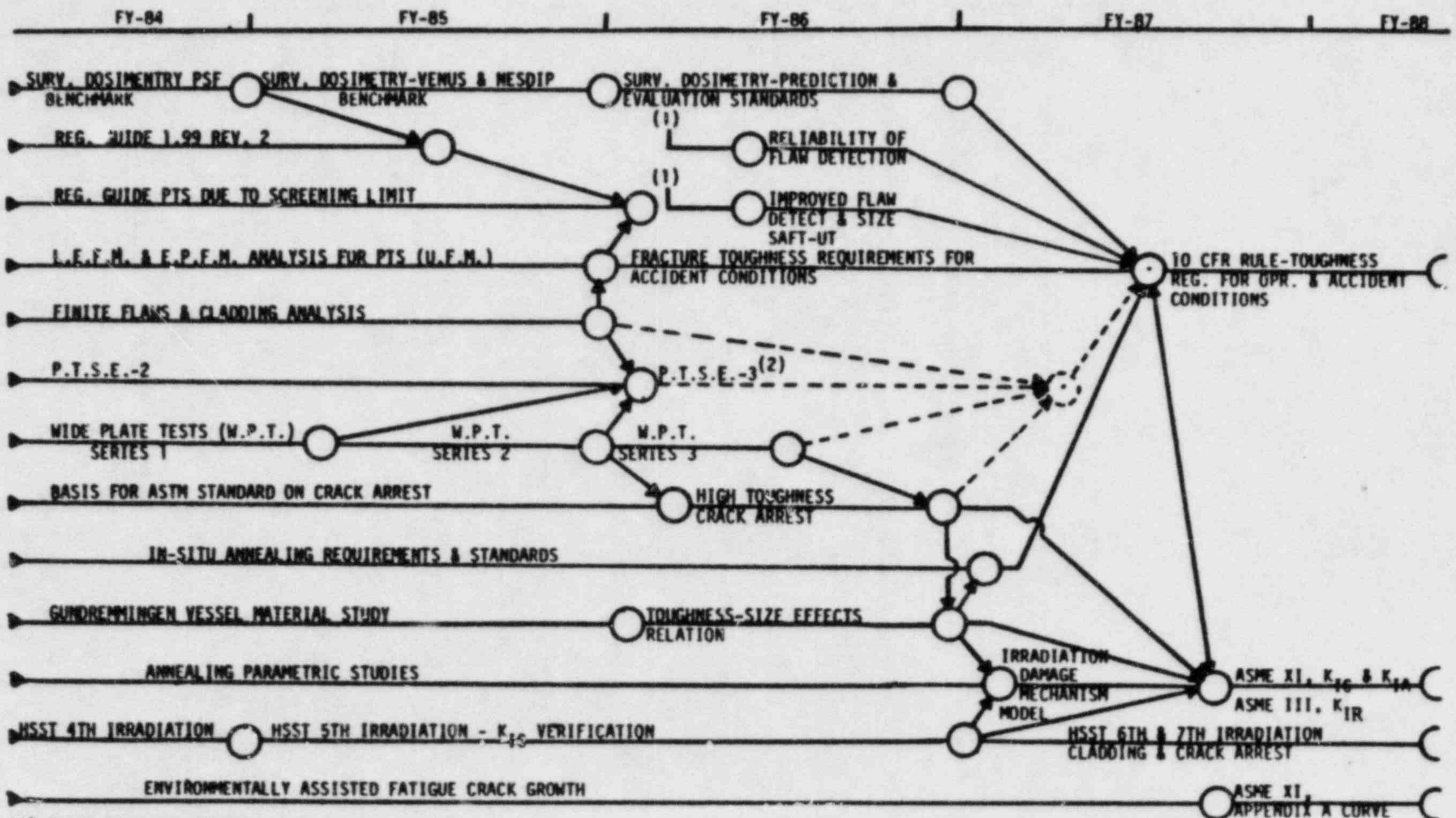


FIGURE 3 REACTOR VESSEL RESEARCH PLAN




(1) INPUT FROM NDE PROGRAM
(2) P.T.S.F.-3 NOT PRESENTLY FUNDED

10

## PROGRAM ELEMENTS TO BE DISCUSSED

- PRESSURIZED THERMAL SHOCK EXPERIMENT RESULTS AND PLANS
- WIDE-PLATE CRACK ARREST EXPERIMENTS
- CLADDING EFFECTS STUDY
- THE HSST 5th IRRADIATION (FRACTURE TOUGHNESS CURVE SHIFT VERIFICATION)
- THE HSST 6th IRRADIATION (IRRADIATED CRACK ARREST)
- ETHERINGTON CONCERNS ON LOW UPPER SHELF ENERGY

## Research Directed Toward Resolving Uncertainties in Fracture Mechanics as Pertinent to the Pressurized Thermal Shock Issue

Issues

1. Applicability of Linear Elastic Fracture Mechanics (LEFM) for initiation, propagation and arrest for reactor pressure vessels subjected to a pressurized thermal shock scenario.

2. Effectiveness of Warm Prestress

3. Vessel failure under nonpressurized thermal shock conditions.

4. Behavior of small finite flaw when subject to PTS conditions.

5. Cladding-flaw interaction; bimetallic effects.

6. Irradiated cladding material and fracture properties.

7. Arrest on the upper shelf.

8. Postarrest performance for a deep crack in upper shelf material toughness.

9. Definition of margin when using $RT_{NDT}$ to set fracture toughness curves.

10. Variation of through-wall fracture toughness degradation.

11. Validation of fracture toughness degradation as a function of fluence for ferritic, welds.

12. Effect of trace elements (copper, nickel, phosphorus) on the embrittlement rate of RPV steels at reactor operating conditions.

13. Effectiveness of thermal annealing on fracture toughness recovery and reembrittlement rate.

14. Establishments of criteria and standards to be applied to any proposed, in situ thermal annealing of operating reactor vessels.

# PRESSURIZED THERMAL SHOCK EXPERIMENTS
# PTSE1, PTSE2

FRACTURE PHENOMENA AT ISSUE IN PRESSURIZED THERMAL SHOCK

- WARM PRESTRESSING EFFECT ON CRACK INITIATION
- CRACK PROPAGATION FROM BRITTLE TO DUCTILE REGIONS
- TRANSIENT CRACK STABILIZATION IN DUCTILE REGIONS
- CRACK SHAPE CHANGES IN BIMETALLIC ZONES OF CLAD VESSELS

ORNL-WS-34058 ETD

# CRITERIA FOR PRESSURIZED–THERMAL–SHOCK EXPERIMENTS

SCALE –

LARGE ENOUGH TO PROVIDE FULL–SCALE RESTRAINT ON FLAW

TEST CONDITIONS –

REALISTIC (PWR) STRESS FIELDS AND GRADIENTS

REALISTIC FRACTURE TOUGHNESS IN ZONE OF ACTION

ATTAINABLE FRACTURE CONDITIONS –

CLEAVAGE INITIATION WITH ARREST BELOW AND ON UPPER SHELF

ARREST IN HIGH $K_I$ GRADIENT

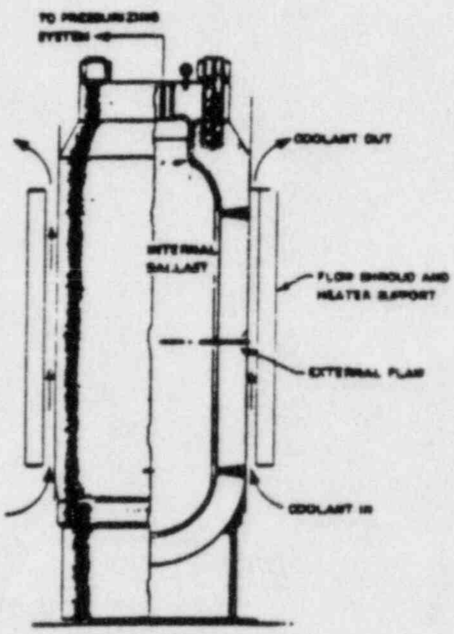
PROGRESSIVE DUCTILE TEARING WITH INTERVENTION OF INSTABILITY AND RESTABILIZATION

STATES OF WARM PRESTRESSING:

SIMPLE ($\dot{K}_I < 0$)
MARGINAL ($\dot{K}_I \simeq 0$)
COMPLEX ($\dot{K}_I > 0$ WITH $K_I < K_{Imax}$)
ALTERNATING SEQUENCES

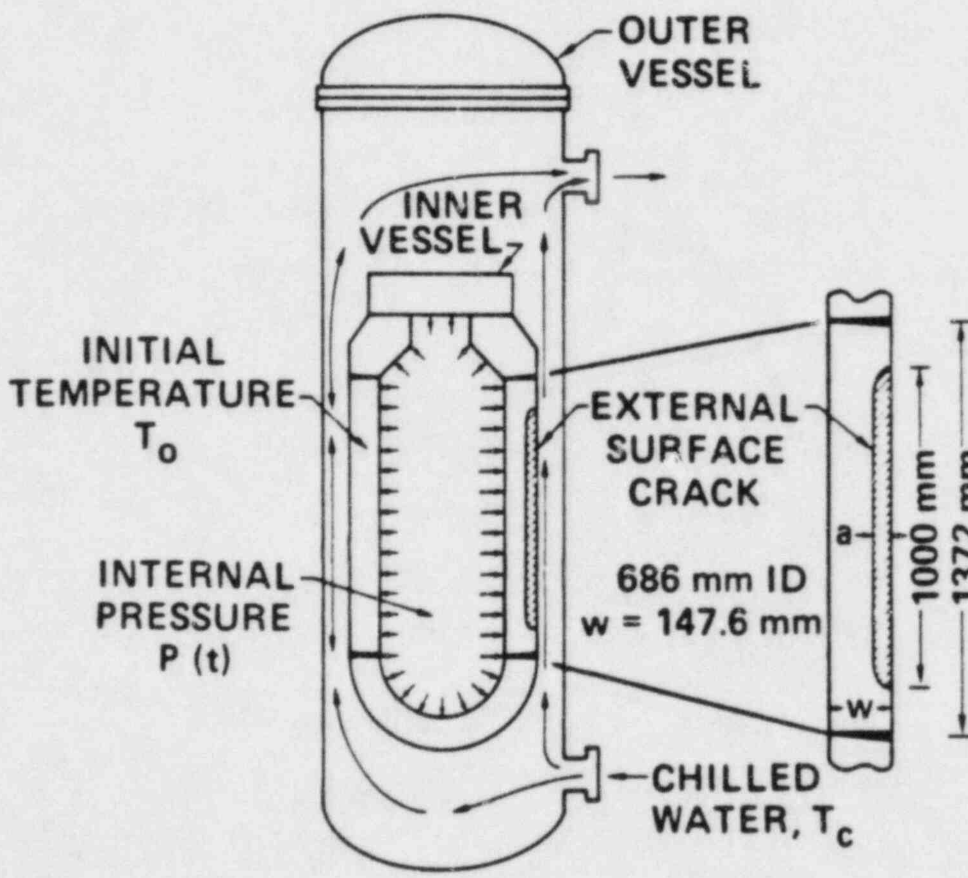
ORNL-DWG 81-8174A

PRESSURIZED-THERMAL-SHOCK EXPERIMENTS USE HSST INTERMEDIATE VESSELS TO INVESTIGATE METHODS OF PREDICTION OF FLAW BEHAVIOR UNDER COMBINED THERMAL AND PRESSURE LOADS IN FRACTURE REGIMES IMPORTANT TO RPV SAFETY



ORNL-DWG 83-5459 ETD

# PRESSURIZED–THERMAL–SHOCK TEST VESSEL WITH LONGITUDINAL OUTER SURFACE CRACK



PRESSURIZED-THERMAL-SHOCK EXPERIMENTS ARE UNIQUE

- IN ABILITY TO PROVIDE CONSTRAINT ON CRACK AS RPV'S DO (PLANE STRAIN). SMALLER STRUCTURES OR SPECIMENS EXHIBIT UNTYPICALLY HIGH (UNCONSERVATIVE) VALUES OF TOUGHNESS IN HIGH $K_I$ SITUATIONS.

- IN ABILITY TO GENERATE RPV-LIKE COMBINED STRESS FIELDS AND TOUGHNESS STATES

- IN ABILITY TO PRODUCE ANTI-WARM-PRESTRESSING TRANSIENTS AT HIGH $K_I$ LEVELS

- IN MAINTAINING PLANE STRAIN CONDITIONS FOR
  - (1) HIGH $K_{Ia}$ OBSERVATIONS OR
  - (2) DUCTILE FRACTURE

ORNL-WS-34056 ETD

# PRESSURIZED-THERMAL-SHOCK EXPERIMENTS ARE DESIGNED TO DETERMINE APPLICABILITY OF METHODS OF ANALYSIS OF FLAWS UNDER COMBINED LOADINGS

| EXPERIMENT | OBJECTIVES |
|---|---|
| PTSE-1 | WARM PRESTRESSING EFFECTIVENESS, ARREST ON DUCTILE SHELF |
| PTSE-2 | ARREST ON DUCTILE SHELF IN LOW-UPPER-SHELF MATERIAL; WARM PRESTRESSING EFFECTIVENESS |
| PTSE-3 | INFLUENCE OF STAINLESS STEEL CLADDING IN RESTRICTING SMALL FLAW GROWTH |

## PRESSURIZED THERMAL SHOCK EXPERIMENT

## PTSE-1

OBJECTIVES

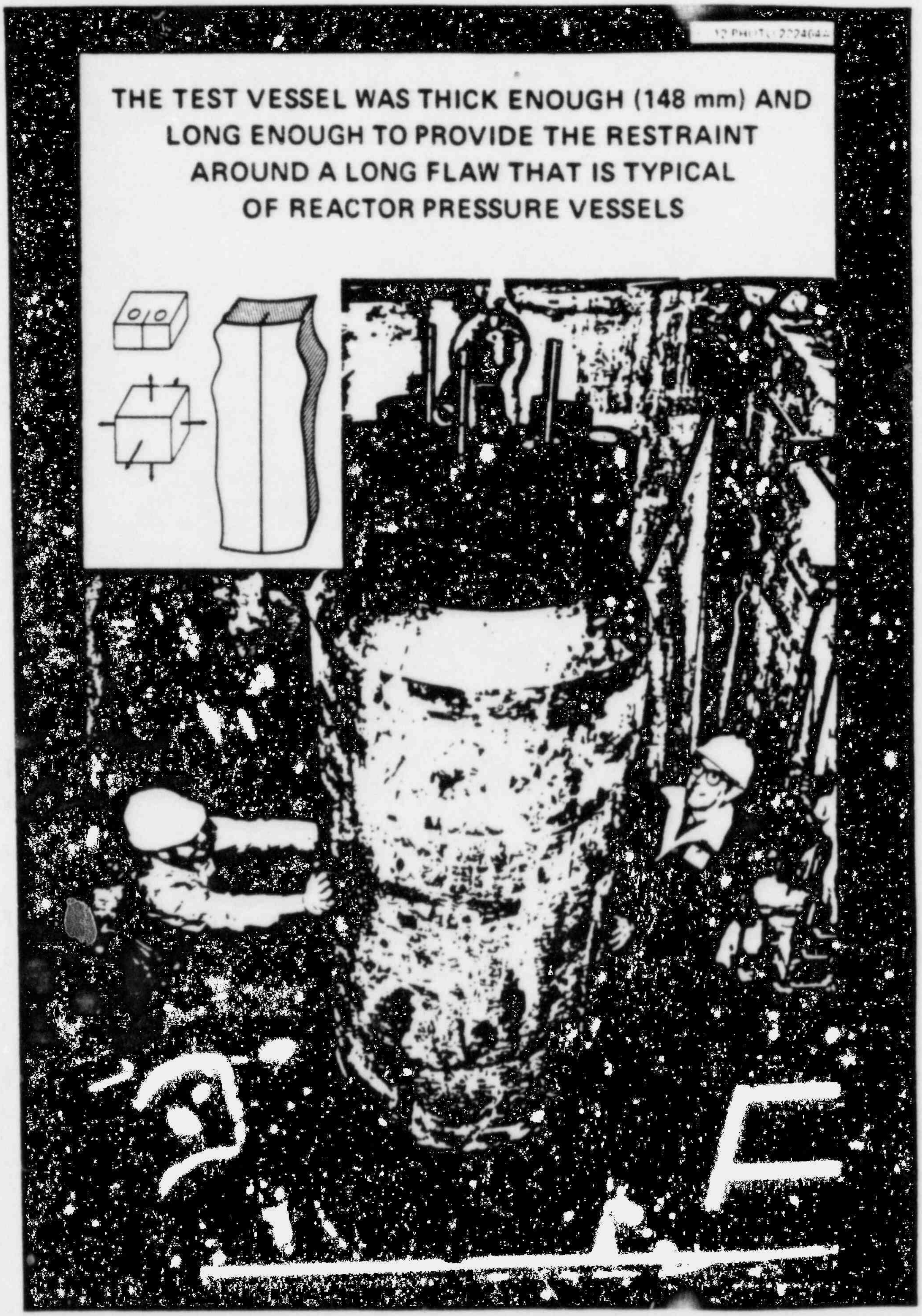
A) VALIDATE DEVELOPED FRACTURE MECHANICS COMPUTER CODES

B) VALIDATE OR SHOW CONSERVATISM OF THE ASME, B&PV CODE, SECTION XI CRACK EVALUATION ANALYTIC PROCEDURES FOR PTS SCENARIOS

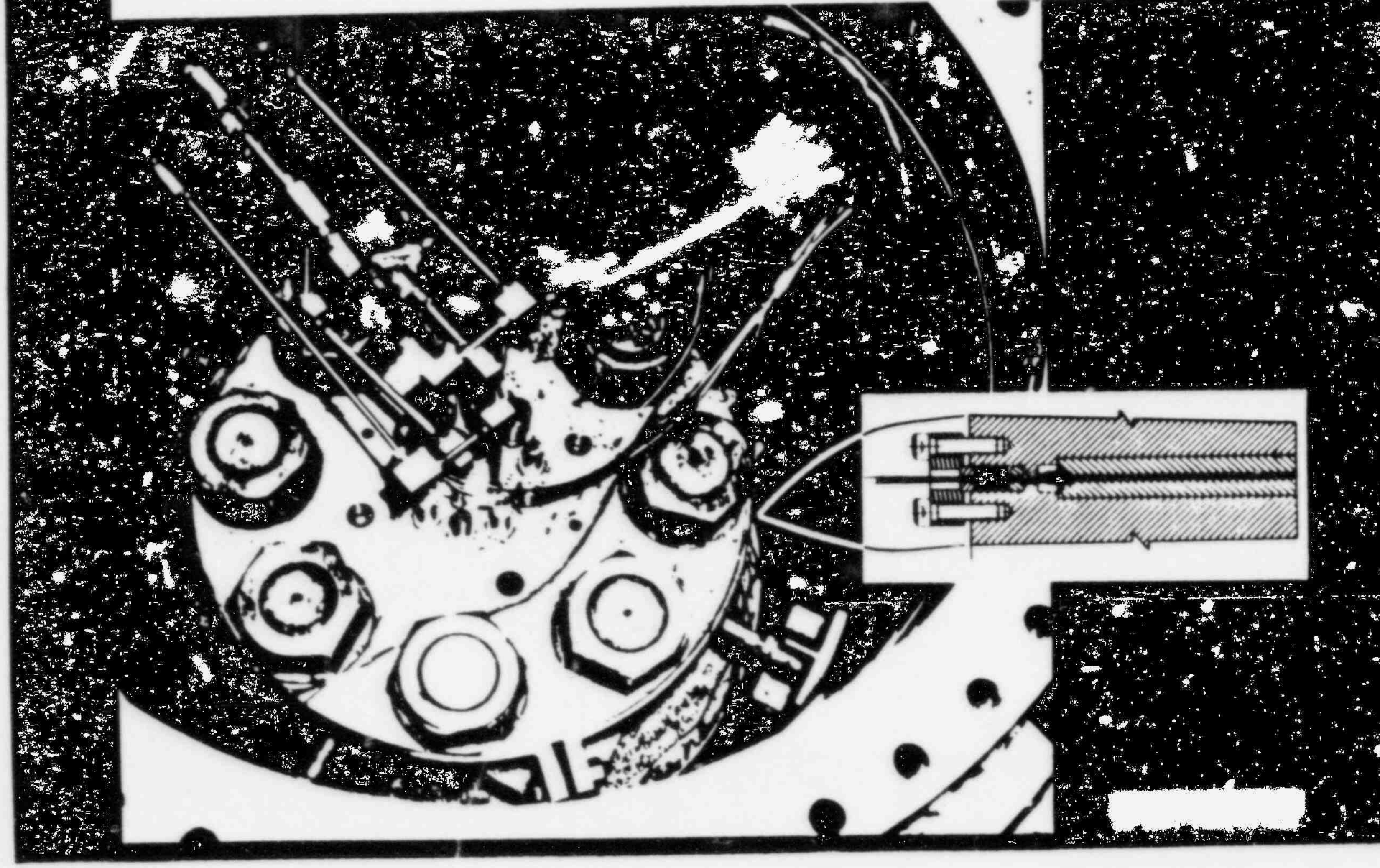
C) DEVELOP DATA INTO REACTOR PRESSURE VESSEL MATERIAL FRACTURE BEHAVIOR AS REGARDS FAST RUNNING CRACKS AT HIGH TOUGHNESS LEVELS

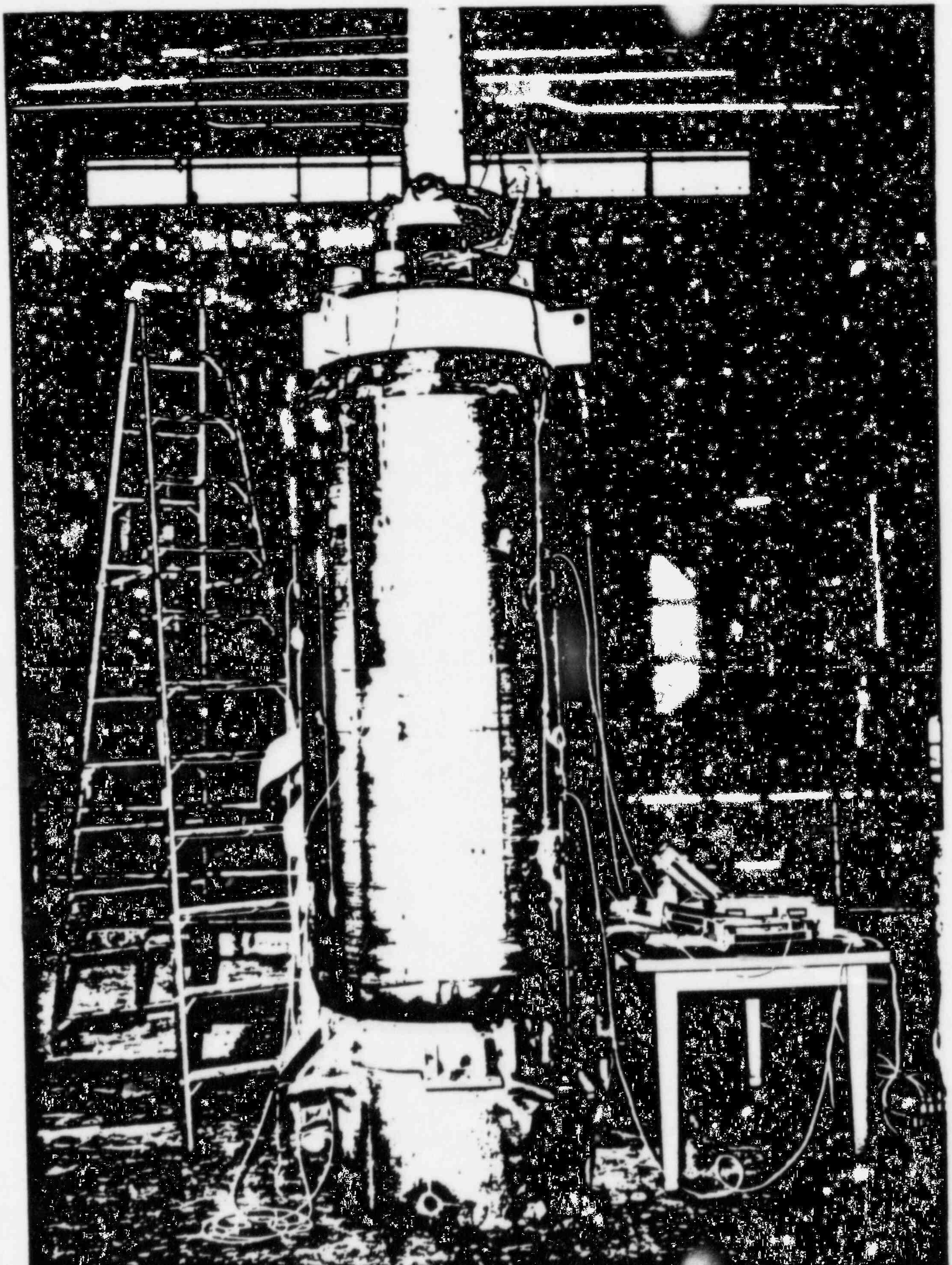
D) VALIDATE NEW METHODOLOGY FOR ACCURATELY DETERMINING REACTOR PRESSURE VESSEL IN-SITU FRACTURE TOUGHNESS CHARACTERISTICS FROM SMALL LABORATORY SPECIMEN DATA

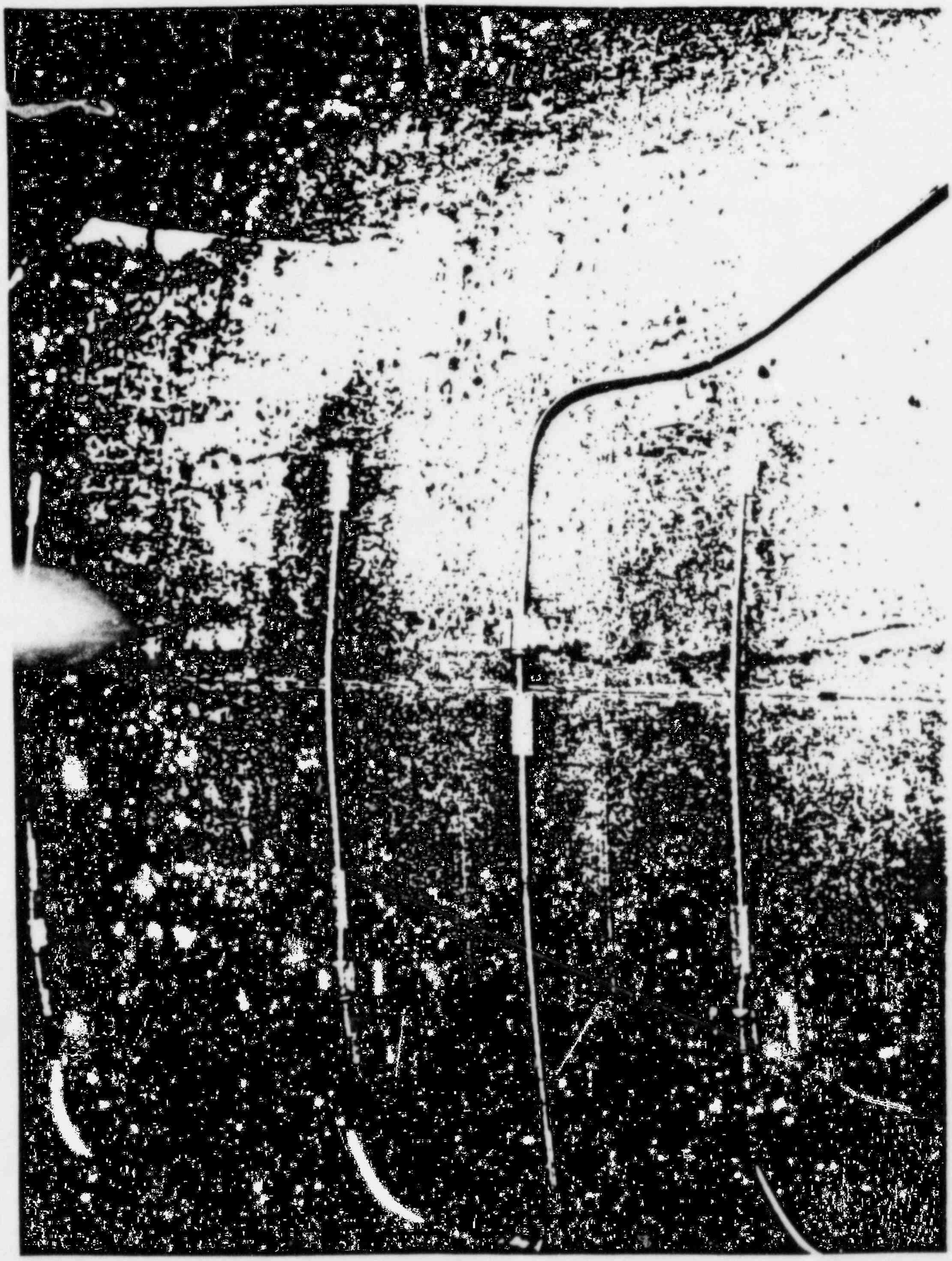
E) VALIDATE OR SHOW CONSERVATISM OF PRESENT POSITION OF THE NRC AS REGARDS THE PTS ISSUE


THE TEST VESSEL WAS THICK ENOUGH (148 mm) AND
LONG ENOUGH TO PROVIDE THE RESTRAINT
AROUND A LONG FLAW THAT IS TYPICAL
OF REACTOR PRESSURE VESSELS

THE TEST VESSEL WAS INSTRUMENTED WITH 161 SENSORS FOR MEASURING INTERNAL PRESSURE, TEMPERATURE PROFILES, AND CRACK–MOUTH–OPENING DISPLACEMENTS AT THE RATE OF 10,000 POINTS PER SECOND



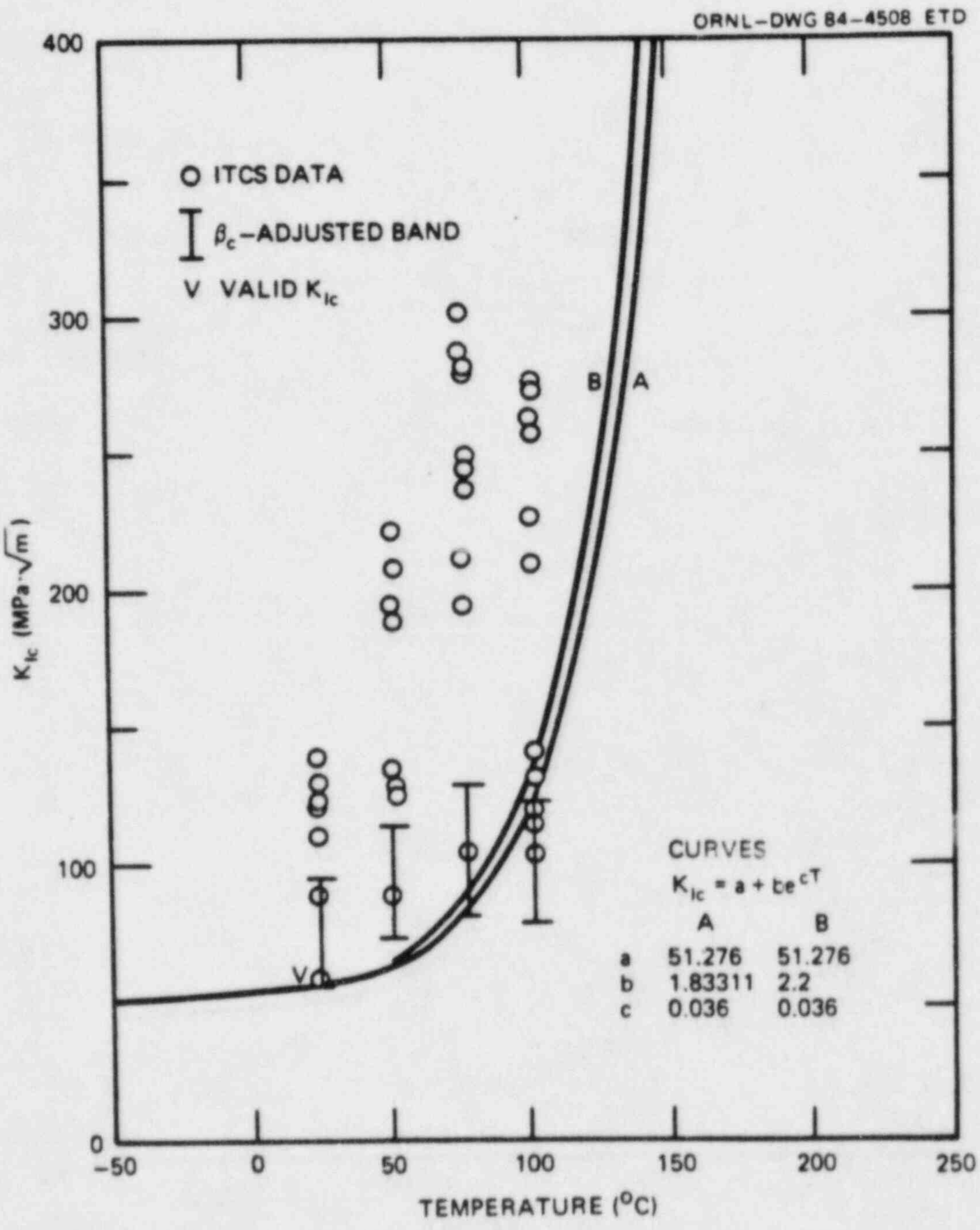


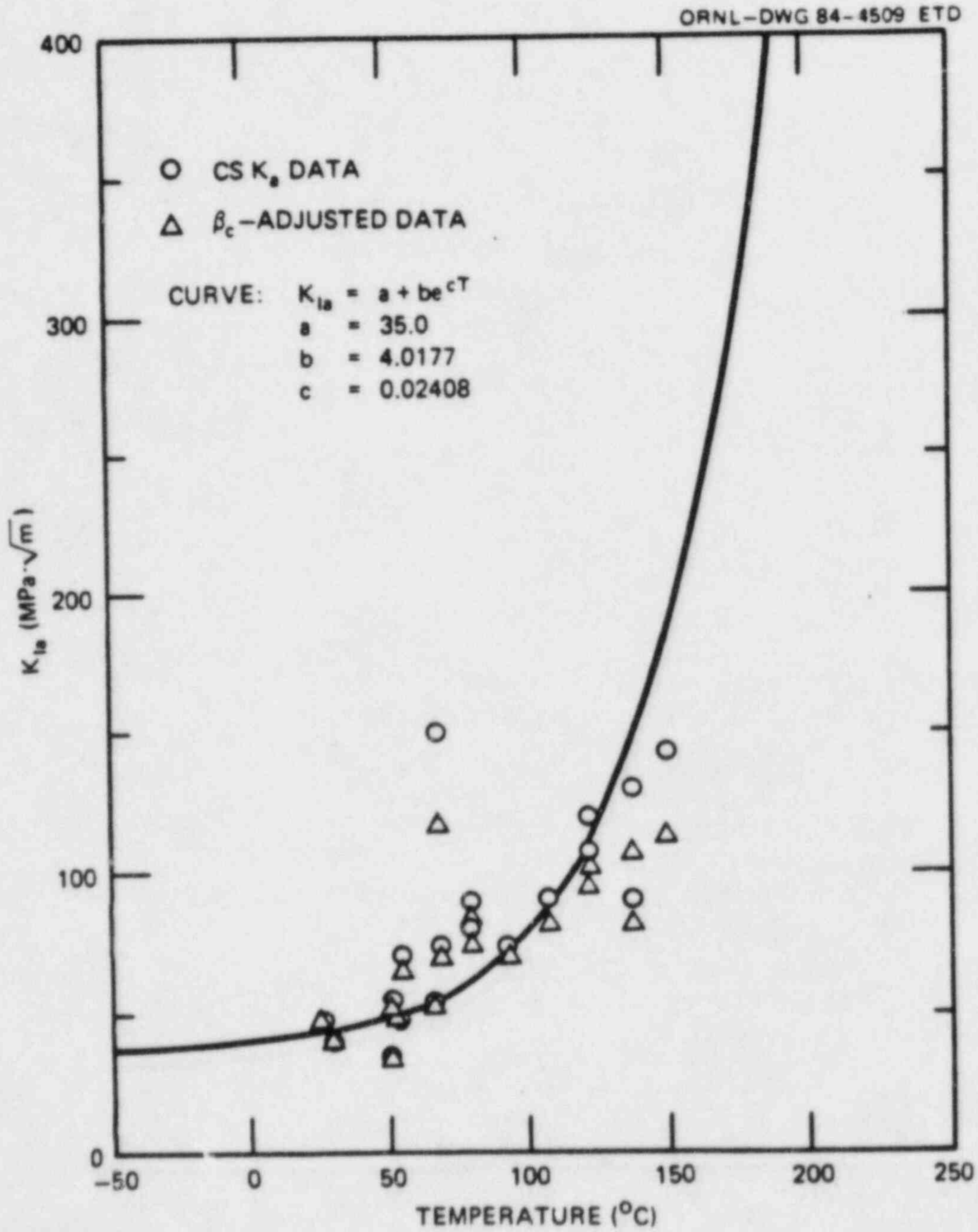


ORNL-WS-34055 ETD

# GEOMETRIC PARAMETERS OF PTSE–1 VESSEL

| PARAMETER | VALUE |
|---|---|
| INSIDE RADIUS, mm | 343 |
| WALL THICKNESS (w), mm | 147.6 |
| FLAW LENGTH, mm | 1000 |
| FLAW DEPTH (a), mm | 12.2 |
| a/w | 0.083 |


ORNL-DWG 84-4508 ETD
ITCS DATA
$\beta_c$-ADJUSTED BAND
V VALID $K_{Ic}$
$K_{Ic}$ (MPa·$\sqrt{m}$)
TEMPERATURE (°C)
400
300
200
100
0
-50
0
50
100
150
200
250
B
A
V
CURVES
$K_{Ic} = a + be^{cT}$
A B
a 51.276 51.276
b 1.83311 2.2
c 0.036 0.036


ORNL-DWG 84-4509 ETD
CS $K_a$ DATA
$\beta_c$–ADJUSTED DATA
CURVE: $K_{Ia} = a + be^{cT}$
a = 35.0
b = 4.0177
c = 0.02408
$K_{Ia}$ (MPa·√m)
TEMPERATURE (°C)
400
300
200
100
0
−50
0
50
100
150
200
250

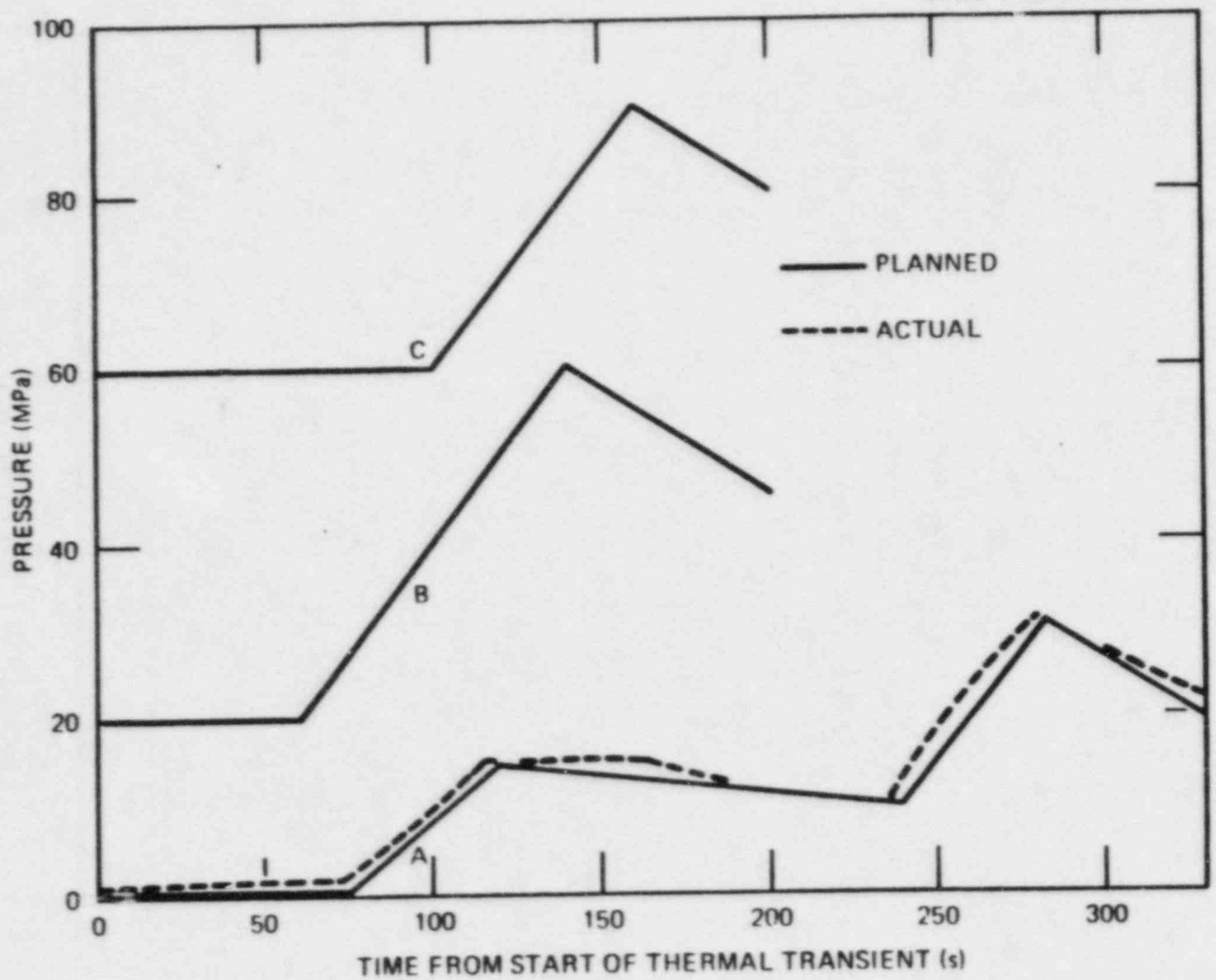
ORNL–WS–34052 ETD

# PROPERTIES OF PTSE–1 VESSEL MATERIAL (A508, CLASS 2 STEEL WITH SPECIAL TEMPERING TREATMENT)

| PROPERTY | VALUE |
|---|---|
| $K_{Ic}$ | CURVE FROM CS DATA |
| $K_{Ia}$ | CURVE FROM CS DATA |
| $J_R$ PARAMETERS[a] | |
| c | 2.60 |
| n | 0.359 |
| ONSET OF CHARPY UPPER SHELF, °C | 150 |
| DUCTILE THRESHOLD TEMPERATURE, °C | 175 |
| RTNDT, °C | 91 |
| YIELD STRESS, MPa | 600 |
| STRESS–STRAIN | CURVE FROM DATA |
| YOUNG'S MODULUS, GPa | 202.3 |
| COEFFICIENT OF THERMAL EXPANSION, $K^{-1}$ | $1.441 \times 10^{-5}$ |
| POISSON'S RATIO | 0.3 |
| THERMAL CONDUCTIVITY, $W \cdot m^{-1} \cdot K^{-1}$ | 41.54 |
| HEAT CAPACITY, $J \cdot kg^{-1} \cdot K^{-1}$ | 502.4 |
| DENSITY, $kg/m^3$ | 7833 |

[a] $J_R = c\,(\Delta a)^n$; $J_R$ in $MJ/m^2$, $\Delta a$ in m

ORNL-DWG 85-4485 ETD



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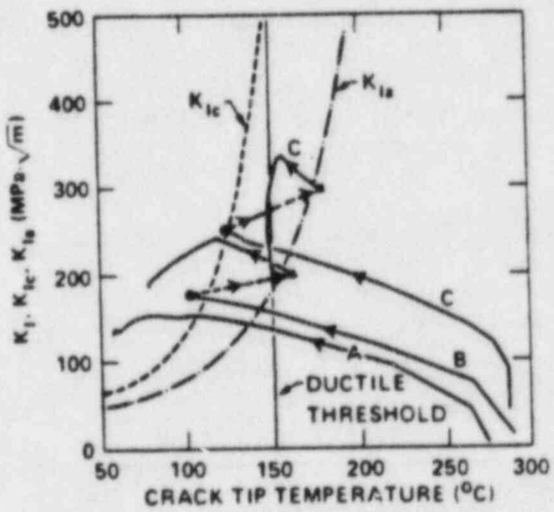
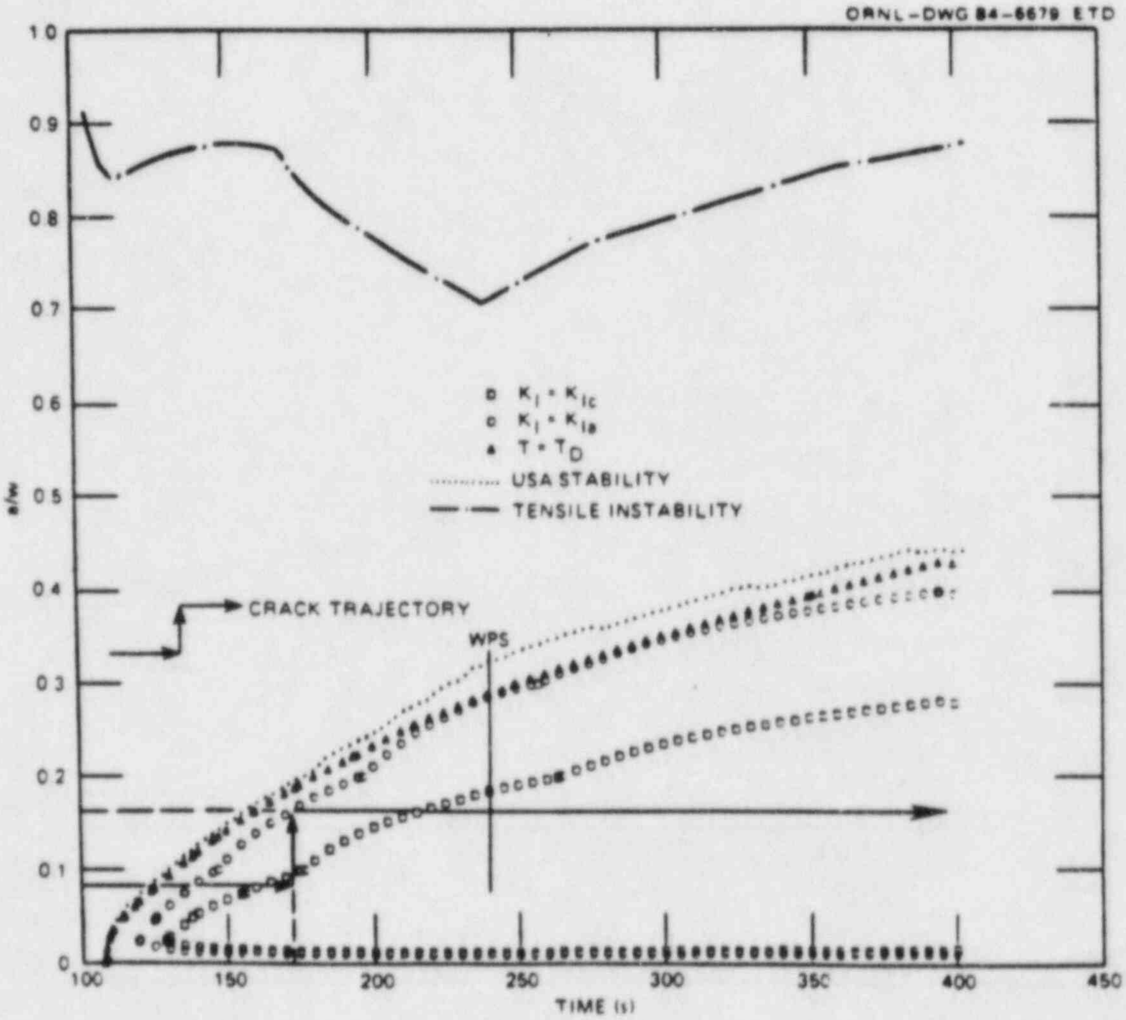
ORNL-DWG 85-4040 ETD

THE THREE TRANSIENTS INDUCED CRACK BEHAVIOR DEMONSTRATING IMPORTANT ASPECTS OF WARM PRESTRESSING AND ARREST IN THE DUCTILE REGION



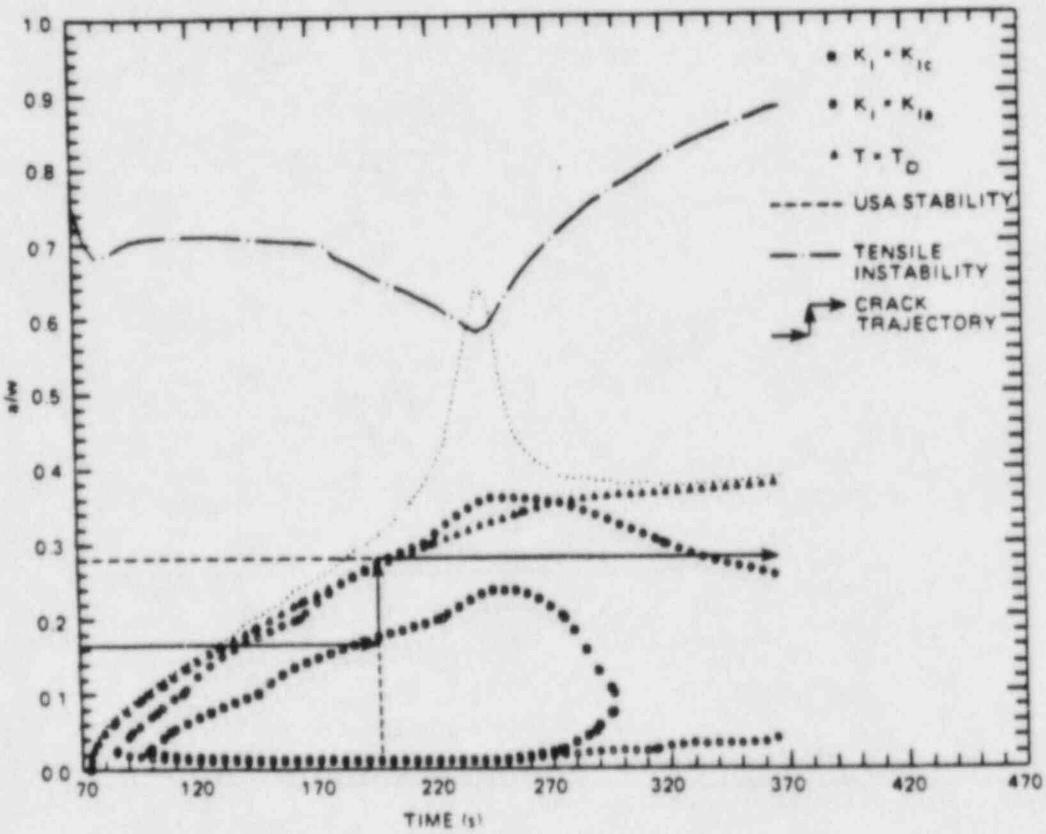
SUMMARY OF FRACTURE CONDITIONS IN PTSE-1

| EXPERIMENT | EVENT | CRACK DEPTH (mm) | CRACK TIP TEMPERATURE (°C) | $K_I$ (MPa·$\sqrt{m}$) |
|---|---|---|---|---|
| PTSE-1A | 1st max $K_I$ | 12.2 | 105 | 152 |
| | 2nd max $K_I$ | 12.2 | 78 | 154 |
| | 3rd max $K_I$ | 12.2 | 57 | 139 |
| PTSE-1B | INITIATION | 12.2 | 104 | 177 |
| | ARREST | 24.4 | 164 | 201 |
| | SUBSEQUENT max $K_I$ | 24.4 | 118 | 247 |
| PTSE-1C | INITIATION | 24.4 | 125 | 254 |
| | ARREST | 41 | 179 | 299 |
| | SUBSEQUENT max $K_I$ | 41 | 156 | 340 |



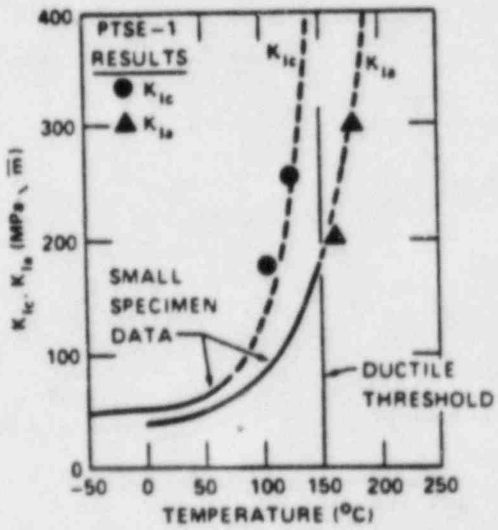
ORNL-DWG 84-6679 ETD
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
a/w
100
150
200
250
300
350
400
450
TIME (s)
$K_I = K_{Ic}$
$K_I = K_{Ia}$
$T = T_D$
USA STABILITY
TENSILE INSTABILITY
CRACK TRAJECTORY
WPS

ORNL-DWG 84-6683 ETD



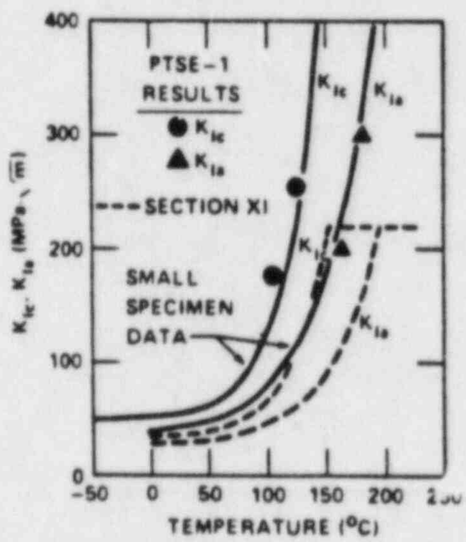
ORNL-DWG 85-4041 ETD

**IN PTSE-1, INITIATION AND ARREST EVENTS WERE WELL PREDICTED BY LINEAR ELASTIC FRACTURE MECHANICS BASED ON SMALL SPECIMEN DATA**



ORNL-DWG 85-4042R ETD

**EXPERIMENTAL TOUGHNESS VALUES ARE SUBSTANTIALLY HIGHER THAN THE VALUES PRESCRIBED BY SECTION XI OF THE ASME BOILER AND PRESSURE VESSEL CODE**



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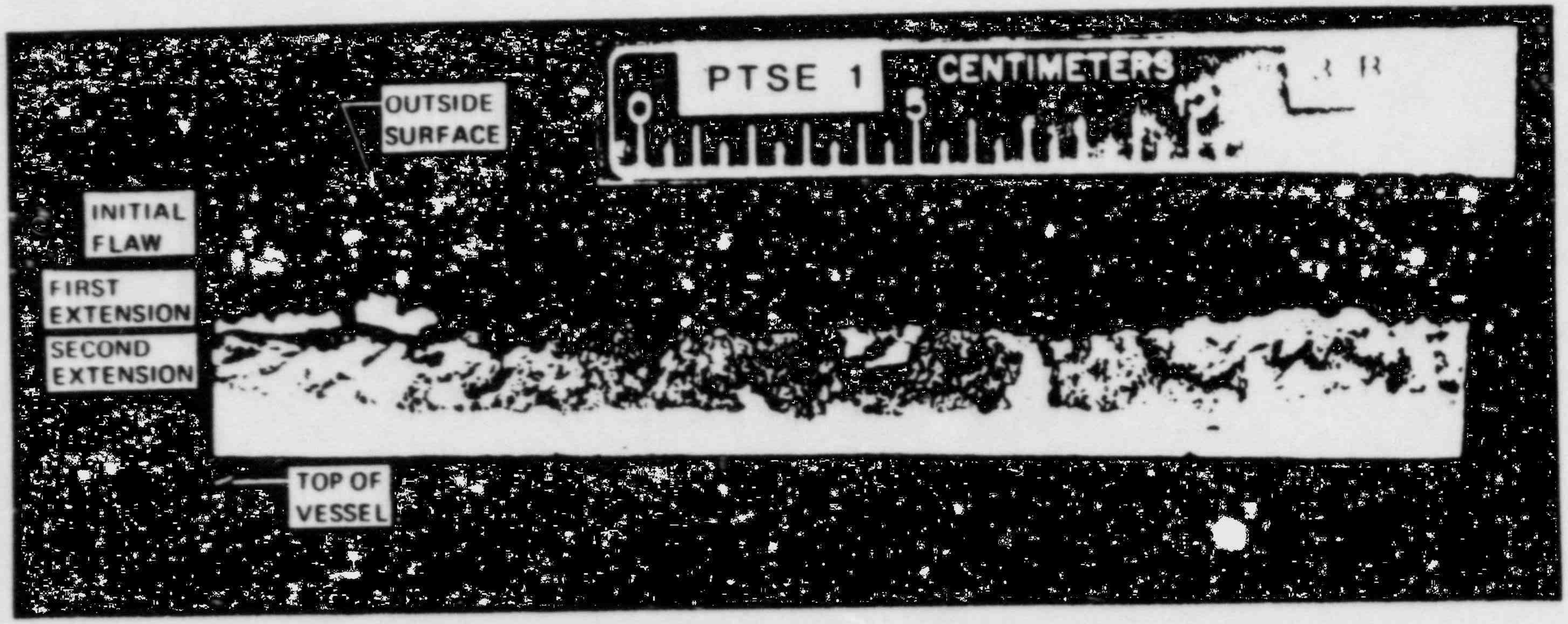
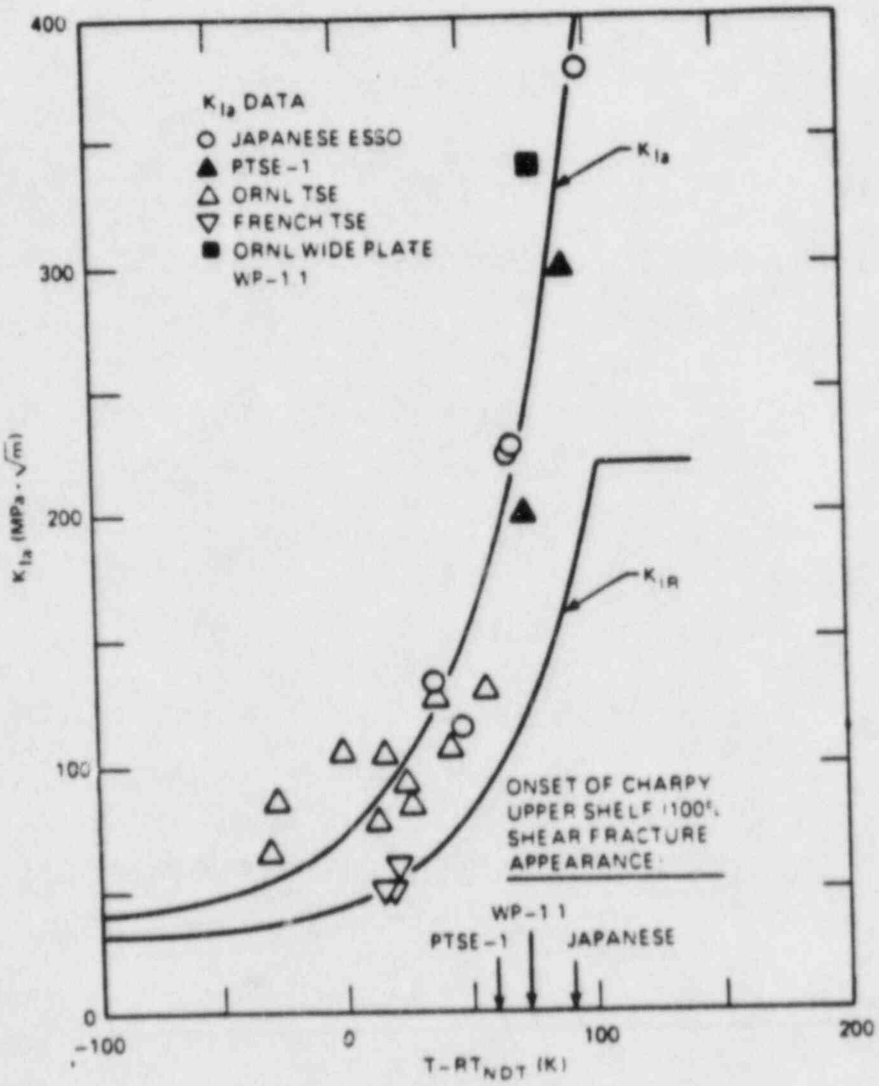


ORNL-DWG 84-6694 ETD



## PTSE-1 ACHIEVEMENTS

1. DEMONSTRATED SECTION III & SECTION XI FLAW EVALUATIONS TO BE CONSERVATIVE
2. DEMONSTRATED EFFECTIVENESS OF WARM PRESTRESS EFFECT
3. DEMONSTRATED ACCURACY OF DEVELOPED METHODOLOGY AND COMPUTER CODES
4. DEMONSTRATED REALITY OF CRACK ARREST IN A STEEPLY RISING K FIELD
5. DEMONSTRATED APPLICABILITY OF LEFM FOR THICK SECTIONS, HIGH IN TRANSITION ZONE
6. DEMONSTRATED THAT THE T-RTNDT METHOD OF DEVELOPING FRACTURE TOUGHNESS CURVES VALID
7. DEMONSTRATED EFFECTIVENESS OF NEW METHOD OF DETERMINING FRACTURE TOUGHNESS OF THICK SECTIONS FROM SMALL LABORATORY SPECIMENS

Impact on NRC Regulatory Postions

The impact of the results of these tests on the NRC regulatory positions for pressure vessel integrity are clear, particularly as regards PTS and overcooling scenarios in general. This can be summarized as follows:

1. The analysis techniques used to establish the fracture mechanics portion of the PTS position are accurate and slightly conservative. If the loading and material toughness properties are known, then an accurate evaluation of the structural integrity of the reactor vessel can be predicted.

2. Warm prestressing is a real factor in the prevention of initiation or extension of cracks for vessels under going an overcooling scenario. Considering that analysis of approximately 95 percent of actual PTS scenarios that have occurred resulted in WPS preventing pressure vessel failure, and that WPS was not treated as a distributed variable in the probability analysis establishing the PTS screening criteria, indicates that the possibility of a PTS event causing pressure vessel failure is probably an order of magnitude lower than presently estimated.

3. The analysis methodology presently used in the PTS scenarios are completely applicable to the analysjs of any transient vessel performance where at least the inner portion of the pressure vessel wall's metal are in the transition fracture toughness range. A case in point is the problem of cold-overpressurization.

LESSONS FROM PRESSURIZED-THERMAL-SHOCK EXPERIMENTS

- WARM PRESTRESSING EFFECTS ARE A RELIABLE MECHANISM FOR INHIBITING CLEAVAGE FRACTURE
- CRACK-ARREST TOUGHNESS MUCH HIGHER THAN THE SECTION XI CUTOFF CAN BE REALIZED
- THE USEFUL RANGE OF LEFM MAY EXTEND ABOVE THE ONSET OF THE CHARPY UPPER SHELF
- CONVENTIONAL $J_R$-CURVE ANALYSIS FOR ESTIMATING STABLE DUCTILE CRACK GROWTH MAY BE VERY CONSERVATIVE

UNRESOLVED PROBLEMS ADDRESSED IN PTSE-2

GENERAL - EXPERIMENTAL EVIDENCE TO SUPPORT THEORETICAL MODELS USED IN RPV EVALUATION

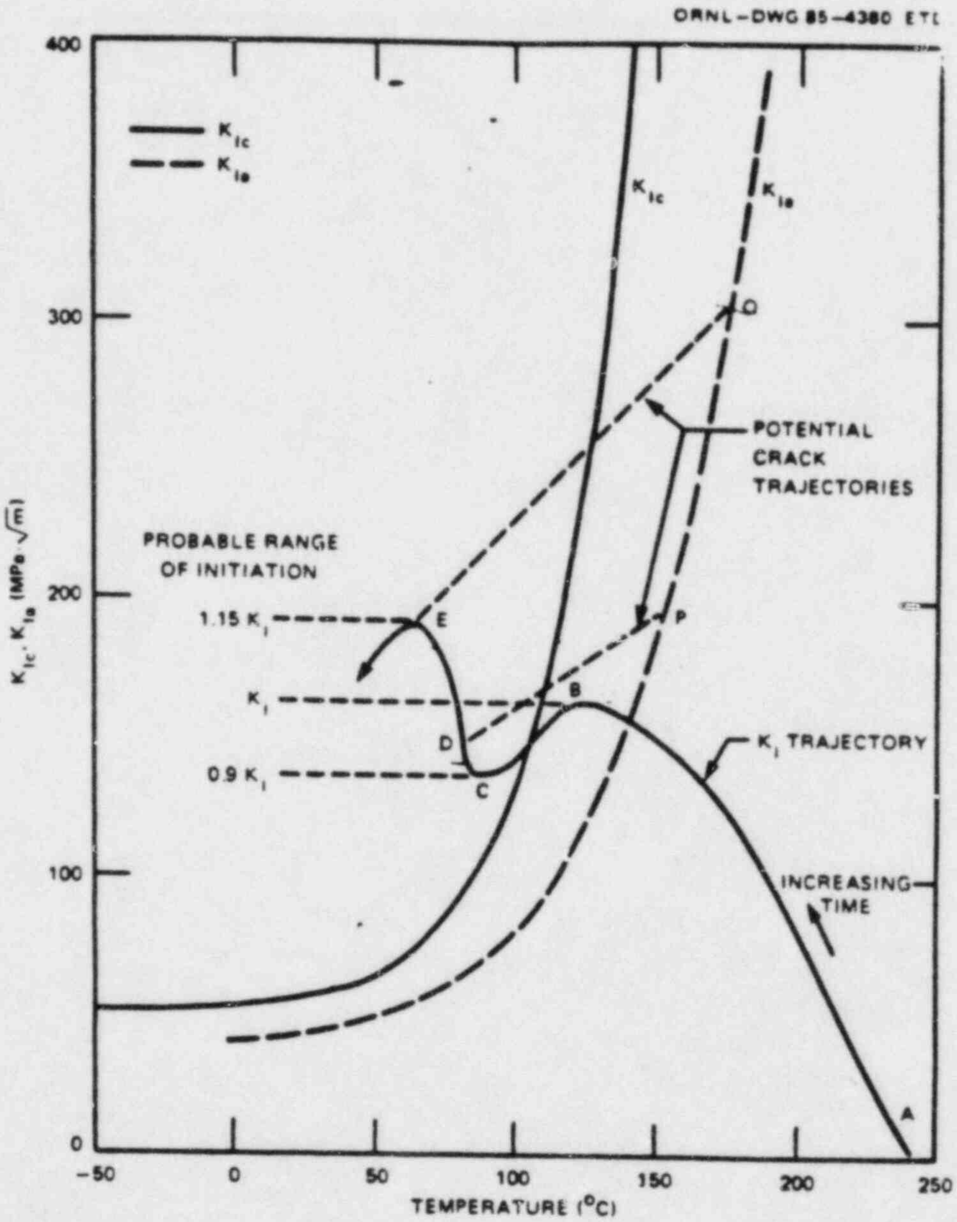
- MODE OF CRACK INITIATION IN LOW-UPPER-SHELF MATERIAL: TEARING PRIOR TO CLEAVAGE?
- MODE CONVERSION (CLEAVAGE TO TEARING) OF A RAPIDLY PROPAGATING CRACK
- LIMITS OF ANTI-WARM-PRESTRESSING BENEFITS (WHEN $K_I$ AND PLASTIC ZONE EXCEED PRIOR MAXIMA)

PLANNED PTSE-2 EXPERIMENT

MATERIAL – LOW-TEARING-RESISTANCE INSERT WITH CHARPY-V IMPACT ENERGY 54 TO 68 J

FLAW – 1-m LONG, UNIFORM DEPTH, CRACKED EB WELD

OBJECTIVES OF TRANSIENT DESIGN – TO PRODUCE A DEEP CRACK JUMP AFTER WARM PRESTRESSING WITH ARREST OCCURRING ONLY AFTER MODE CONVERSION FROM BRITTLE TO DUCTILE FRACTURE


ORNL-DWG 85-4380 ETD
$K_{Ic}$
$K_{Ia}$
$K_{Ic}$, $K_{Ia}$ (MPa·$\sqrt{m}$)
TEMPERATURE (°C)
PROBABLE RANGE
OF INITIATION
1.15 $K_I$
$K_I$
0.9 $K_I$
POTENTIAL
CRACK
TRAJECTORIES
$K_I$ TRAJECTORY
INCREASING
TIME
A
B
C
D
E
O
P
400
300
200
100
0
-50
0
50
100
150
200
250

# UNIRRADIATED CRACK ARREST STUDIES
# INCLUDING
# THE
# WIDE-PLATE TEST SERIES

ORNL-WS-26950 ETD

# HSST TASK H.5, CRACK ARREST TECHNOLOGY

OBJECTIVE:

TO PROVIDE CRACK ARREST TEST DATA OVER RANGES OF TEMPERATURES AND MATERIALS, TO SUPPORT STRUCTURAL TESTS, TO VALIDATE ASTM TEST PROCEDURES, AND TO DEVELOP PROCEDURES FOR REMOTE TESTING

KEY ACCOMPLISHMENTS TO DATE:

- DEVELOPED CONCEPTS TO OBTAIN REFERENCE DATA FOR ASME B&PV CODES
- PRODUCED DATA IN SUPPORT OF HSST EXPERIMENTAL PROGRAMS
- ACTIVELY PARTICIPATED IN FORMULATION OF ASTM DRAFT STANDARD FOR CRACK ARREST TESTING

ORNL-WS-26951 ETD

# HSST TASK H.5, CRACK ARREST TECHNOLOGY

CURRENT GOALS:

- COORDINATE AND PARTICIPATE IN ASTM ROUND ROBIN TESTING PROGRAM
- DEVELOP SPECIMENS AND PROCEDURES FOR TESTING SURVEILLANCE SPECIMENS
- DEVELOP MODIFIED SPECIMEN TO INCREASE MEASURING CAPACITY
- DEFINE AND PERFORM PLATE TESTS FOR CRACK ARREST IN THE UPPER-SHELF REGION AND IN A RISING $K_I$ FIELD
- ASSESS VISCOPLASTIC ASPECTS OF RUN-ARREST BEHAVIOR

ORNL WS–37753 ETD

# UNDERSTANDING CRACK–ARREST BEHAVIOR IS IMPORTANT FOR ASSESSING INTEGRITY OF LWR PRESSURE VESSELS

- INNER–SURFACE FLAWS MAY PROPAGATE DURING OCA's
  - HIGH THERMAL STRESS
  - LOW TEMPERATURE
  - RADIATION DAMAGE GREATEST
- RUNNING CRACK CAN STOP (ARREST) UPON ENTERING REGIONS OF LOWER LOAD, HIGHER TEMPERATURE, LESS DAMAGE
- PRESSURE VESSEL CAN RETAIN INTEGRITY AFTER ARREST OF PROPAGATING CRACK

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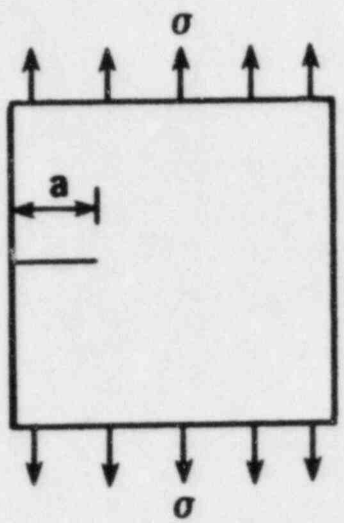
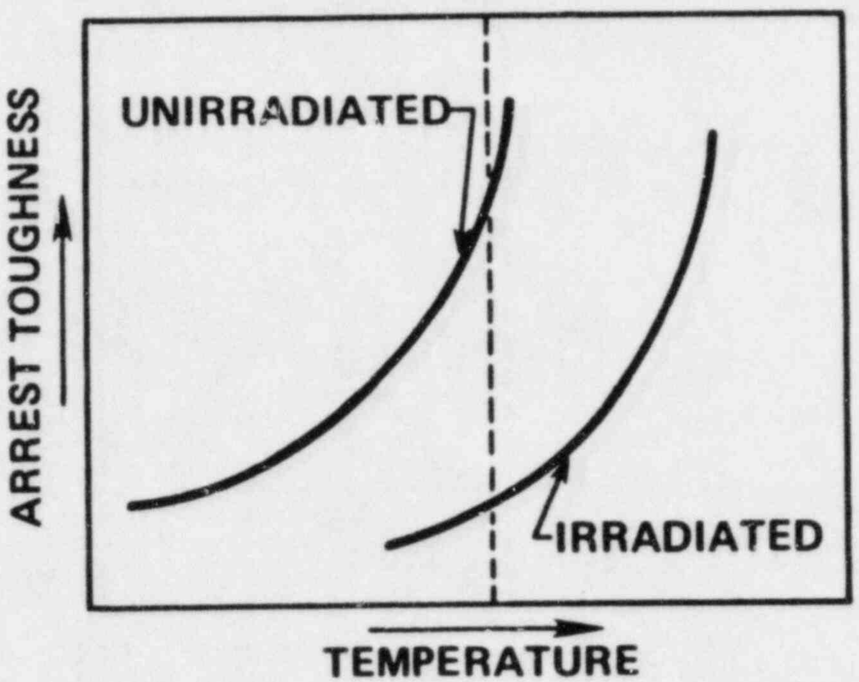
# CRACK ARREST OCCURS WHEN THE DRIVING FORCE ($K_I$) REACHES A CRITICAL VALUE ($K_{Ia}$)

$K_I = f(\sigma, a)$




$K_{Ia} = g(T, \text{FLUENCE})$

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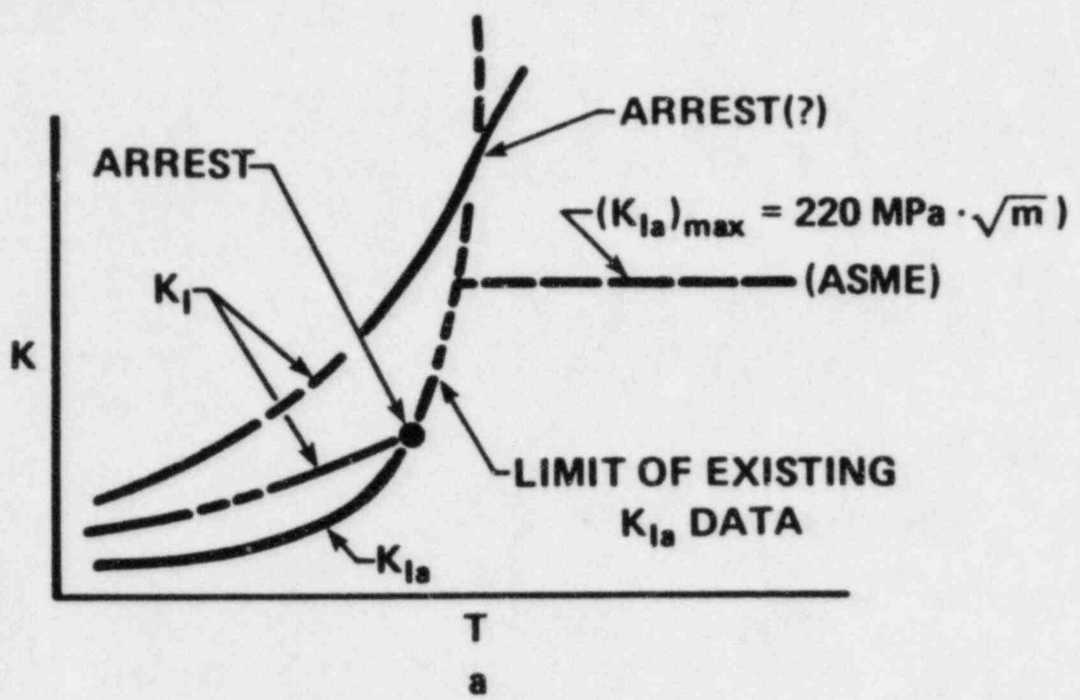
# $K_{Ia}$ DATA DO NOT EXTEND TO HIGH ENOUGH TEMPERATURES FOR ADEQUATE FAILURE ASSESSMENT OF PTS SCENARIOS

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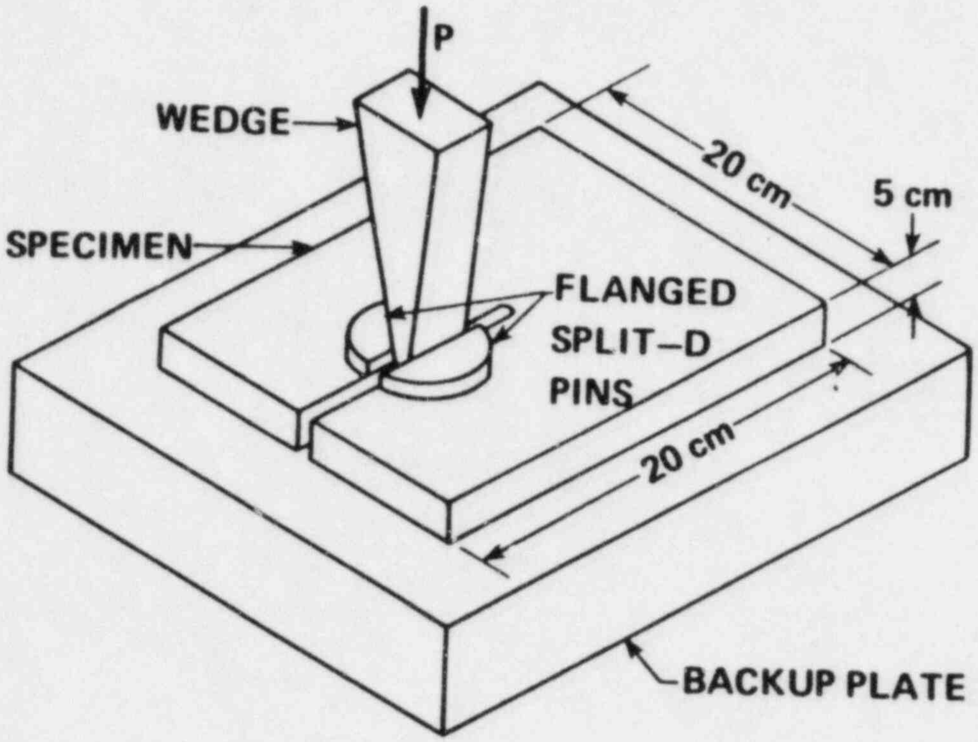
# AVAILABLE $K_{Ia}$ DATA OBTAINED WITH "SMALL" SIDE–WEDGE–LOADED RECTANGULAR COMPACT SPECIMEN

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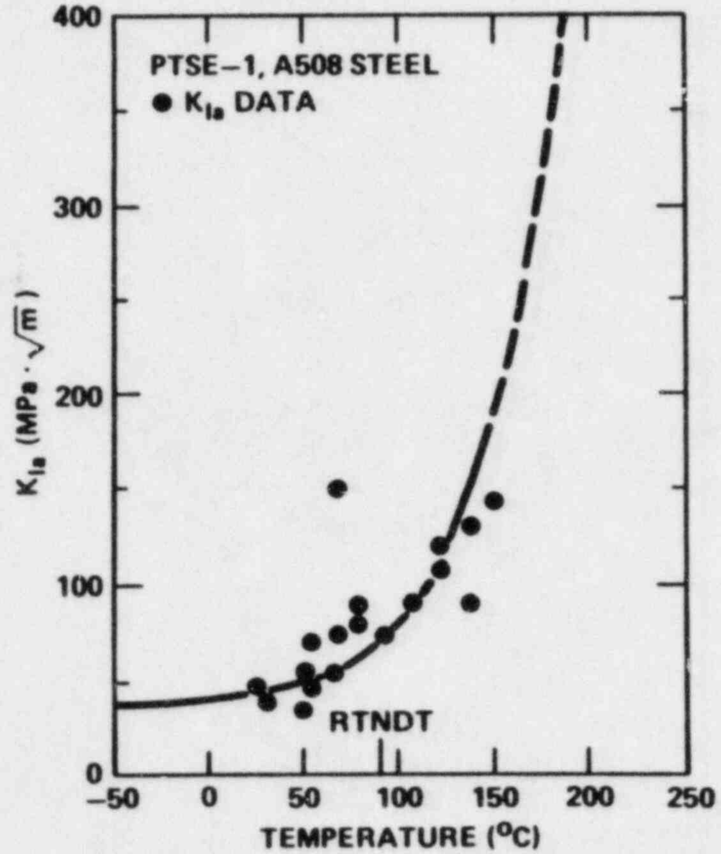
# CURRENT (SMALL) CRACK–ARREST SPECIMENS YIELD DATA FOR LOW AND MODERATELY LOW TEMPERATURES

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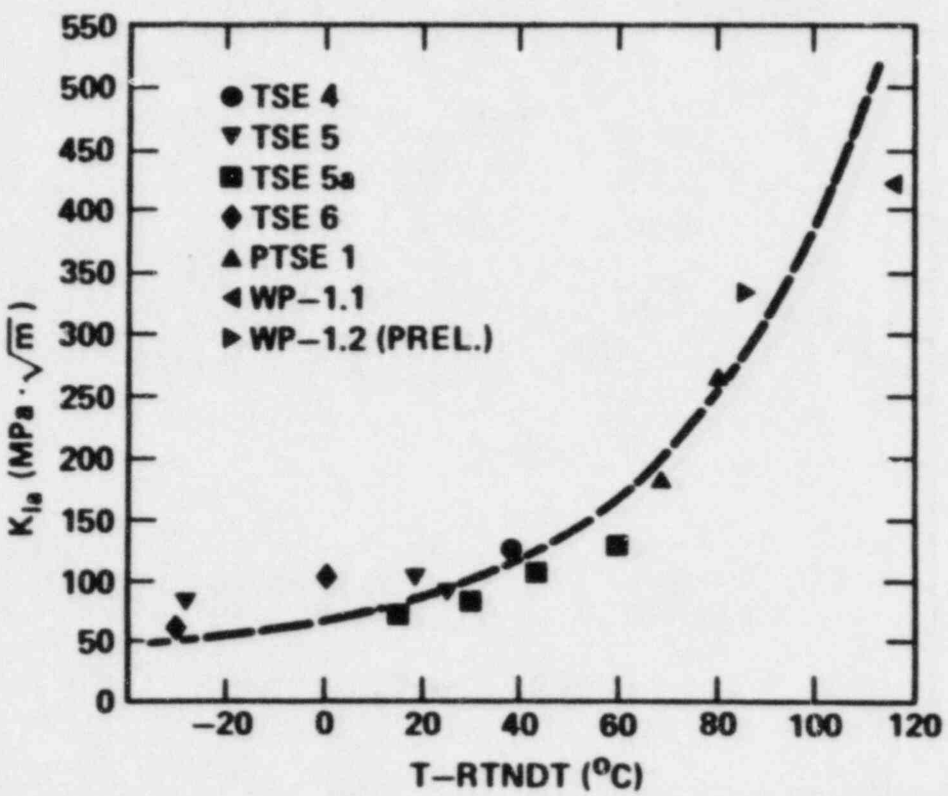
# THE HSST PROGRAM IS EXTENDING THE RANGE OF $K_{Ia}$ VS TEMPERATURE DATA THROUGH WIDE-PLATE, THERMAL-SHOCK, AND PRESSURIZED-THERMAL-SHOCK TESTS

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# WIDE–PLATE CRACK–ARREST TESTS ARE BEING PERFORMED TO

- PROVIDE $K_{Ia}$ DATA ABOVE THE ASME UPPER LIMIT CRITERION FOR A PROTOTYPICAL LWR–RPV STEEL
- PROVIDE DATA FROM WHICH DYNAMIC FRACTURE MODELS CAN BE VERIFIED OR DEVELOPED
- EVALUATE APPROACHES FOR DYNAMIC MEASUREMENTS

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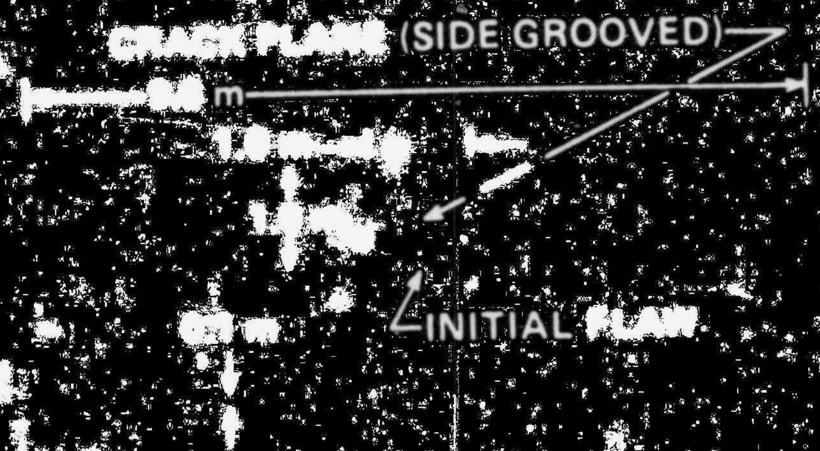
- TEMPERATURE GRADIENT IN CRACK PLANE
- "EXTREME" LENGTH MINIMIZES DYNAMIC EFFECTS
- REASONABLE COST
- MAY SUFFER FROM LACK OF RESTRAINT

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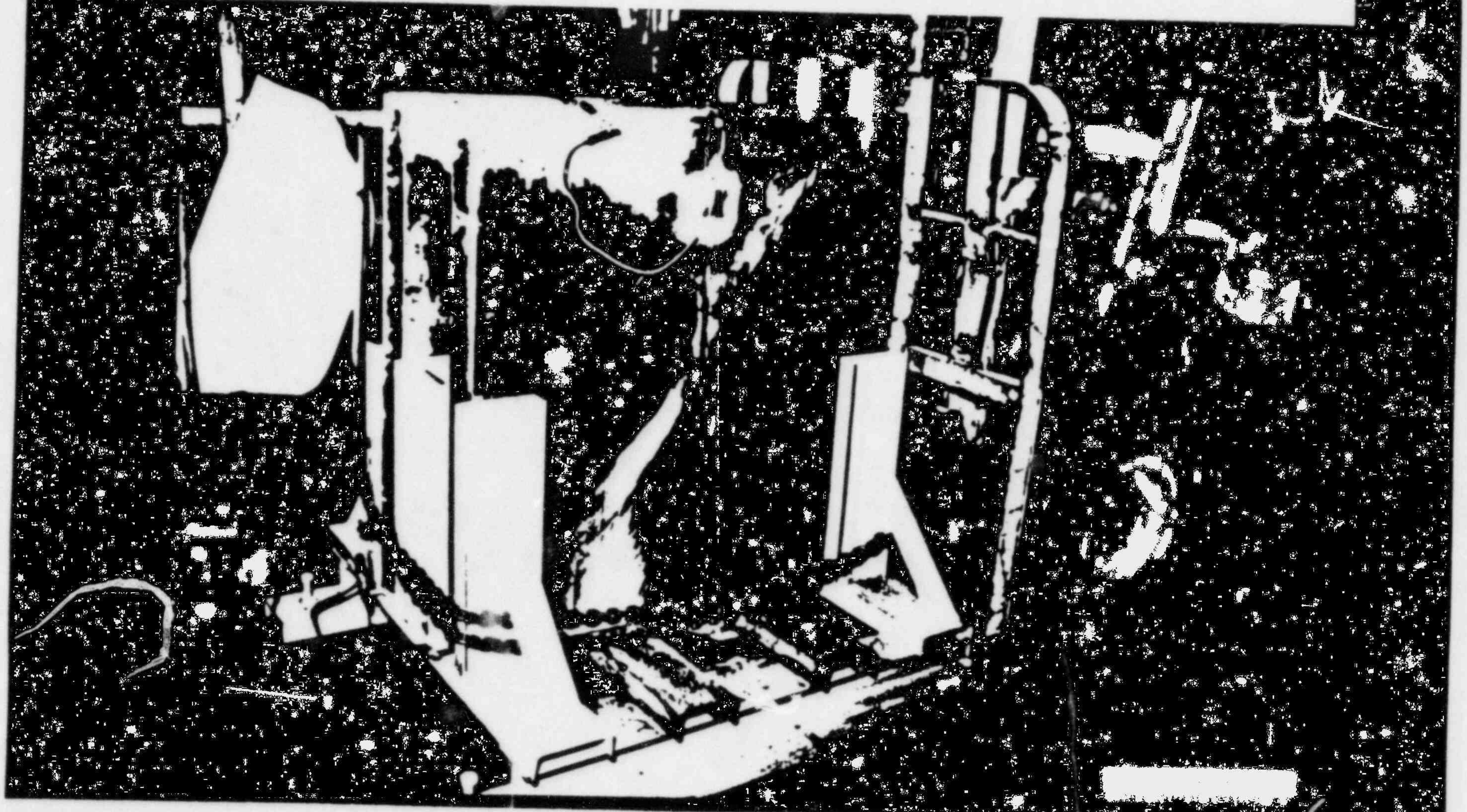
ORNL PHOTO 7176-84B

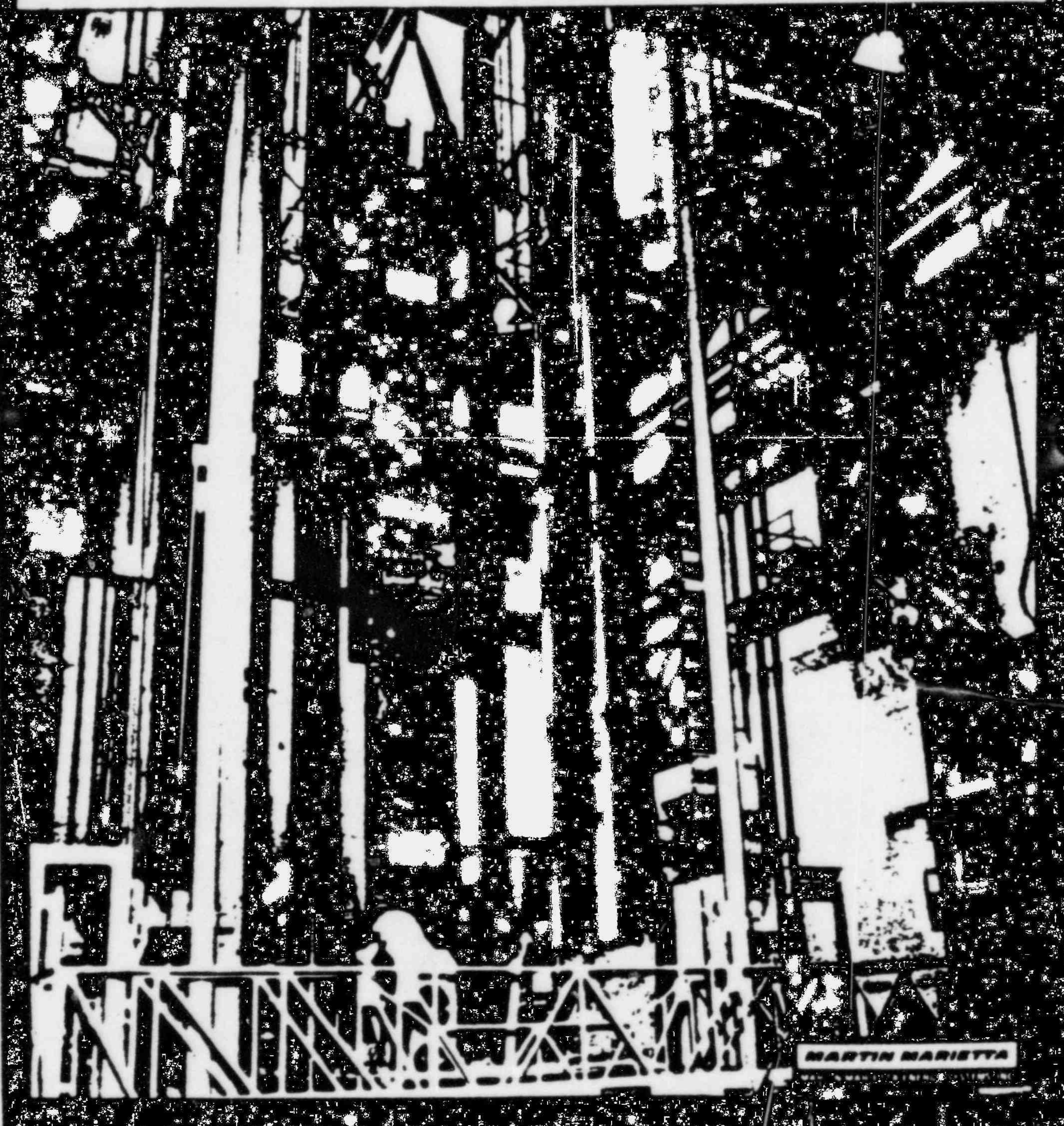
**HSST WIDE–PLATE CRACK–ARREST SPECIMENS ARE INITIALLY CRACKED BY HYDROGEN CHARGING AN EB WELD**



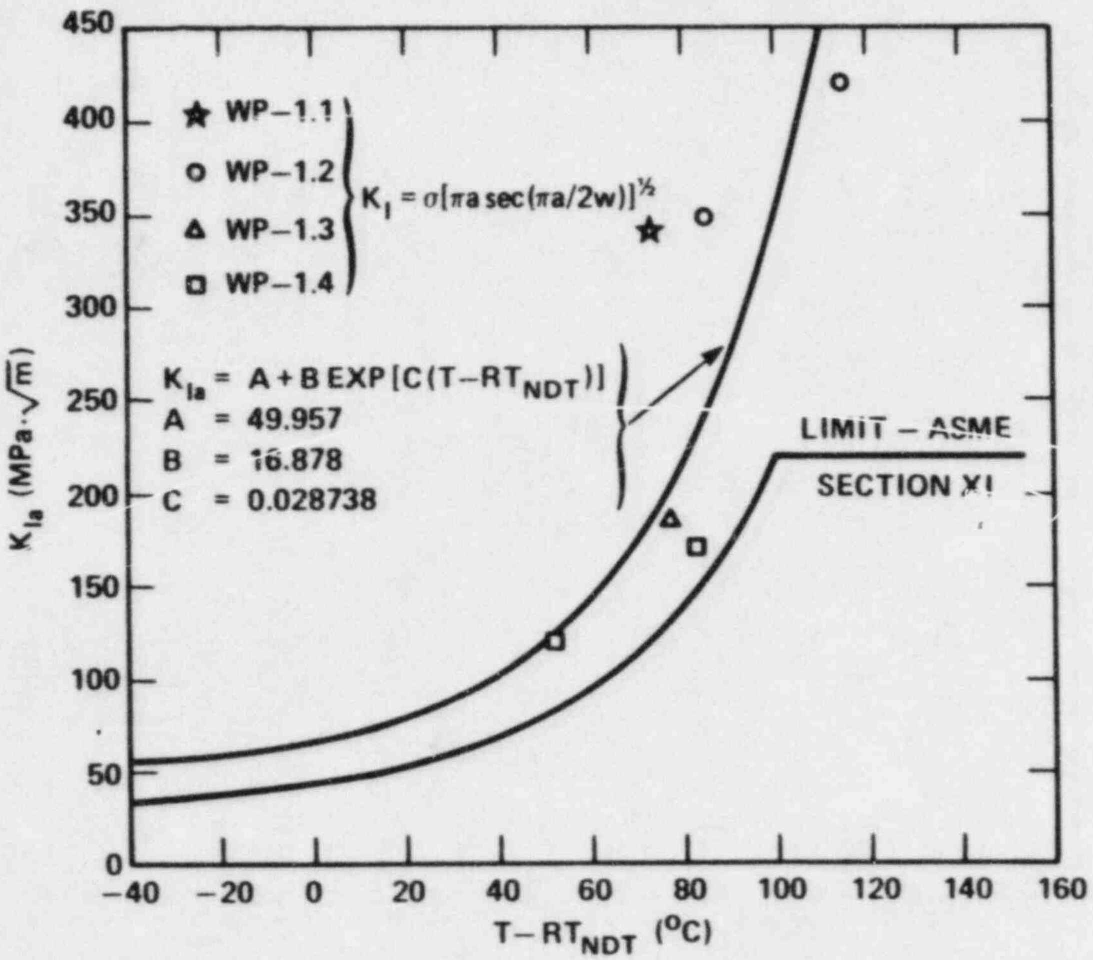
ORNL PHOTO 0476-85

ORNL PHOTO 0474-85

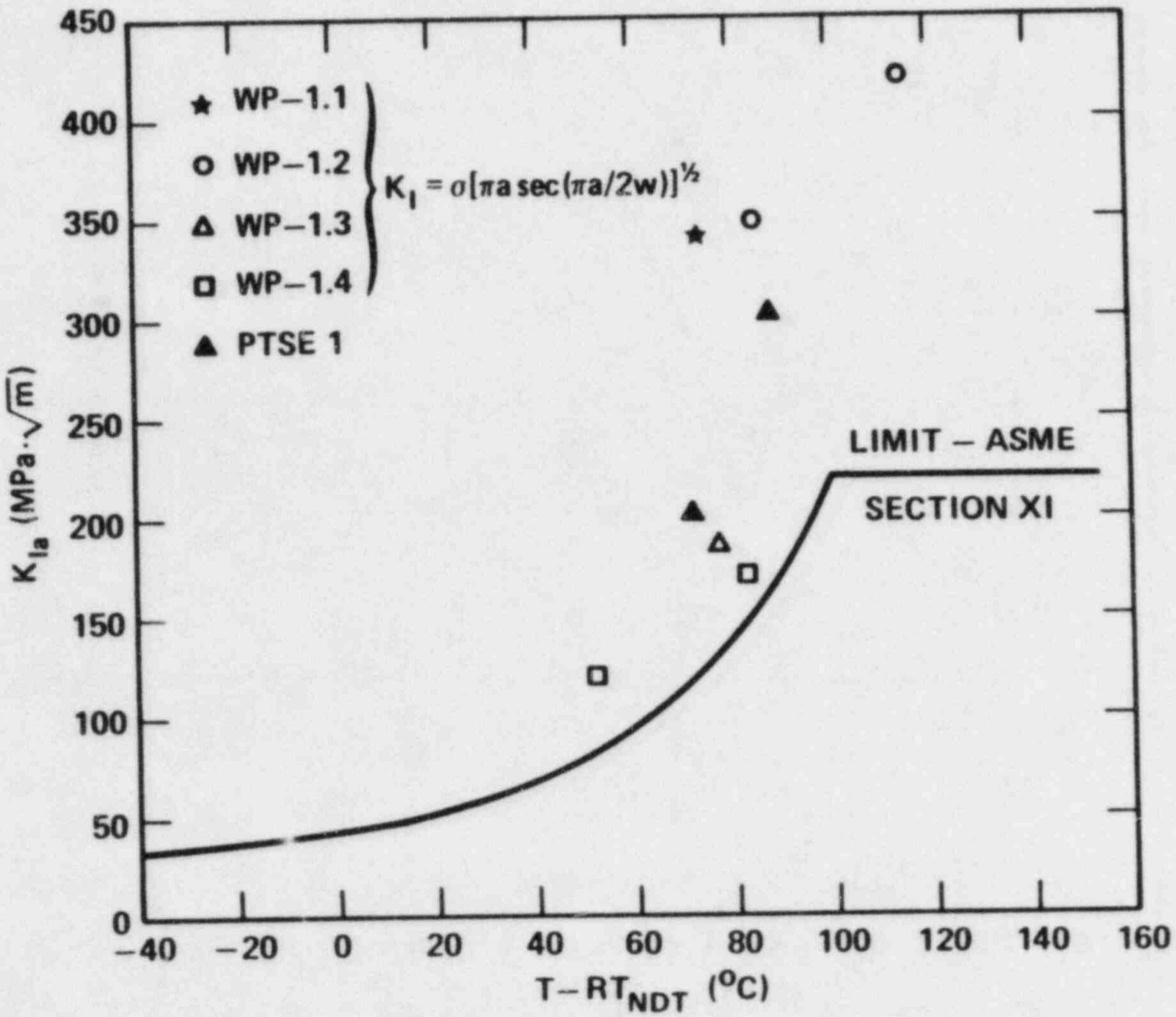
# HSST WIDE–PLATE CRACK–ARREST SPECIMENS ARE VERTICALLY MOUNTED IN NBS TEST MACHINE



# WIDE-PLATE CRACK-ARREST TESTS ON HSST PLATE 13-A OF A 533B STEEL ARE PROVIDING DATA ABOVE THE ASME UPPER-LIMIT CRITERION



# LARGE–SPECIMEN HIGH–TEMPERATURE CRACK–ARREST DATA SHOW A CONSISTENT TREND ABOVE ASME LIMIT



# LARGE-SPECIMEN HIGH-TEMPERATURE CRACK-ARREST DATA SHOW A CONSISTENT TREND ABOVE ASME LIMIT

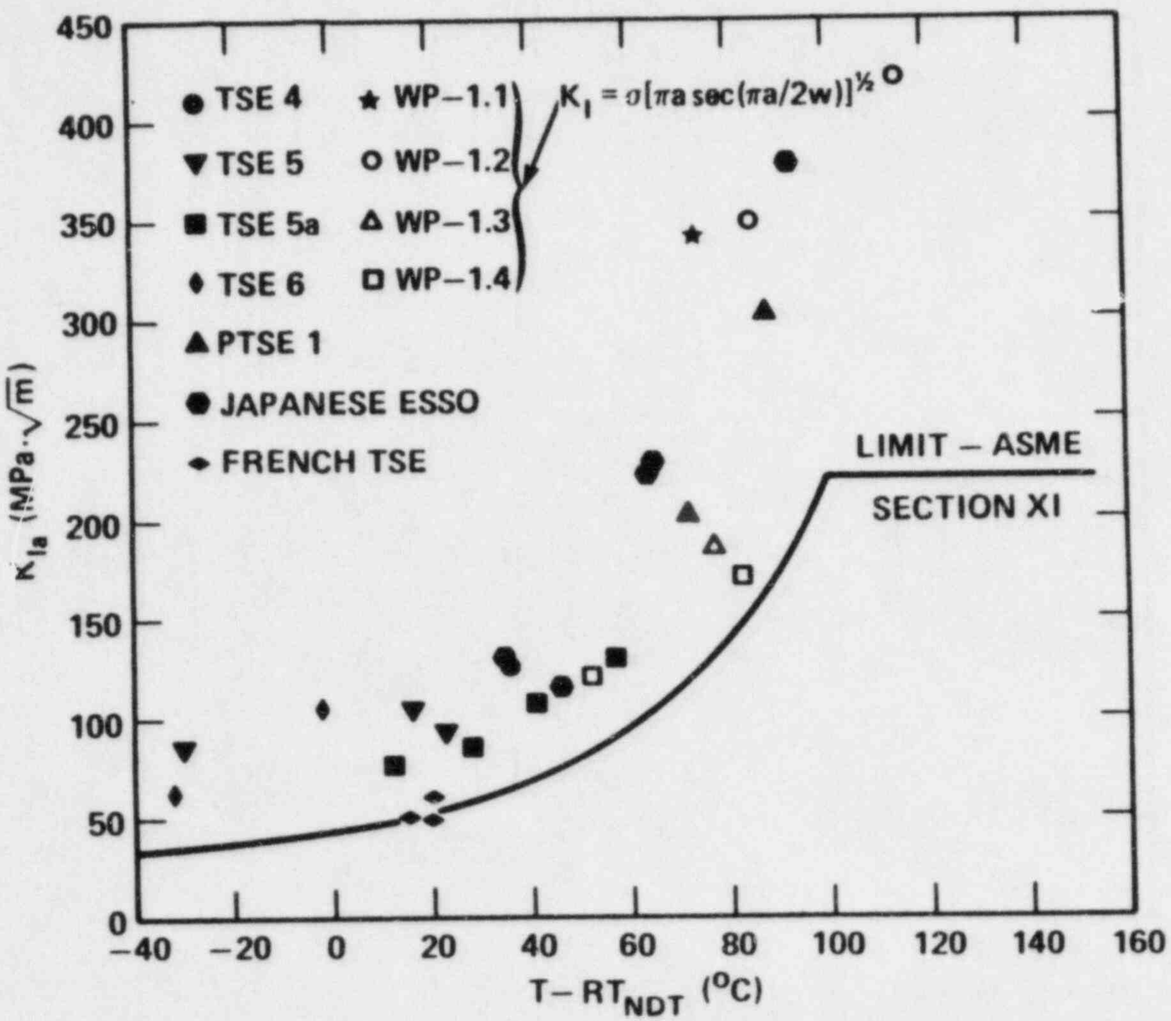


Fig. B.6 STRAIN VS TIME AT LOCATIONS NEAR CRACK-LINE GAGES FROM POSTTEST GENERATION-MODE DYNAMIC ANALYSIS OF TEST WP-1.2

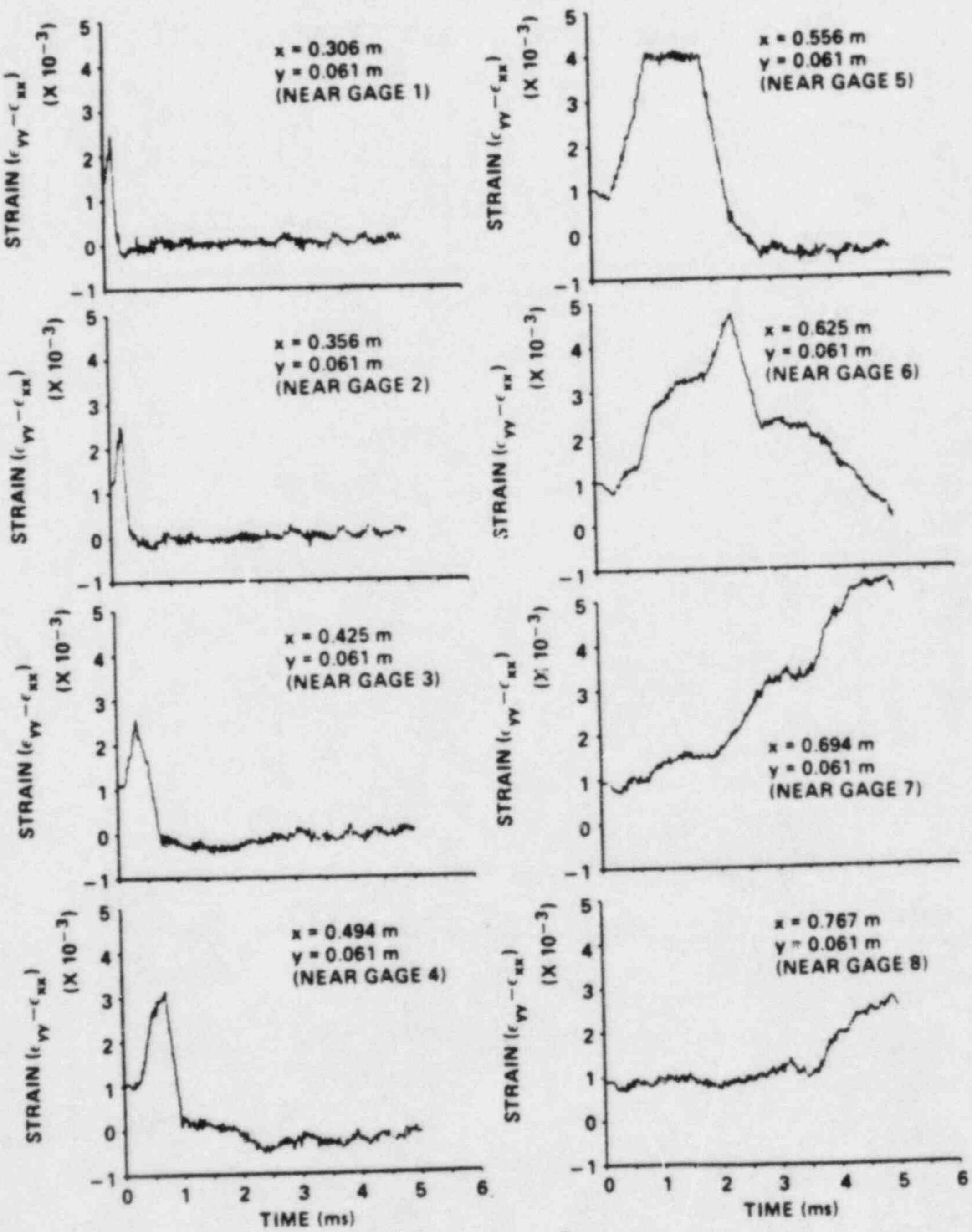
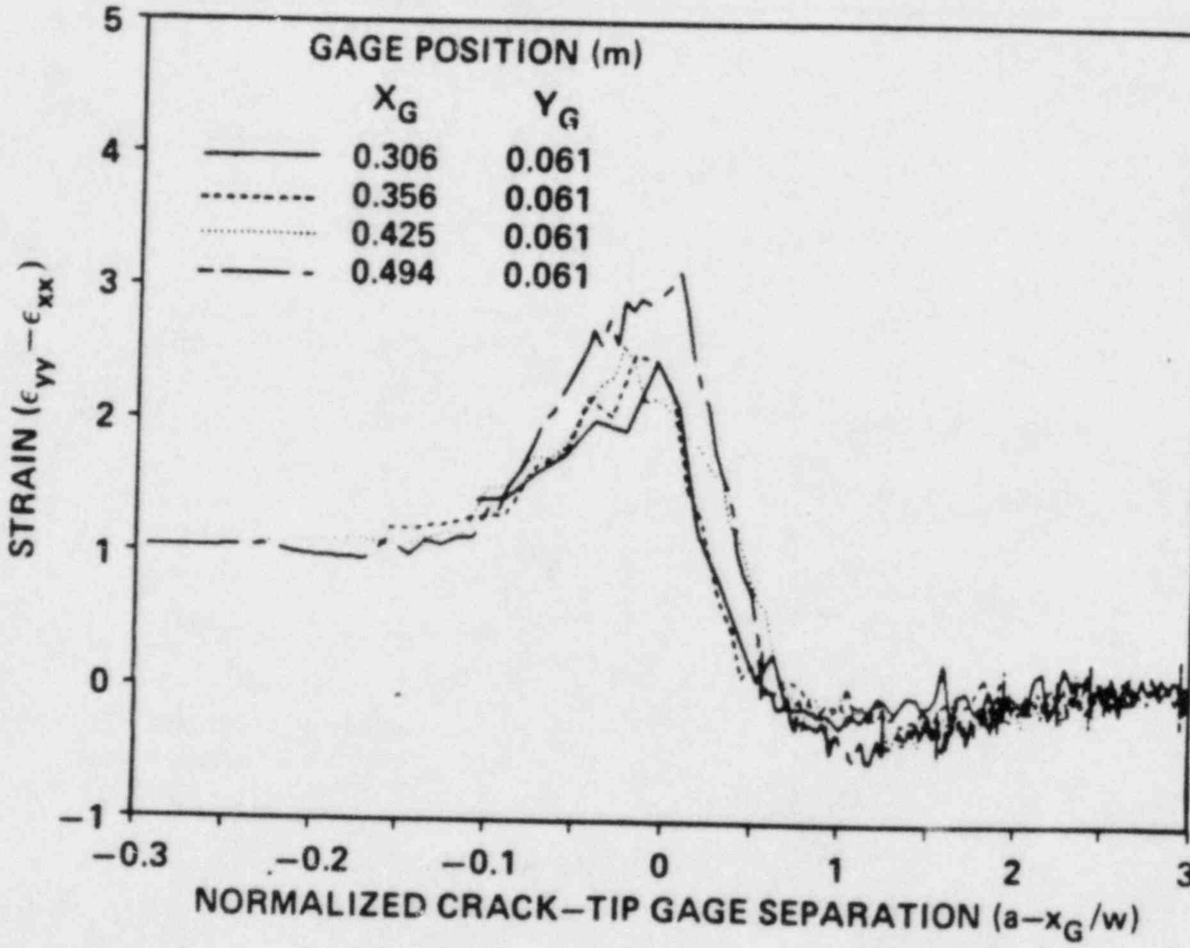
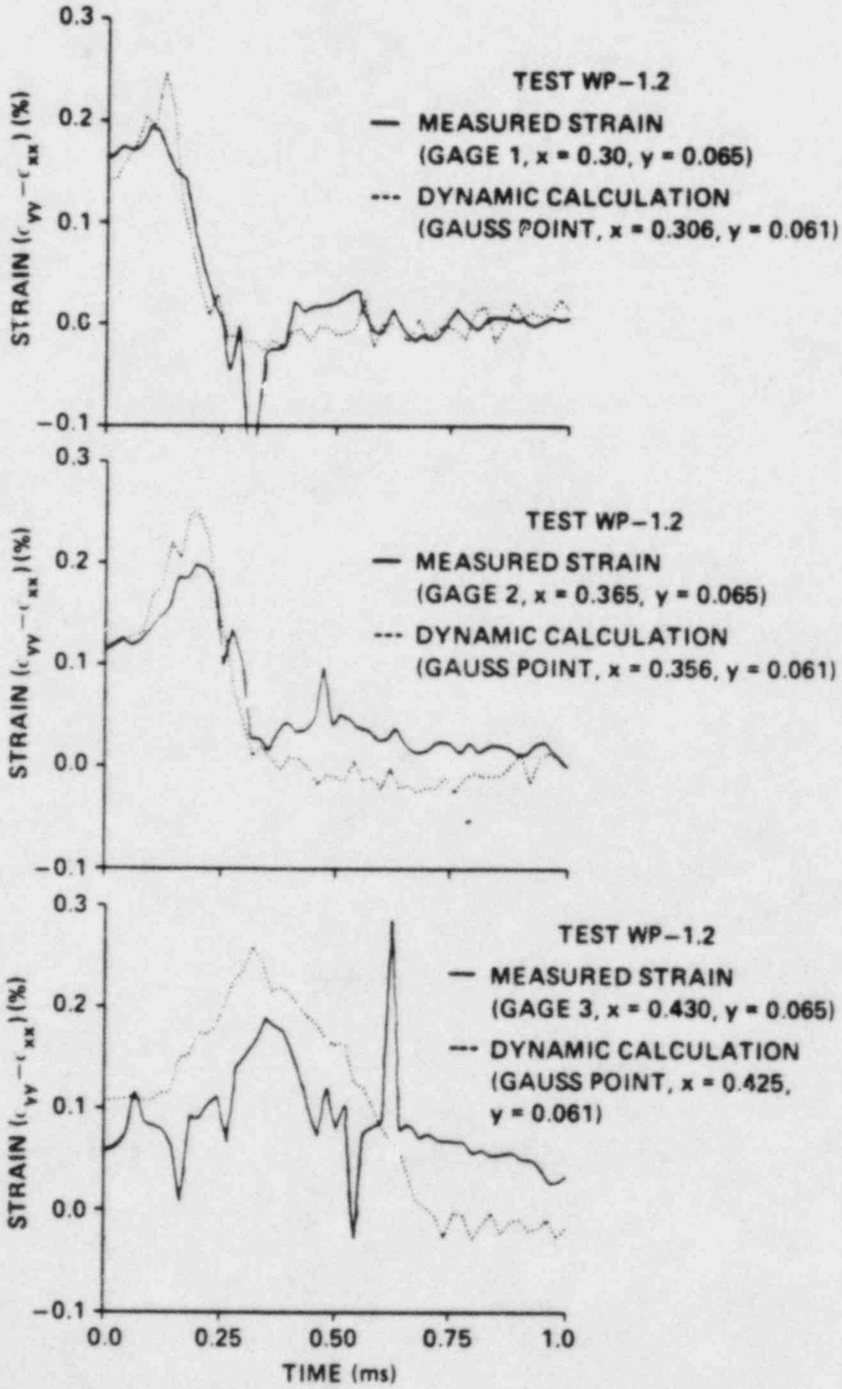


Fig. B.7 **STRAIN VS NORMALIZED CRACK–TIP GAGE SEPARATION FROM POSTTEST GENERATION–MODE DYNAMIC ANALYSIS OF TEST WP–1.2**



# g. B.8 COMPARISON BETWEEN STRAIN–TIME HISTORIES FROM MEASURED DATA AND DYNAMIC CALCULATIONS AT GAGES 1, 2, AND 3 FOR GENERATION–MODE ANALYSIS OF TEST WP–1.2



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# IN CONCLUSION THE HSST PROGRAM IS INVOLVED IN COMPREHENSIVE DEVELOPMENT OF IMPROVED METHODS FOR CRACK–ARREST ASSESSMENTS

- APPLICABILITY OF SMALL SPECIMEN PROCEDURES BEING VALIDATED BY ROUND–ROBIN TESTING
- LARGE SPECIMEN DATA INDICATE THAT CRACK–ARREST TOUGHNESS EXTENDS WELL ABOVE ASME LIMIT
- ANALYTICAL METHODS BEING EXTENDED INCLUDE ELASTODYNAMIC AND VISCOPLASTIC TECHNIQUES

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# SEPARATE-EFFECTS PRESSURE VESSEL CLADDING STUDIES

# OBJECTIVE

- Assess the effect of Stainless Cladding on the Initiation Fracture Behavior of Base Metals
  - –Ductile Cladding vs. Brittle Base Metal
  - –Residual and Thermal Stresses

# APPROACH

- Fracture Tests on Surface–Flawed Panels
  - –Clad vs. Unclad Behavior
  - –Irradiated vs. Unirradiated Behavior
- Evaluate Residual and Differential Thermal Expansion Stresses
- Relate the Clad Specimens to Vessel via (ORNL) Analysis

# EXPECTED ACCOMPLISHMENTS

Data for use in assessing the role of cladding in mitigating crack initiation due to PTS

Study of the effect of radiation-induced strengthening of the cladding on the "cladding effect"

Quantification of residual and thermal expansion stresses due to cladding

THE POTENTIAL OF TOUGH WELD OVERLAY CLADDING FOR REDUCING THE LIKELIHOOD OF VESSEL FAILURE DURING SEVERE TRANSIENTS HAS BEEN POSTULATED

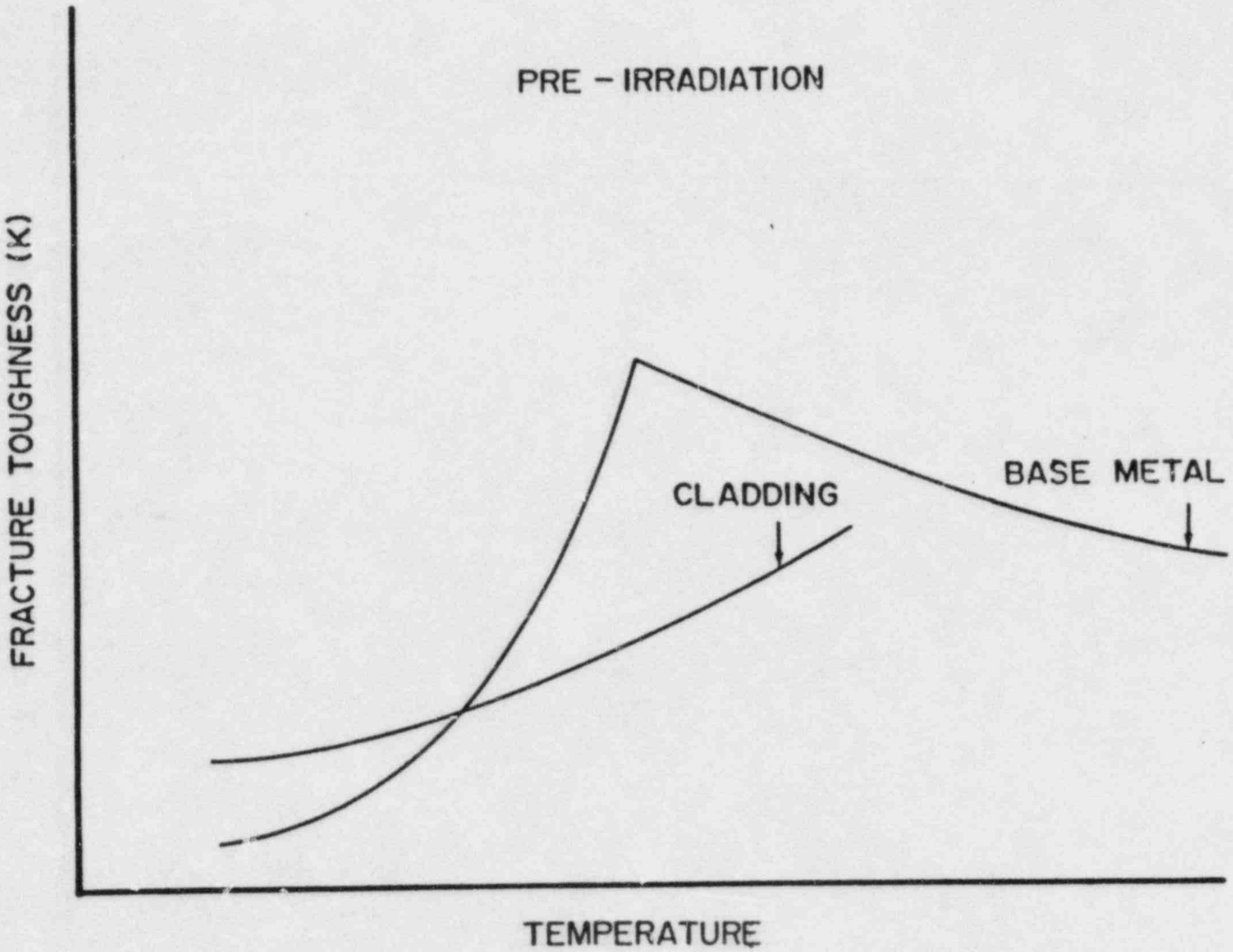
- CLADDING MAY KEEP SHORT FLAWS FROM EXTENDING INTO LONG FLAWS
- POTENTIAL FOR EXTENDING LIFE BEYOND SCREENING CRITERIA BY PLANT-SPECIFIC ANALYSIS
- REDUCTION OF CUMULATIVE FAILURE PROBABILITY BY ALTERING FLAW SIZE/DENSITY DISTRIBUTIONS

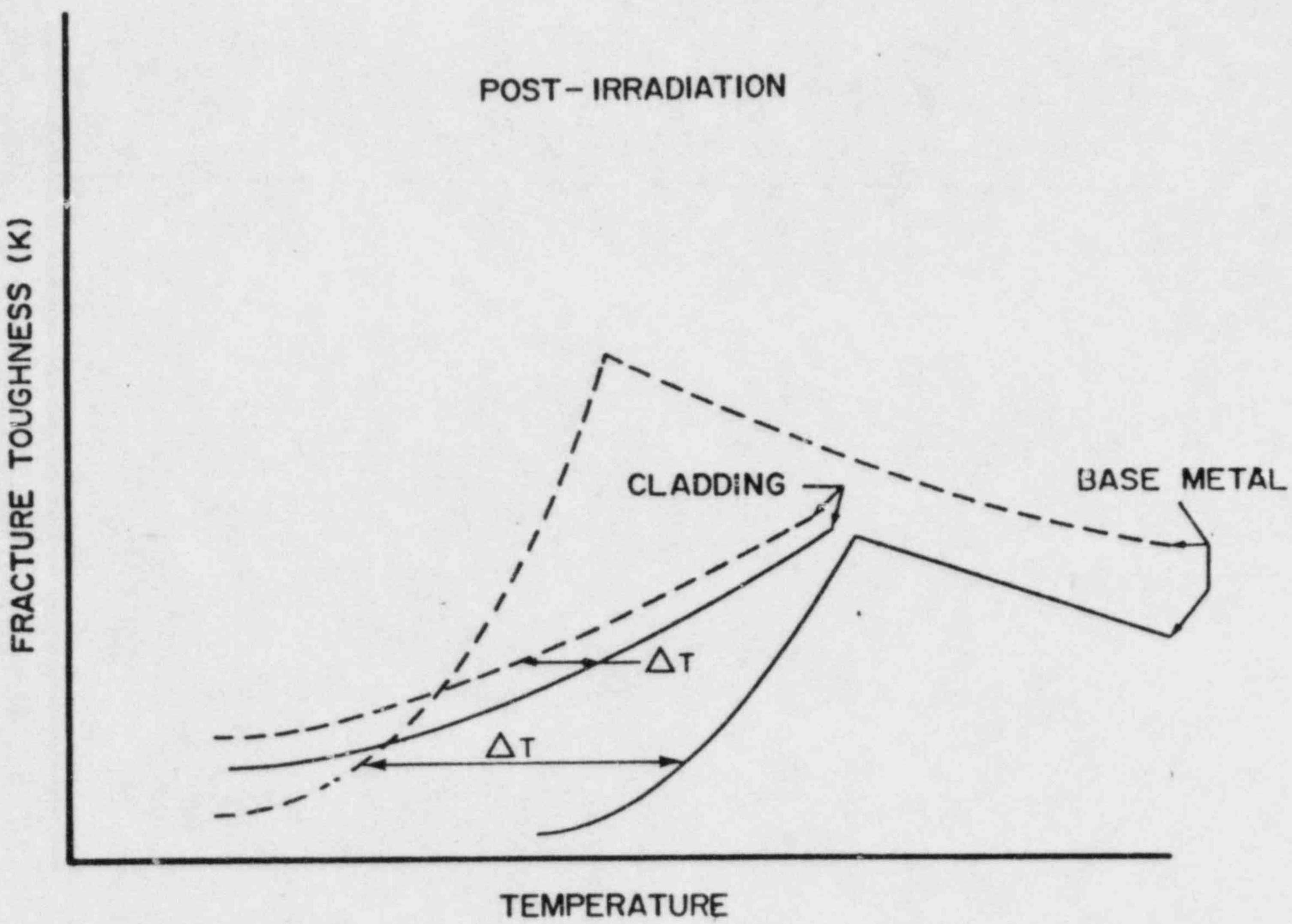
**BY PINNING THE ENDS OF A SURFACE CRACK, THE CLADDING CAN LIMIT THE GROWTH OF THE FLAW IN DEPTH AND ARREST THE ENTIRE PROPAGATING CRACK**

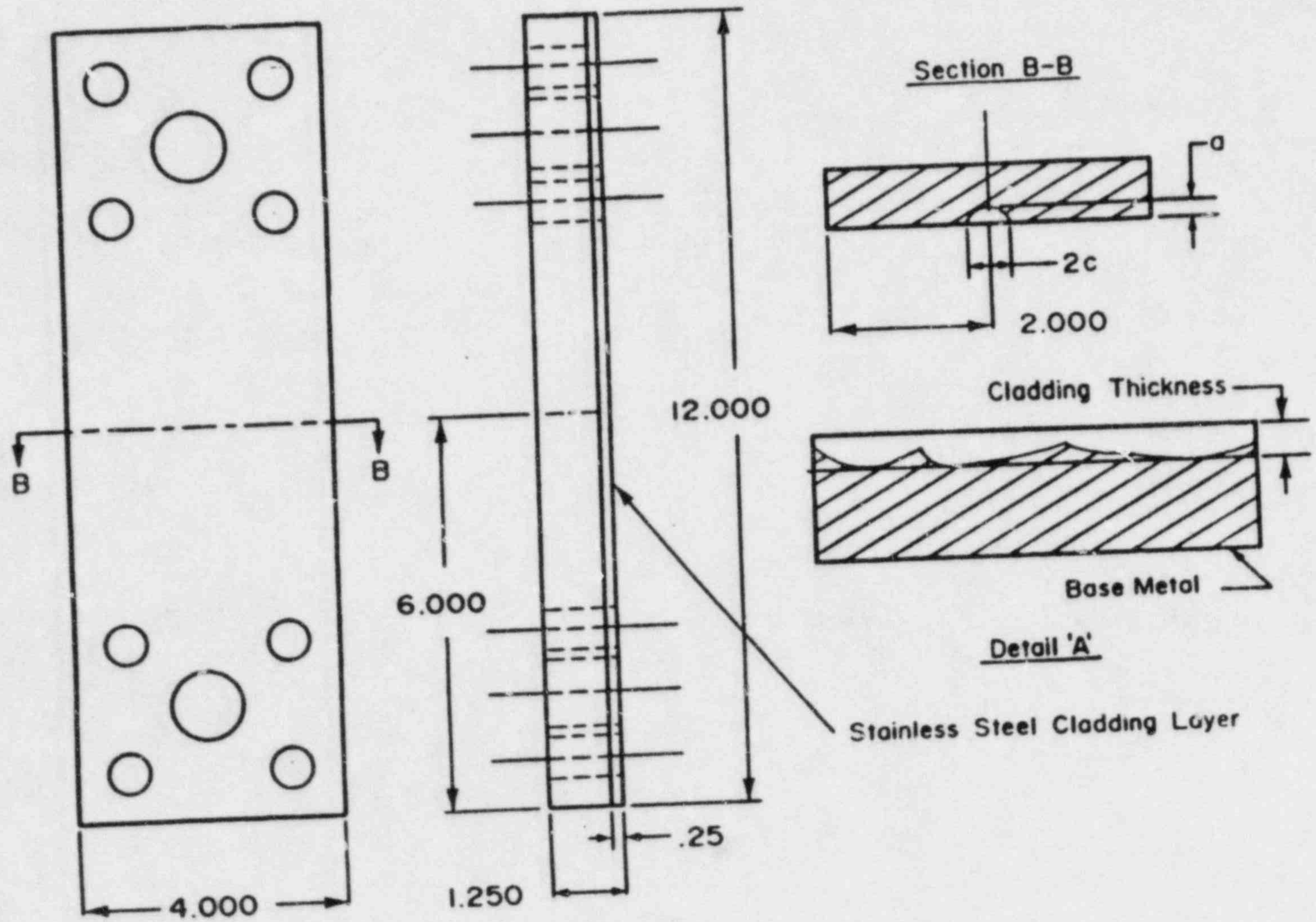
- STRESS INTENSITY OF A SHALLOW SURFACE FLAW IN LINEAR STRESS GRADIENT INCREASES ALONG ITS ENTIRE CRACK FRONT AS IT GROWS

- IF THE CRACK CANNOT EXTEND ON SURFACE (DUE TO TOUGH CLADDING), STRESS INTENSITY AT BOTTOM OF FLAW FIRST INCREASES AND THEN DECREASES TO $K_{Ia}$ VALUE OF SUBSTRATE

- CLADDING THAT IS SUFFICIENTLY TOUGH TO CONTAIN INCREASING STRESS INTENSITY OF FLAW AT SURFACE UNTIL ARREST TOUGHNESS OF SUBSTRATE IS REACHED AFFECTS COMPLETE CRACK ARREST


PRE - IRRADIATION
FRACTURE TOUGHNESS (K)
CLADDING
BASE METAL
TEMPERATURE


POST-IRRADIATION
FRACTURE TOUGHNESS (K)
CLADDING
BASE METAL
ΔT
ΔT
TEMPERATURE




MEA SPECIMEN FOR CLADDING STUDY

# COMPARISONS WITH ORNL STUDIES

| Program Aspect | MEA | ORNL |
|---|---|---|
| CLADDING | Typical of Early Construction | Chem. and Heat Treatment Adjusted |
| IRRADIATION EFFECT | Irradiated 1*10^19 n/cm^2 | Simulated By Heat Treatment |
| FRACTURE BEHAVIOR | Initiation | Arrest |
| SPECIMEN LOADING | Tension | 4-Pt Bending |
| PLATE TYPES | Clad/Unclad | Clad/Unclad |

STRUCTURAL RESPONSE OF CLADDING AS A FUNCTION OF ITS TOUGHNESS AS WELL AS IRRADIATION-INDUCED CHANGES IN ITS PROPERTIES ARE VITAL TO ASSESS ANY POTENTIAL BENEFIT

- BEAMS, CLAD AND FLAWED ON THEIR TENSILE SURFACE, AND TESTED IN FOUR-POINT BENDING, ASSESS RESPONSE OF STRUCTURES IN PRESENCE OF CLADDING

- NEUTRON IRRADIATION OF SMALL MECHANICAL AND FRACTURE SPECIMENS TO END-OF-LIFE CONDITIONS EVALUATE RADIATION DAMAGE

## FIRST PHASE OF THE CLAD BEAM EXPERIMENTS SHOWED CLADDING OF MODERATE TOUGHNESS HAS LIMITED ABILITY TO MITIGATE CRACK EXTENSION

- TYPE 308/309 MULTILAYER CLADDING WITH 12- TO 30-J CHARPY IMPACT ENERGY ON FRANGIBLE BASE PLATE OF A533 GRADE B CLASS 2

- BEAM (914 x 406 x 51 mm) STATICALLY LOADED IN FOUR-POINT BENDING. FLAW INITIATED USING HYDROGEN CHARGING

- UNCLAD BEAMS FAILED COMPLETELY UPON CRACK INITIATION

- SIMILAR CLAD BEAMS EXPERIENCED CRACK PINNING AND ARREST AT STRESS INTENSITY LEVELS SLIGHTLY ABOVE $K_{Ia}$

- CLAD BEAMS FAILED COMPLETELY AT LOADINGS WELL IN EXCESS OF $K_{Ia}$

ORNL-DWG 82-6651 ETD

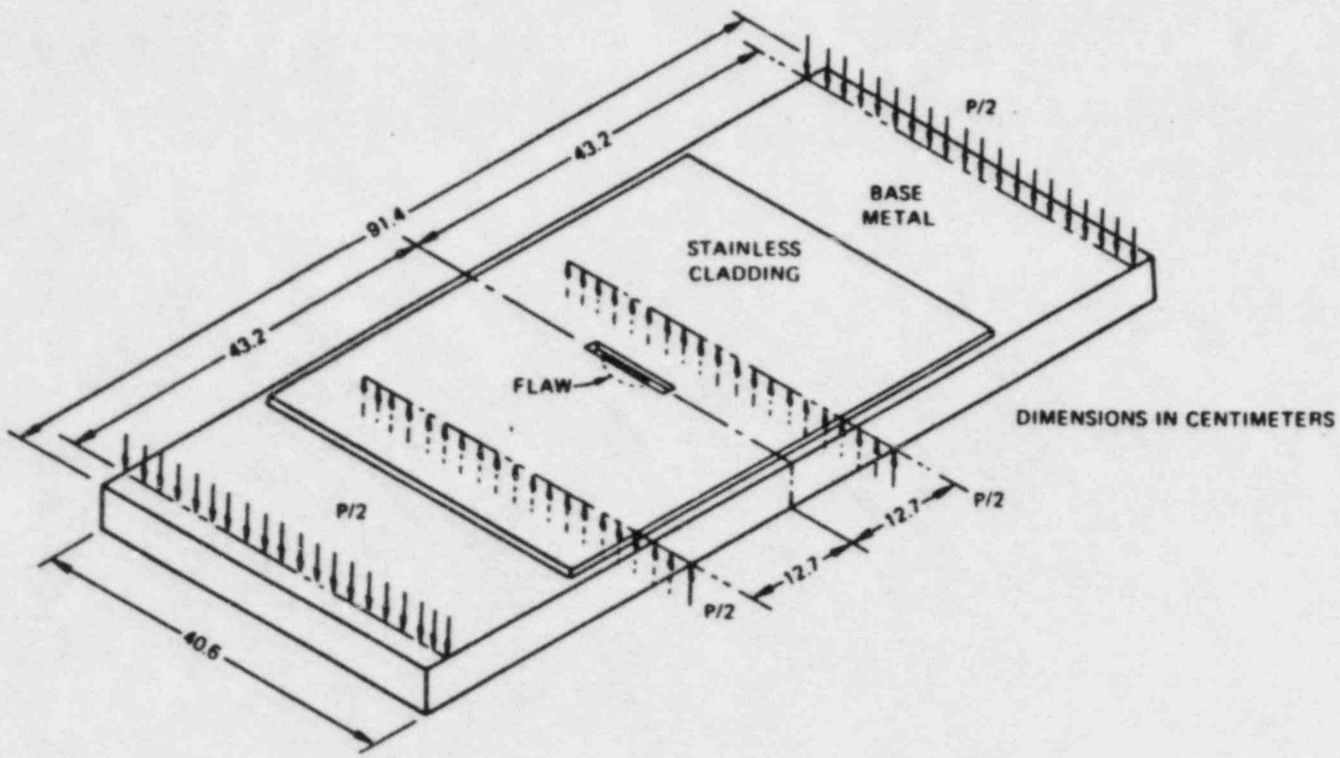



Fig. 6.1. Specimen dimensions and load locations.

ORNL-DWG 82 6652 ETD

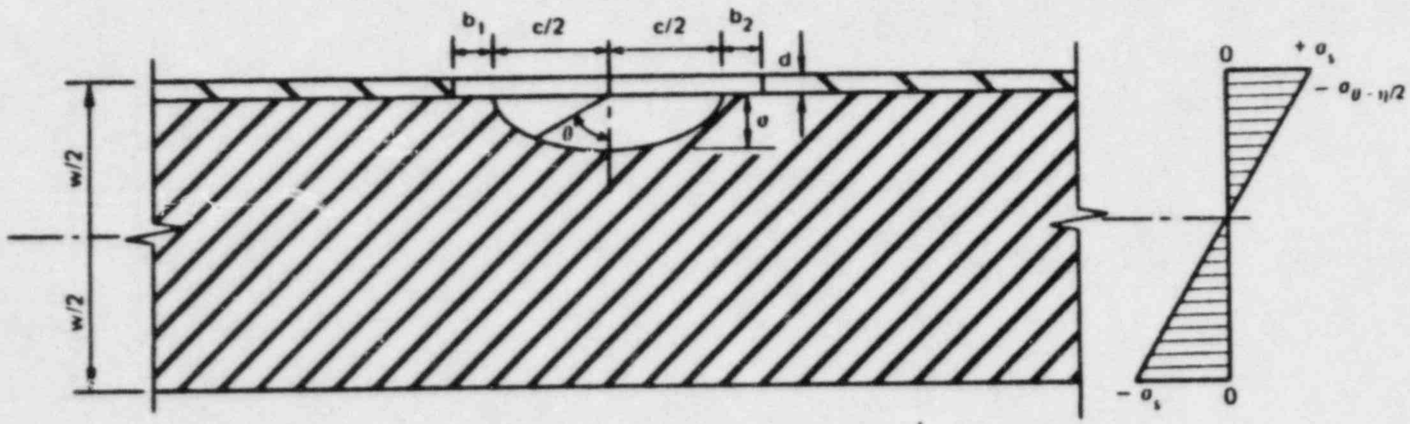



**Fig 6.2. Dimensions and stress distribution of flaws located in clad plate specimens.**

ORNL-DWG 82 5826R ETD

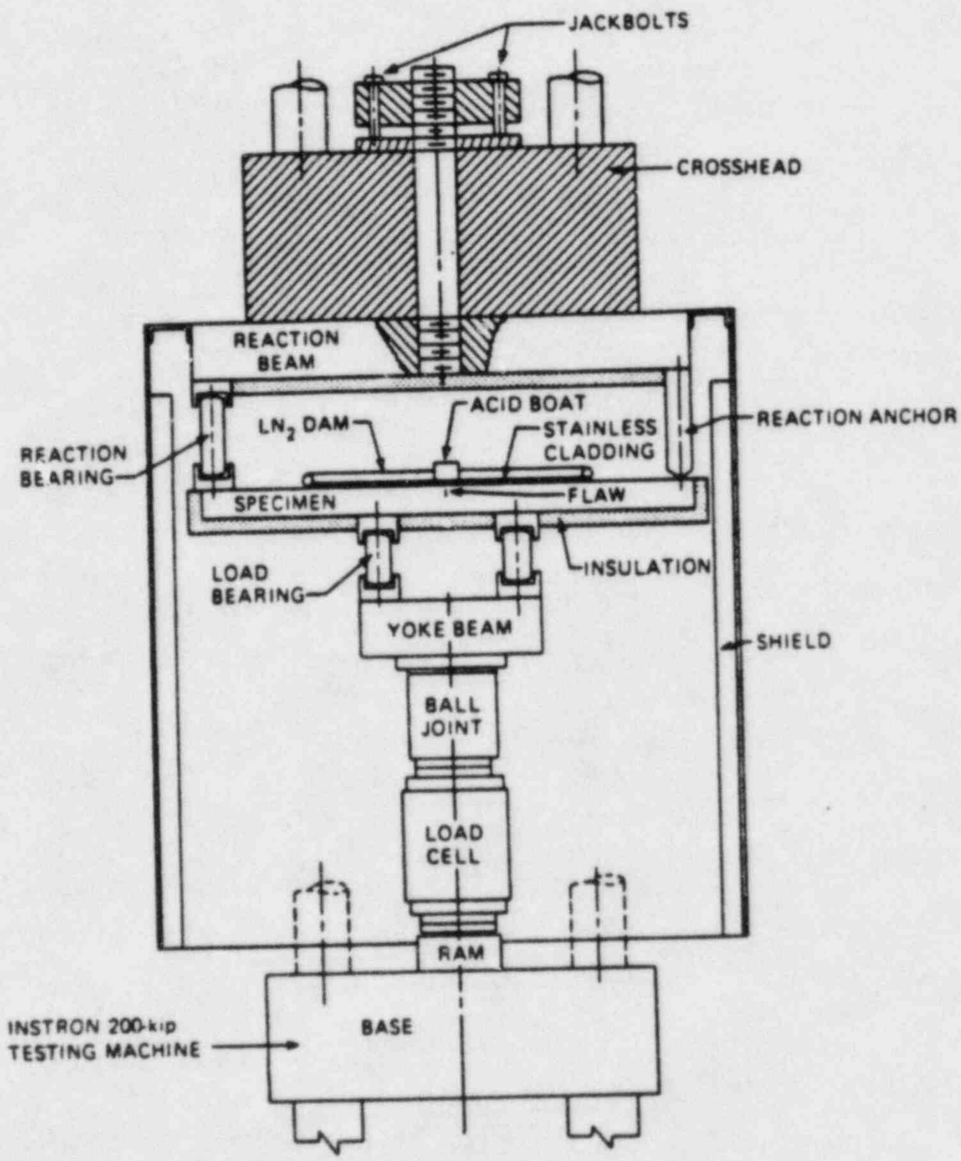
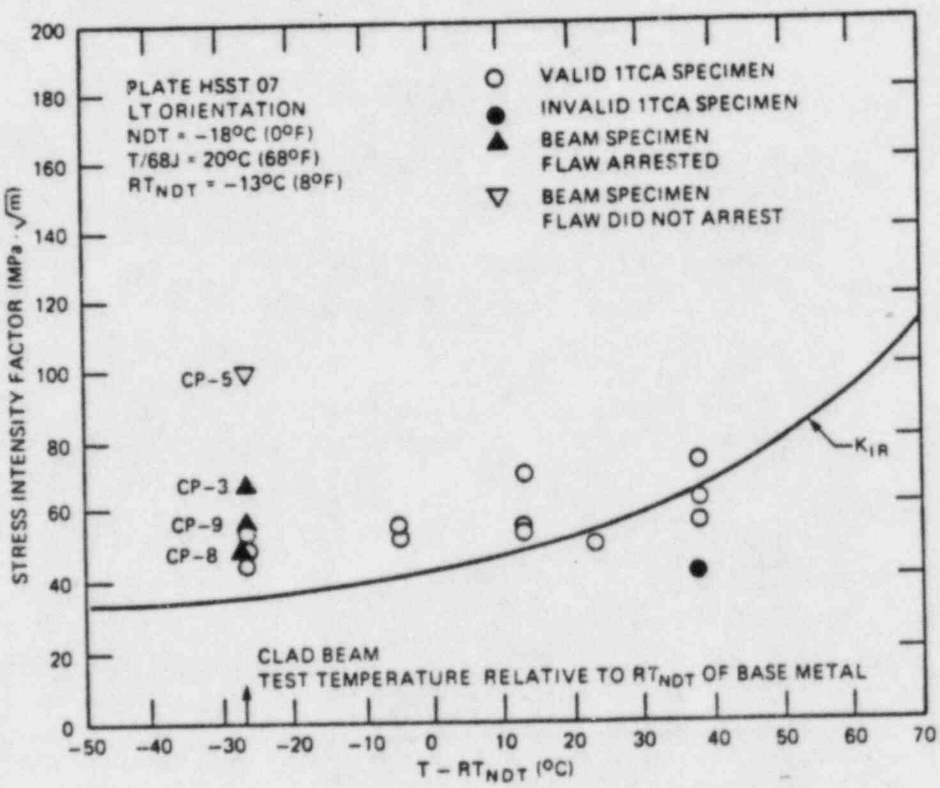



Fig. 6.3. Section elevation of clad plate task test setup.

CRACK ARREST VALUES FOR FLAWS IN BEAMS WITH MODERATELY TOUGH CLADDING THAT ARRESTED WERE ONLY MARGINALLY ABOVE THOSE FOR THE BASE METAL



**NEW SPECIMENS HAVE BEEN FABRICATED FROM OPTIMIZED MATERIALS THAT WILL PERMIT SIMILAR BEAM TESTING OF MUCH TOUGHER CLADDING**

- ESTABLISH STRUCTURAL BENEFIT OF CLADDING AS FUNCTION OF CLADDING TOUGHNESS
- CLADDING TOUGHNESS MORE GERMANE TO OPERATING CONDITIONS
- ENHANCED EXPERIMENTAL TECHNIQUES ALLOW EXAMINATION OF CLADDING EFFECTS ON CRACK INITIATION
- TESTING TO BE COMPLETED IN FY 1986

IRRADIATION EFFECTS ON CLADDING TOUGHNESS WERE EVALUATED ON THE SAME CLADDING USED ON THE CLAD BEAMS

- SINGLE WIRE SUBMERGED-ARC WELDMENT
- CHARPY IMPACT AND TENSILE PROPERTIES
- IRRADIATED TO $2 \times 10^{23}$ NEUTRONS/$m^2$ (>1 MeV) AT 288°C
- ONE SPECIMEN SET WAS HIGH QUALITY (TYPICAL RPV CLADDING)
- ONE SPECIMEN SET WAS POOR QUALITY (HIGHLY DILUTED BY BASE METAL, ATYPICAL OF, BUT STILL DOCUMENTED IN EXISTING RPVs)

HIGH QUALITY CLADDING EXHIBITED LITTLE DEGRADATION WHEREAS POOR QUALITY WAS HIGHLY AFFECTED

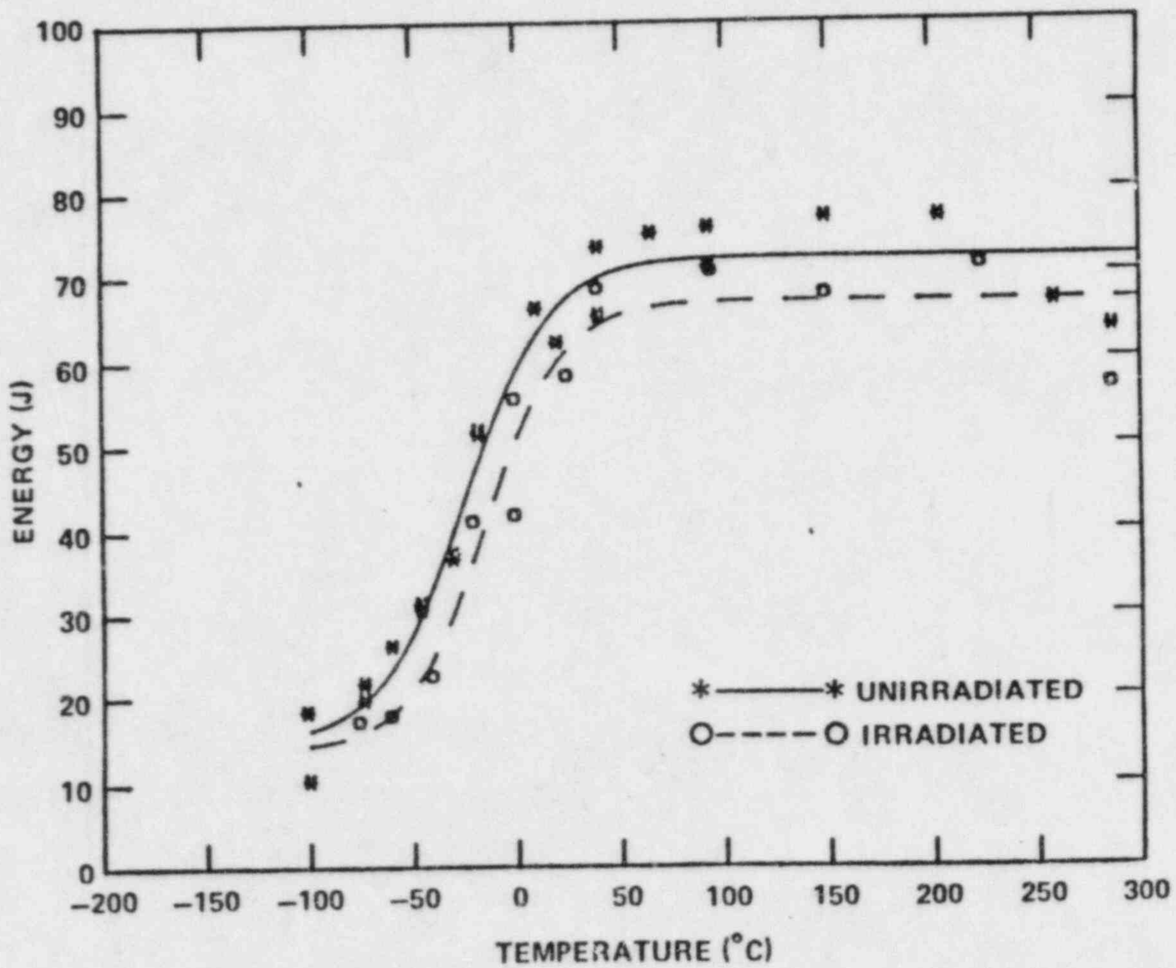
- CHARPY AND TENSILE PROPERTIES OF GOOD CLADDING SHOWED VERY LITTLE EMBRITTLEMENT

- POOR QUALITY CLADDING EXHIBITED MARKED DROP IN CVN DUCTILITY AND SLIGHT RADIATION-INDUCED STRENGTHENING

HOWEVER, BOTH SPECIMEN SETS EXHIBITED DUCTILE-TO-BRITTLE TRANSITION BEHAVIOR DUE TO LOW-TEMPERATURE FAILURE OF δ-FERRITE IN THE CLADDING

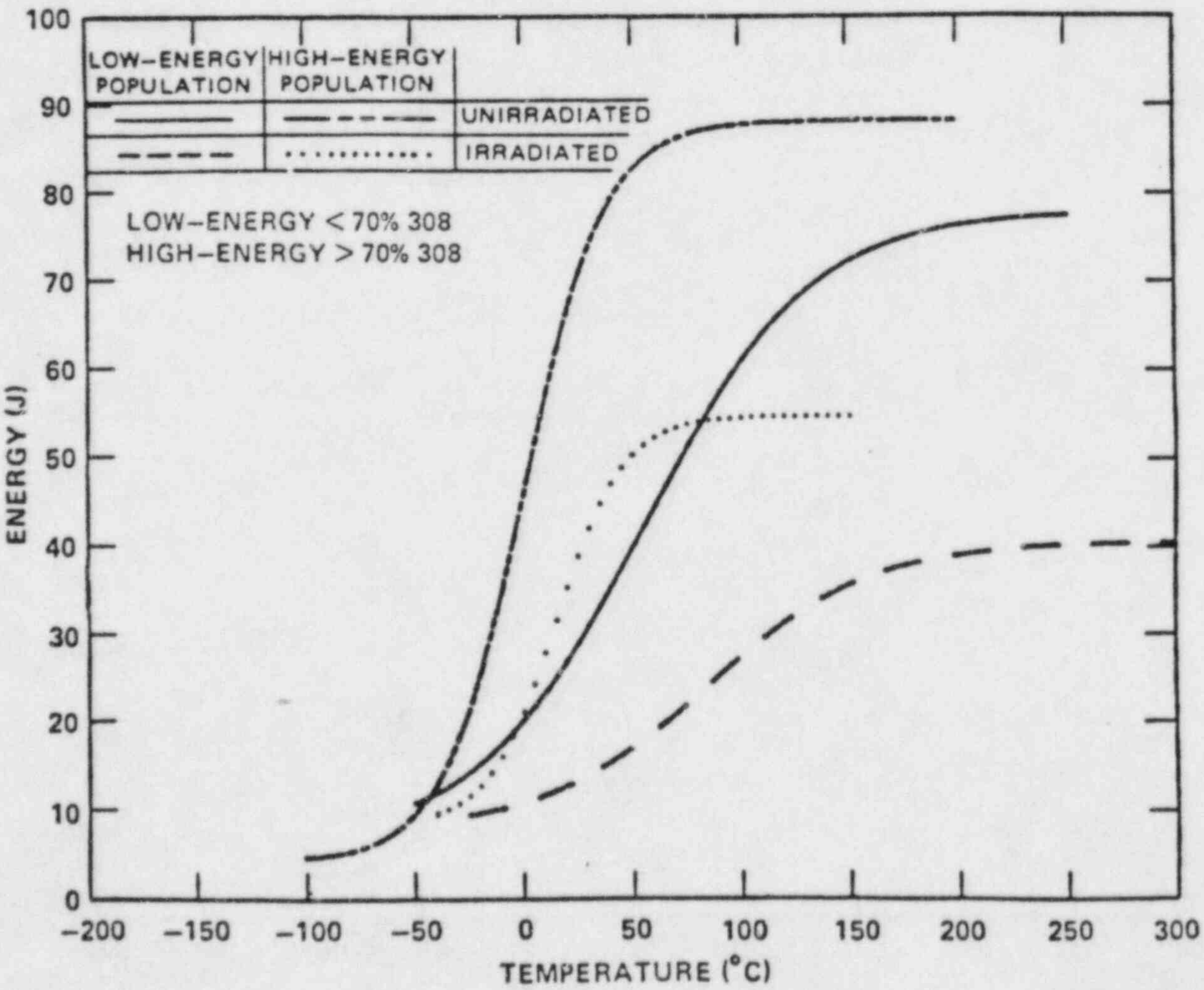
ORNL-DWG 84-4501A ETD

# THE CHARPY IMPACT TOUGHNESS OF TYPE 308 STAINLESS STEEL CLADDING IS ONLY SLIGHTLY DEGRADED BY IRRADIATION AT 288°C TO A FLUENCE OF $2 \times 10^{23}$ n/m$^2$ (E > 1 MeV)



ORNL-DWG 84-4504A ETD

# THE CHARPY TOUGHNESS OF TWO POPULATIONS FORMED BY TYPES 308 AND DILUTED 309 WELD PASSES ARE SEVERELY DEGRADED BY IRRADIATION AT 288°C TO A FLUENCE OF $2 \times 10^{23}$ n/m$^2$ (E > 1 MeV)



**SECOND PHASE OF CLADDING IRRADIATION EXPERIMENTS WILL EXAMINE PROTOTYPIC MATERIALS, HIGHER FLUENCES, AND FRACTURE TOUGHNESS**

- THREE-WIRE SERIES-ARC SUBMERGED-ARC COMMERCIAL WELDMENT

- FLUENCES UP TO $5 \times 10^{23}$ NEUTRONS/$m^2$ (>1 MeV)

- COMPACT SPECIMENS AS WELL AS CHARPY AND TENSILE

- IRRADIATIONS WILL BEGIN AT THE END OF FY 1985; TESTING COMPLETED IN FY 1986

# ON–GOING HSST IRRADIATION STUDIES

## HSST IRRADIATION PROJECT OBJECTIVES

- OBTAIN FRACTURE TOUGHNESS PROPERTIES OF IRRADIATED PRESSURE VESSEL STEELS FOR FRACTURE ANALYSIS OF IN-SERVICE PRESSURE VESSELS

- DETERMINE SPECIMEN GEOMETRY AND SIZE REQUIREMENTS FOR SURVEILLANCE PROGRAMS

- VERIFICATION OF REGULATORY GUIDE 1.99 AND ASME BOILER AND PRESSURE VESSEL CODE

THE HSST IRRADIATION PROGRAM PROVIDES ANSWERS TO QUESTIONS BY THE NRC REGARDING NUCLEAR PRESSURE VESSEL INTEGRITY AFTER EXPOSURE TO NUCLEAR RADIATION

1. DOES FRACTURE TOUGHNESS ($K_{Ic}$) OF IRRADIATED PRESSURE VESSEL STEELS REACH HIGH LEVELS?

2. IF CHARPY V-NOTCH UPPER-SHELF DROPS TO LESS THAN 50 FT-LB, DOES THE TEARING RESISTANCE DECREASE TO LOW LEVELS?

3. WHAT IS THE FRACTURE TOUGHNESS CURVE AND TEARING RESISTANCE OF CURRENT PRACTICE WELDS AFTER IRRADIATION? APPLY STATISTICAL METHODS.

4. VALIDATE THE $K_{IR}$ CURVE TO ~120 KSI$\sqrt{\text{IN.}}$ USING STATISTICAL METHODS.

5. HOW IS CRACK ARREST TOUGHNESS AFFECTED BY IRRADIATION?

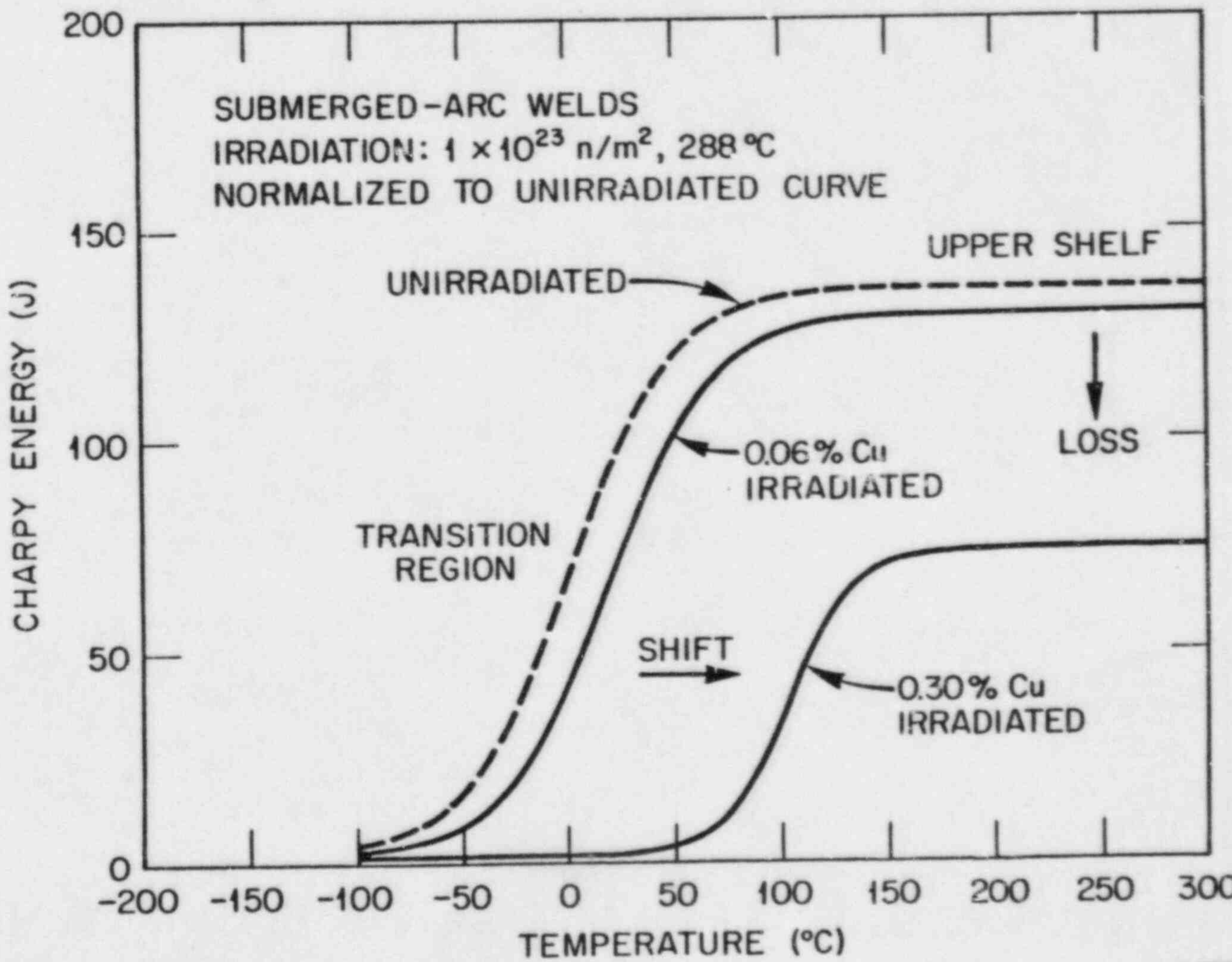
6. IS STAINLESS STEEL CLADDING DEGRADED BY NEUTRON IRRADIATON?

CHANGES IN PRESSURE VESSEL STEEL PROPERTIES
FROM IRRADIATION ARE A FUNCTION OF:

- NEUTRON FLUENCE
- IRRADIATION TEMPERATURE
- CHEMICAL COMPOSITION OF STEEL
- MICROSTRUCTURE OF STEEL
- NEUTRON ENERGY SPECTRUM

ORNL-DWG 85-14709

# IRRADIATION CAUSES DUCTILE/BRITTLE TRANSITION TEMPERATURE SHIFT AND UPPER SHELF ENERGY LOSS — COPPER INCREASES THE EFFECT

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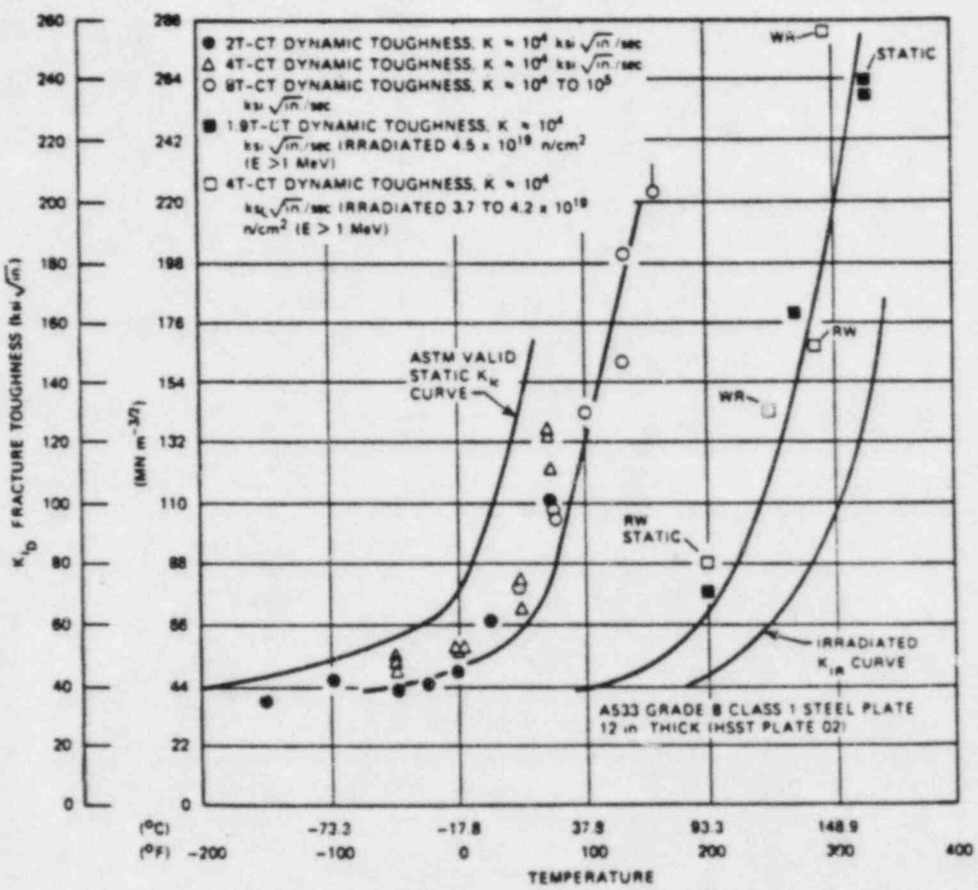
ORNL WSC-40907

# THE HSST IRRADIATION PROGRAM IS CURRENTLY COMPOSED OF SEVEN IRRADIATION SERIES

| SERIES NUMBER | OBJECTIVE & MATERIALS | SPECIMEN TYPES | NEUTRON FLUENCE n/cm² x 10¹⁹ (E>1 MeV) | IRRADIATION TEMPERATURE (°C) | STATUS AS OF JULY 1985 |
|---|---|---|---|---|---|
| 1 | UPPER TRANSITION PLATE AND WELD METAL | 0.4-4T CS CVN, TEN | 2.2-7.0 | 270-300 | COMPLETE |
| 2&3 | DUCTILE SHELF LOW-$C_v$ SHELF, HIGH-COPPER WELDS | 0.5-4T S CVN, TEN | 0.4-1.2 | 233-343 | COMPLETE |
| 4 | DUCTILE SHELF HSST PLATE 02 AND STATE-OF-THE-ART LOW COPPER FRG MATERIAL WELDS | 1T CS CVN, TEN | 0.5-2.7 | 288±5 | TESTING COMPLETED 6/85 |
| 5 | $K_{Ic}$ CURVE SHIFT HIGH-$C_v$ SHELF, HIGH-COPPER WELD METAL | 1-4T CS CVN, TEN, DWT | TARGET: 1.7 | 288±10 | IRRADIATIONS BEGAN 5/84 |
| 6 | $K_{Ia}$ CURVE SHIFT SAME AS SERIES 5 | 1.0-1.3T CCA | TARGET: 1.7 | TARGET: 288 | BEGIN IRRADIATION 12/85 |
| 7 | STAINLESS STEEL CLADDING SINGLE-AND MULTIWIRE | 0.5T CS CVN, TEN | TARGET: 1,2,5 | TARGET: 288 | ONE-WIRE COMPLETE THREE-WIRE BEGIN 8/85 |

FIRST HSST IRRADIATION SERIES SHOWED HIGH DYNAMIC FRACTURE TOUGHNESS (ABOVE PREDICTED $K_{IR}$ CURVE) AFTER IRRADIATION

ORNL-DWG 76-6486R




SUMMARY OF LARGE CT SPECIMEN POSTIRRADIATION TOUGHNESS

# HSST TASK H.6, IRRADIATION EFFECTS STUDIES

CURRENT GOALS:

- PROVIDE STATISTICAL INFORMATION ON FRACTURE TOUGHNESS CHANGES OF STATE-OF-THE-ART WELD METALS (SERIES 4)
- VALIDATE SHIFT IN ASME $K_{Ic}$ CURVE WITH MULTIPLE LARGE SPECIMENS FROM HIGH-COPPER WELDS (SERIES 5)
- VALIDATE SHIFT IN ASME $K_{Ia}$ CURVE (SERIES 6)
- EVALUATE EFFECTS OF NEUTRON IRRADIATION ON TOUGHNESS OF STAINLESS STEEL CLADDING (SERIES 7)

FOURTH IRRADIATION SERIES EXAMINES "CURRENT PRACTICE" WELDS USING STATISTICAL METHODS

- PRIMARY OBJECTIVE IS TO CHARACTERIZE FRACTURE TOUGHNESS OF SELECTED "CURRENT PRACTICE" (LOW COPPER, LOW NICKEL) IRRADIATED PRESSURE VESSEL STEELS WITH EMPHASIS ON UPPER-SHELF PROPERTIES AND USING STATISTICAL METHODS

- INCLUDE A RANGE OF METALLURGICAL PROPERTIES TO EVALUATE CHEMISTRY, UPPER-SHELF ENERGY, AND PRODUCT FORM

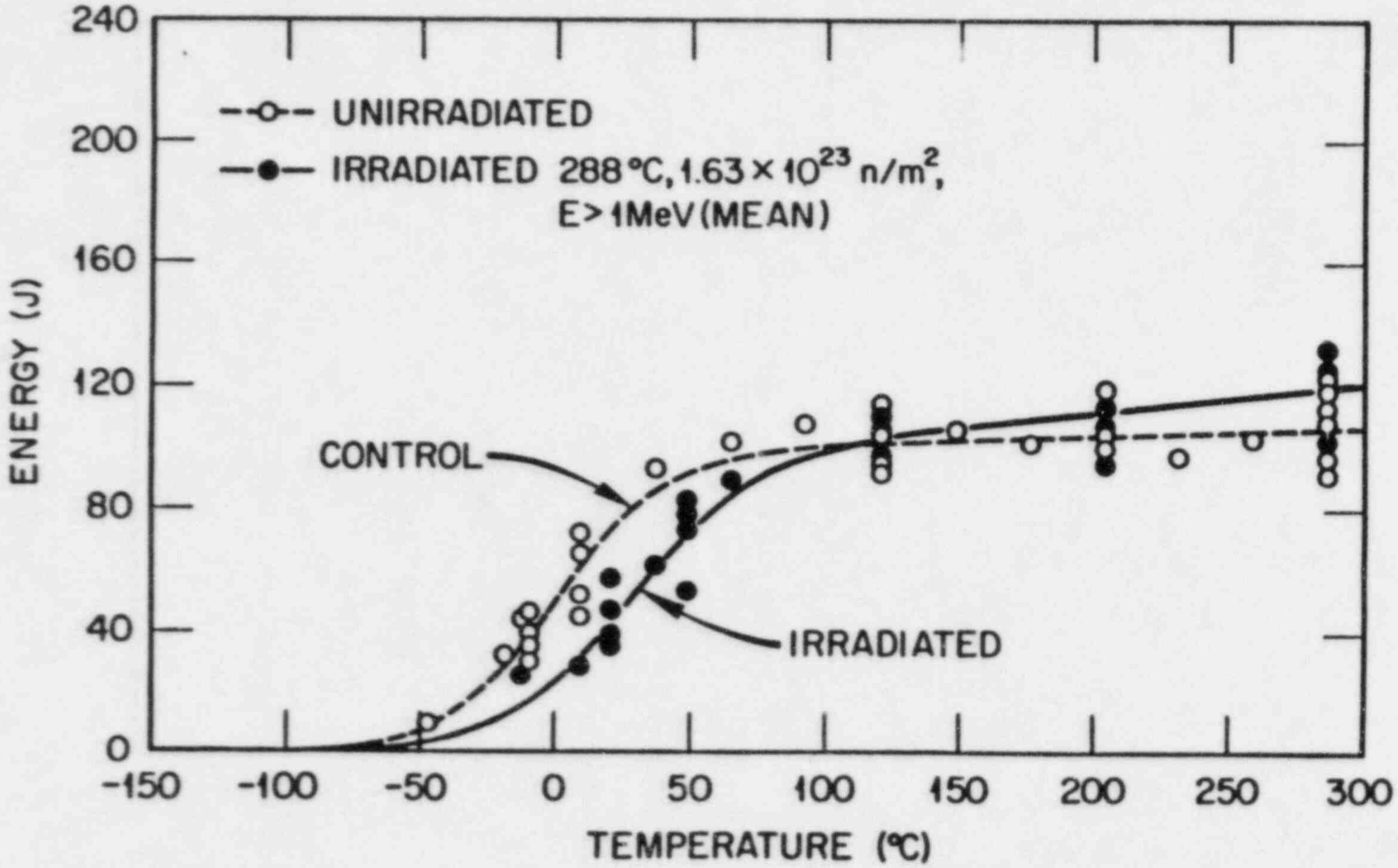
- UTILIZE 1TCS SPECIMENS TO DEVELOP J-R PROPERTIES

- STUDY EFFECT OF CHANGE

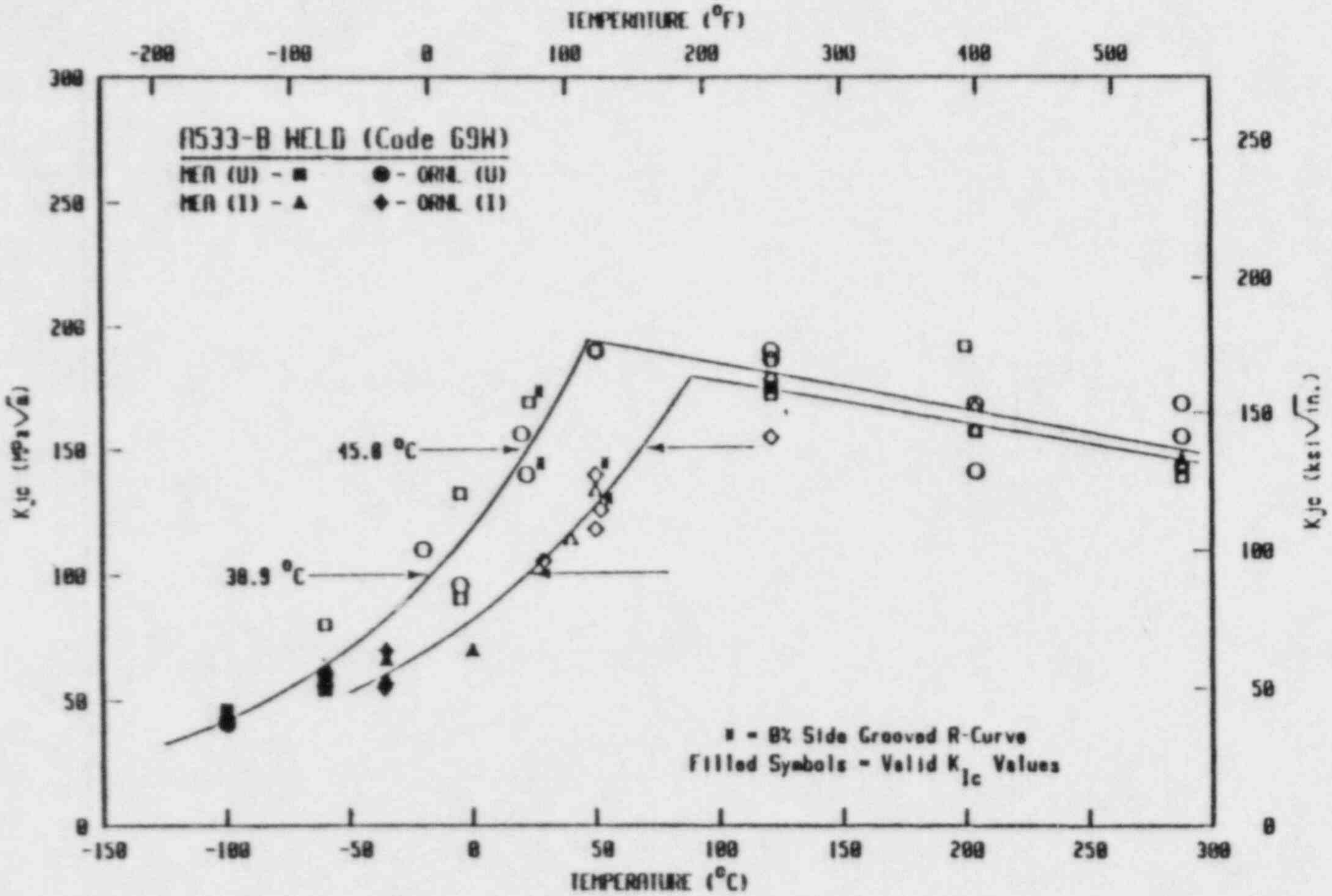
- UTILIZE EXISTING BSR FACILITY

ORNL-DWG 84-11759

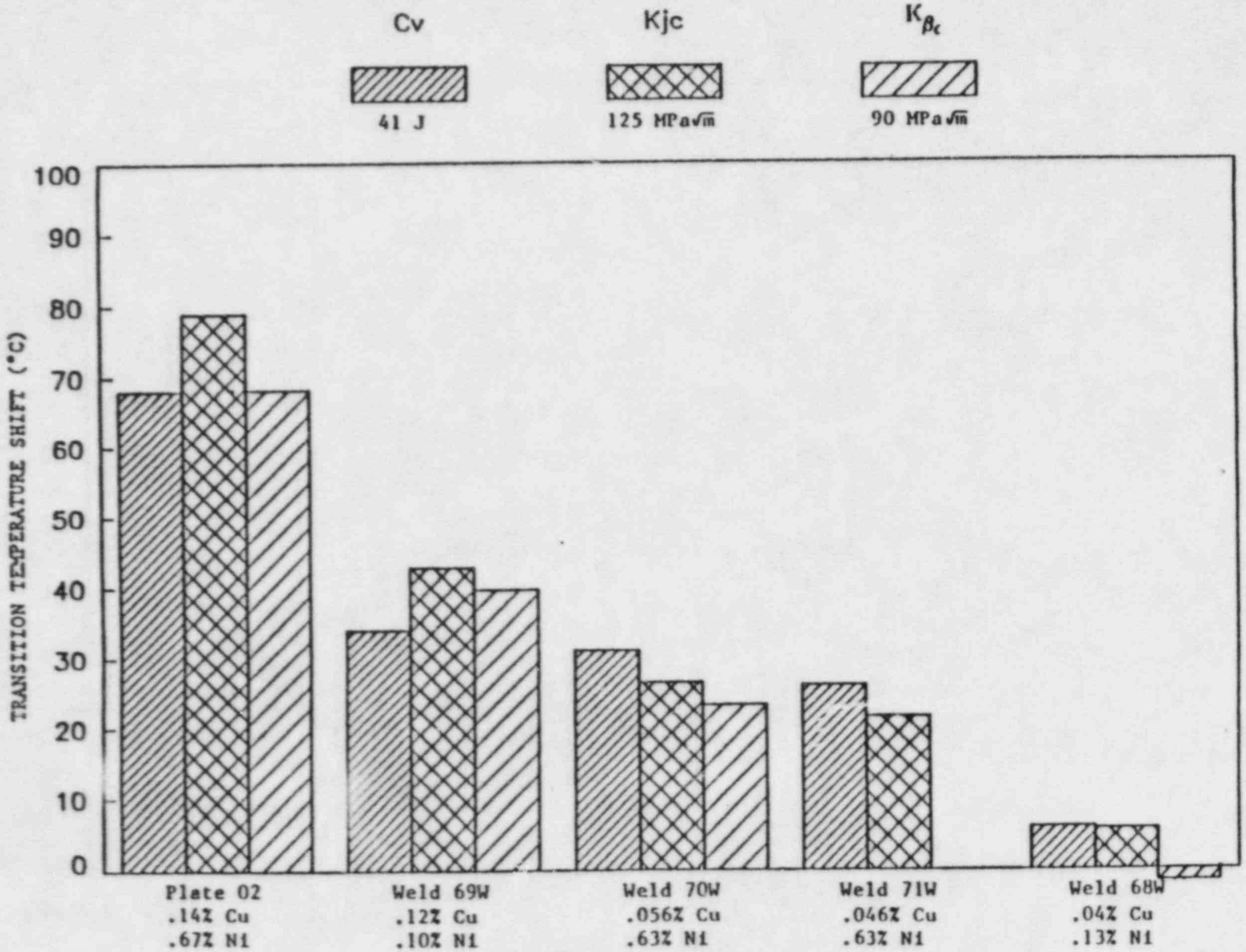
CHARPY-V ENERGY OF SUBMERGED-ARC WELD (HSST-71W) BEFORE AND AFTER IRRADIATION. FITTED TO HYPERBOLIC TANGENT (Sloping Shelf) FUNCTION



FRACTURE TOUGHNESS TESTS SHOW RESULTS SIMILAR TO CHARPY AND GOOD AGREEMENT FOR TWO-LABORATORY TESTING



FOURTH IRRADIATION RESULTS SHOW IRRADIATION RESISTANCE
OF CURRENT PRACTICE WELDS



THE FOURTH HSST IRRADIATION SERIES HAS LED TO THREE CONCLUSIONS TO DATE

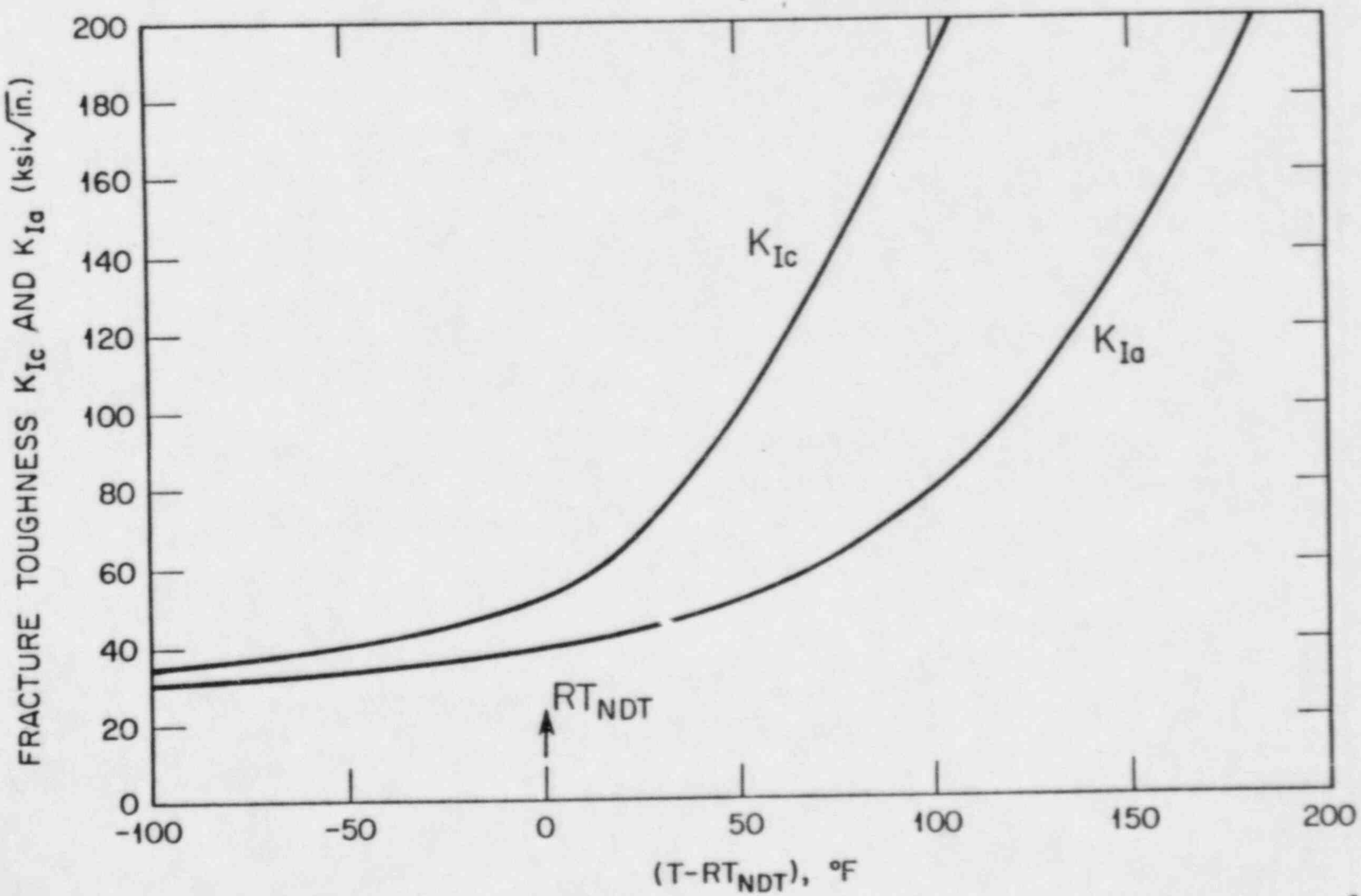
- REGULATORY GUIDE 1.99 GUIDELINE VALUES FOR CHARPY-TRANSITION TEMPERATURE SHIFT WERE CONSERVATIVE FOR THESE "CURRENT PRACTICE" WELDMENTS

- "CURRENT PRACTICE" WELDMENTS EXHIBITED NO SIGNIFICANT DROP IN CHARPY UPPER-SHELF ENERGIES

- THE NEED FOR USING STATISTICAL METHODS OF ANALYSIS FOR CHARPY RESULTS WAS DEMONSTRATED

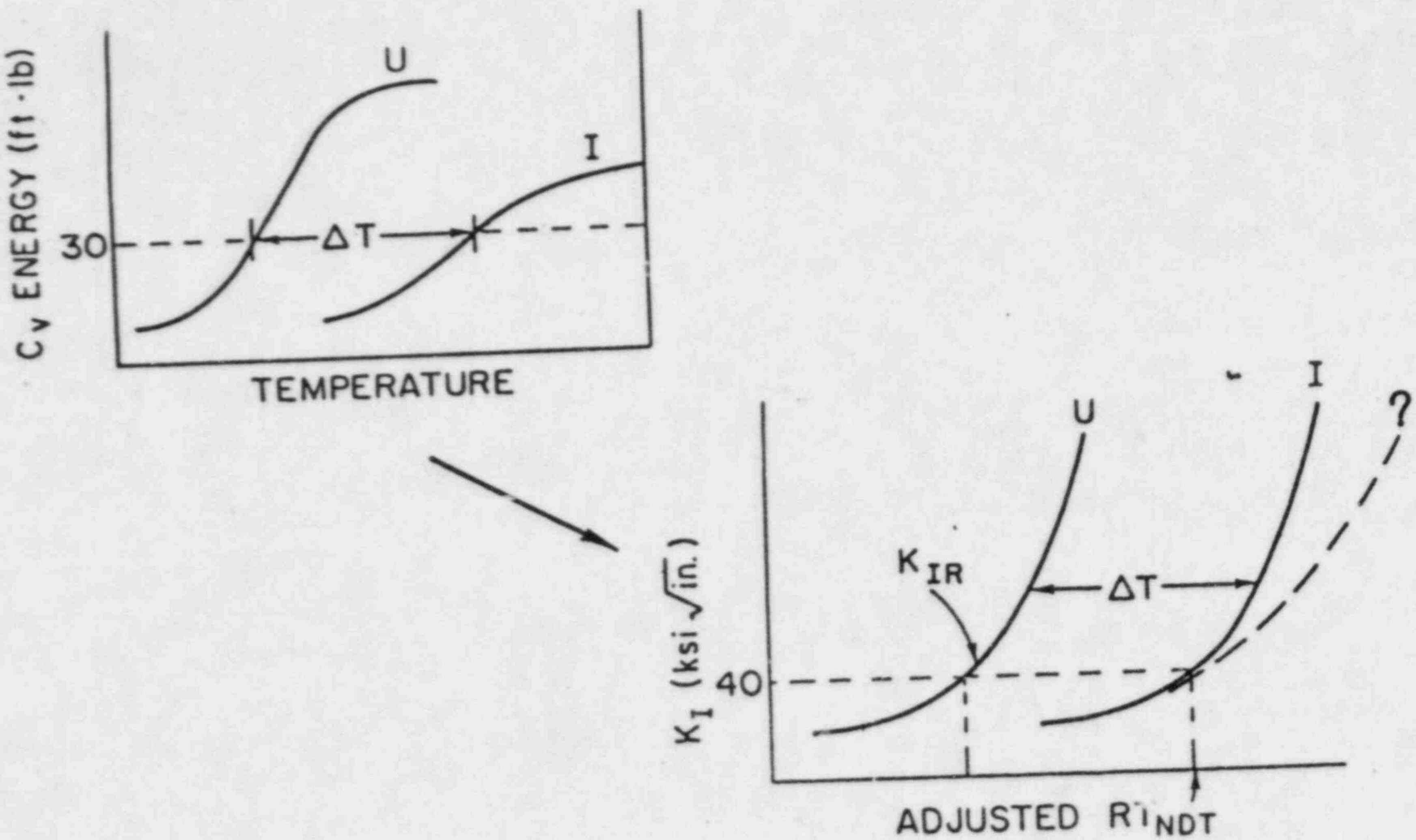
ORNL-DWG 85-14710

SERIES 5 AND 6 WILL VALIDATE SHIFTS AND SHAPE OF THE INITIATION ($K_{Ic}$) AND ARREST ($K_{Ia}$) TOUGHNESS CURVES OF SECTION XI, ASME CODE




ornl

## $K_I$ Curve Shift and Shape Change Due to Irradiation



FIFTH HSST IRRADIATION SERIES WILL VERIFY IRRADIATED $K_{Ic}$ CURVES WITH TWO HIGH-COPPER WELD MATERIALS

OBJECTIVES:

- VERIFY IRRADIATED $K_{Ic}$ CURVE TO AS HIGH A $K_{Ic}$ LEVEL AS POSSIBLE
- CORRELATE $K_{Ic}$-TEMPERATURE SHIFT WITH CV-TRANSITION TEMPERATURE SHIFT AND DW NDT SHIFT
- MULTIPLE TESTS FOR STATISTICAL ANALYSES

MATERIALS:

- TWO SA WELDS, 0.25 AND 0.34% Cu

SPECIMENS:

- 1-, 2-, 4TCS, CVN, DW, TENSILE

## SPECIMEN COMPLEMENT FOR THE FIFTH IRRADIATION SERIES ALLOWS FOR STATISTICAL ANALYSES

- SMALL SPECIMENS WILL BE TESTED FIRST TO CHARACTERIZE MATERIAL:

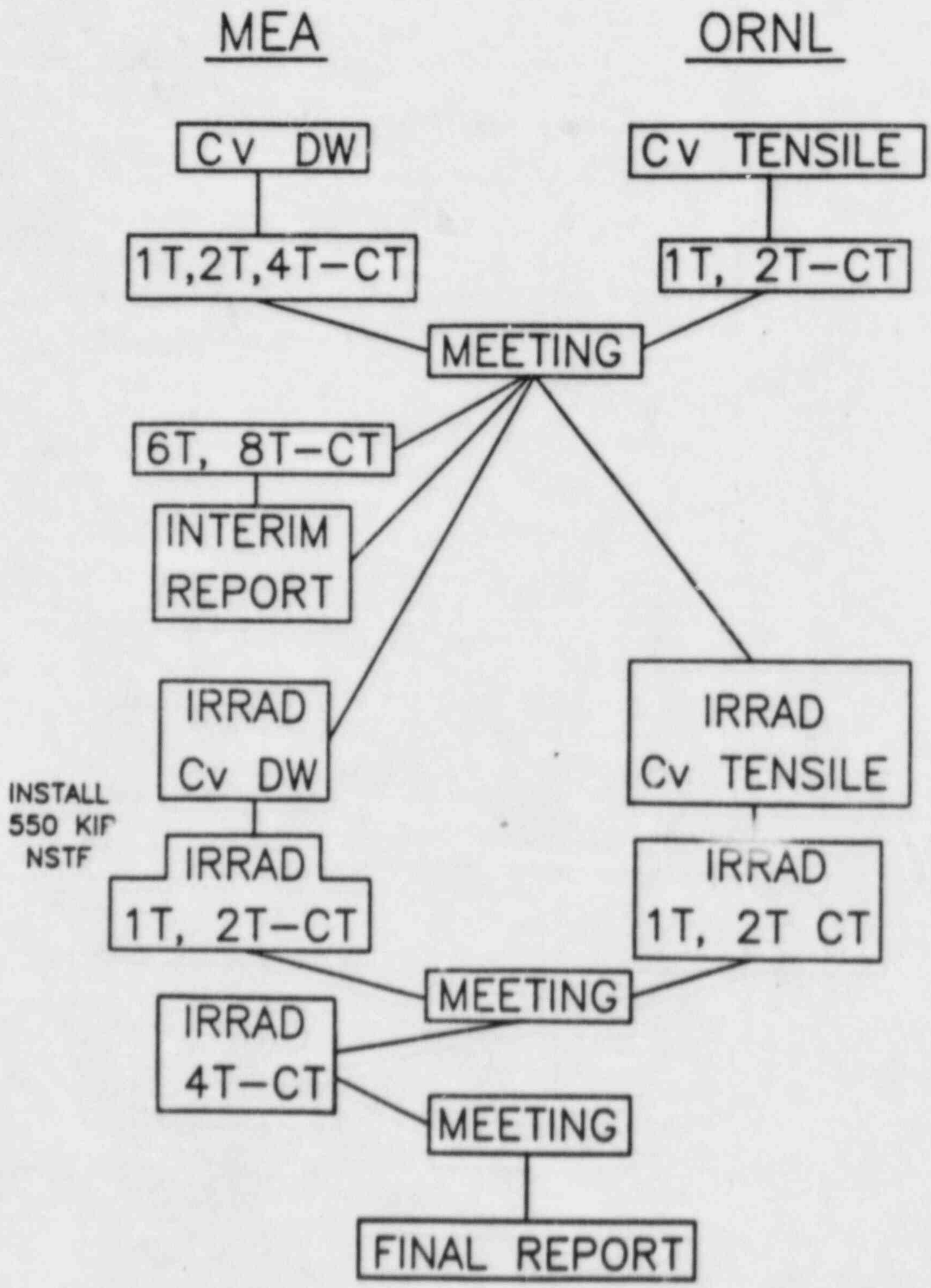
  CVN - 160 UNIRRADIATED, 110 IRRADIATED
  DWT - 24 UNIRRADIATED, 32 IRRADIATED
  TEN - 48 UNIRRADIATED, 32 IRRADIATED

- COMPACT SPECIMENS WILL BE TESTED IN ORDER BY SIZE:

  1TCS - 68 UNIRRADIATED, 60 IRRADIATED
  2TCS - 32 UNIRRADIATED, 36 IRRADIATED
  4TCS - 24 UNIRRADIATED, 16 IRRADIATED
  6TCS - 8 UNIRRADIATED
  8TCS - 8 UNIRRADIATED

- SMALL COMPACT SPECIMENS WILL BE TESTED BY J-INTEGRAL TO HELP DETERMINE TEMPERATURE FOR VALID $K_{Ic}$ WITH LARGE SPECIMENS

- PREDICTED MAXIMUM VALID $K_{Ic}$ WITH IRRADIATED 4TCS IS ABOUT 130 $MPa\sqrt{m}$


MEA
ORNL
Cv DW
Cv TENSILE
1T,2T,4T-CT
1T, 2T-CT
MEETING
6T, 8T-CT
INTERIM REPORT
IRRAD Cv DW
IRRAD Cv TENSILE
INSTALL 550 KIP NSTF
IRRAD 1T, 2T-CT
IRRAD 1T, 2T CT
MEETING
IRRAD 4T-CT
MEETING
FINAL REPORT

THE FIFTH IRRADIATION SERIES IS PROGRESSING ON SCHEDULE

- CAPSULES 1–4 (4TCS), IRRADIATIONS COMPLETE
- CAPSULES 5–6 (1TCS, TEN, CVN, DWT), IRRADIATIONS COMPLETE
- CAPSULES 7–8 (2TCS), IRRADIATIONS COMPLETE
- CAPSULES 9–10 (4TCS), IRRADIATIONS COMPLETE
- CAPSULES 11–12 (4TCS), IRRADIATIONS, 9/85–11/85
- TESTING OF UNIRRADIATED SPECIMENS WELL UNDER WAY
- TESTING OF IRRADIATED SPECIMENS BEGINS 9/85
- COMPLETE TESTING, ORNL AND MEA, 9/86

THE SIXTH IRRADIATION ON CRACK ARREST WILL
IMMEDIATELY FOLLOW THE FIFTH IRRADIATION
PROGRAM CURRENTLY UNDER WAY

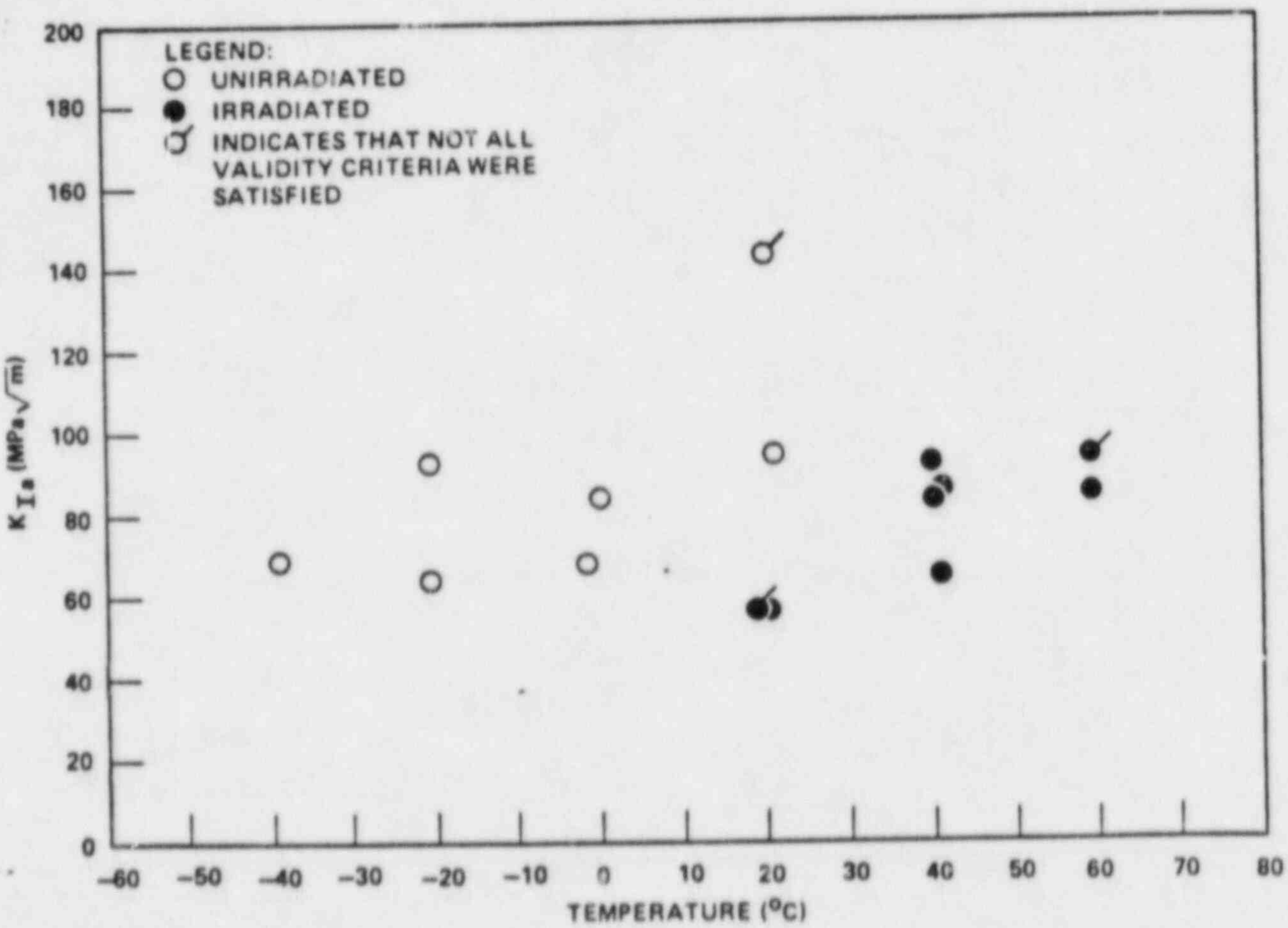
- ALL TEST MATERIALS AND IRRADIATION CONTROL EQUIPMENT ARE ON HAND AND FABRICATION DRAWINGS OF THE CAPSULES AND SUPPORTS ARE IN PROGRESS

- CAPSULE ASSEMBLY WILL START BY OCTOBER 1985

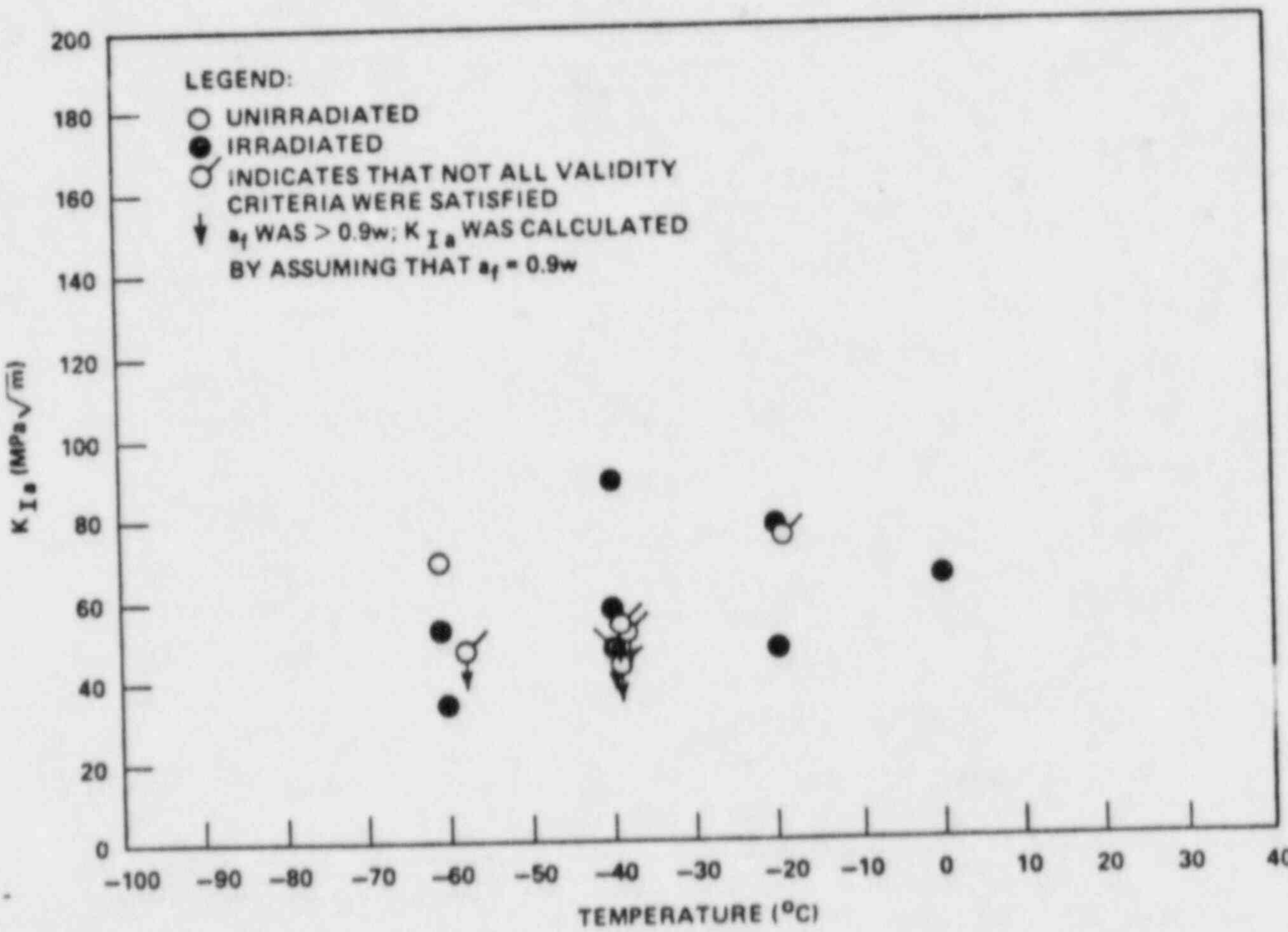
- IRRADIATION WILL BEGIN JANUARY 1986

- TESTING WILL BE COMPLETED IN MID-FY 1987

IRRADIATED CRACK ARREST DATA (EPRI) HAVE ONLY BEEN GENERATED ON ONE HIGH-COPPER WELDMENT (0.20 wt % Cu, 0.54 wt % Ni, 0.010 wt % P)



IRRADIATED CRACK ARREST DATA (EPRI) HAVE BEEN DEVELOPED ON ONLY ONE LOW-COPPER WELDMENT (0.03 wt % Cu, 0.05 wt % Ni, 0.004 wt % P)



THE SIXTH HSST IRRADIATION PROGRAM WILL GREATLY EXPAND THE EXISTING BASE OF IRRADIATED CRACK ARREST DATA ON REACTOR VESSEL STEELS

| | NUMBER OF DATA POINTS | |
|---|---|---|
| | UNIRRADIATED | IRRADIATED |
| BASE METAL | 518* | 19 |
| WELDMENT | 28 | 17 |

*DOES NOT INCLUDE ~250 ASTM CO-OP AND ROUND ROBIN TESTS

THIRTY TRANSVERSE-LOADED CRACK ARREST SPECIMENS
OF EACH MATERIAL WILL BE IRRADIATED

- EIGHT WELD-EMBRITTLED, 25 x 75 x 75 mm
- SEVEN WELD-EMBRITTLED, 25 x 150 x 150 mm
- THREE WELD-EMBRITTLED, 33 x 150 x 150 mm
- TWELVE DUPLEX, 33 x 150 x 150 mm

$K_{Ia}$ MEASUREMENT RANGE SHOULD EXCEED 50 TO 200 $MPa\sqrt{m}$

THE MATERIALS AND FACILITIES WILL BE IDENTICAL TO THOSE OF THE FIFTH HSST IRRADIATION ON THE $K_{Ic}$ SHIFT

- EXTENSIVE BASE OF SMALL SPECIMEN DATA AVAILABLE (CVN, TEN, DWT, $K_J$)
- RESULTS OF $K_{Ia}$ AND $K_{Ic}$ IRRADIATIONS IN CONJUNCTION WITH CVN AND DWT ALLOW QUANTITATIVE ASSESSMENT OF $K_{IR}$ SHIFT AS $F(RT_{NDT})$

PRESENTATION
TO
ACRS
METAL COMPONENTS
SUBCOMMITTEE

ON
PIPING DEGRADATION

5 SEPTEMBER 1985

BY

M. E. MAYFIELD
MATERIALS ENGINEERING BRANCH
DIVISION OF ENGINEERING TECHNOLOGY
OFFICE OF NUCLEAR REGULATORY RESEARCH

PIPING DEGRADATION RESEARCH

PIPING FRACTURE

IWB-3640

LEAK BEFORE BREAK

PIPING FRACTURE RESEARCH PROGRAMS

- DEGRADED PIPING PROGRAM - PHASE II

CONTRACTOR: BATTELLE'S COLUMBUS LABORATORIES

- ANALYTICAL AND EXPERIMENTAL EFFORT
    - o PIPE FRACTURE EXPERIMENT DATA BASE
    - o ASSESS DEGREE OF CONSERVATISM IN ANALYSES
    - o REVISE AND/OR DEVELOP ANALYSES

PIPING RESEARCH PROGRAMS

- ELASTIC-PLASTIC FRACTURE OF PRESSURE VESSEL AND PIPING STEELS

  CONTRACTOR: DAVID TAYLOR NAVAL SHIP R&D CENTER

  - PREDOMINANTLY EXPERIMENTAL EFFORT

    - o CHARACTERIZE FRACTURE BEHAVIOR OF PIPING AND PIPING MATERIALS

    - o EVALUATE EFFECT OF CRACK MORPHOLOGY

    - o DEVELOP AND EVALUATE FRACTURE PROPERTY MEASUREMENT TECHNIQUES

## PIPING FRACTURE RESEARCH PROGRAMS

- STRUCTURAL INTEGRITY OF LWR PRESSURE BOUNDARY COMPONENTS - TASK 1E

  CONTRACTOR: MATERIALS ENGINEERING ASSOCIATES

  - ESTABLISH A NUMERIC DATA BASE OF PIPE FRACTURE PROPERTIES
    - Collect Existing Data
    - Perform Tests as Necessary
    - Implement Data Base on Computer

PIPING FRACTURE RESEARCH PROGRAMS

- RELATED PROGRAMS
  - Aging of Cast Stainless Steels - ANL
  - Environmentally Assisted Cracking - ANL & MEA
  - Susceptibility of Weld Repairs to SCC - PNL
  - NDE - PNL

# PIPING FRACTURE

- FRACTURE BEHAVIOR OF FLAWED PIPE
  - Experiments
  - Analysis Methods
- REPRESENTATIVE MATERIAL PROPERTY DATA

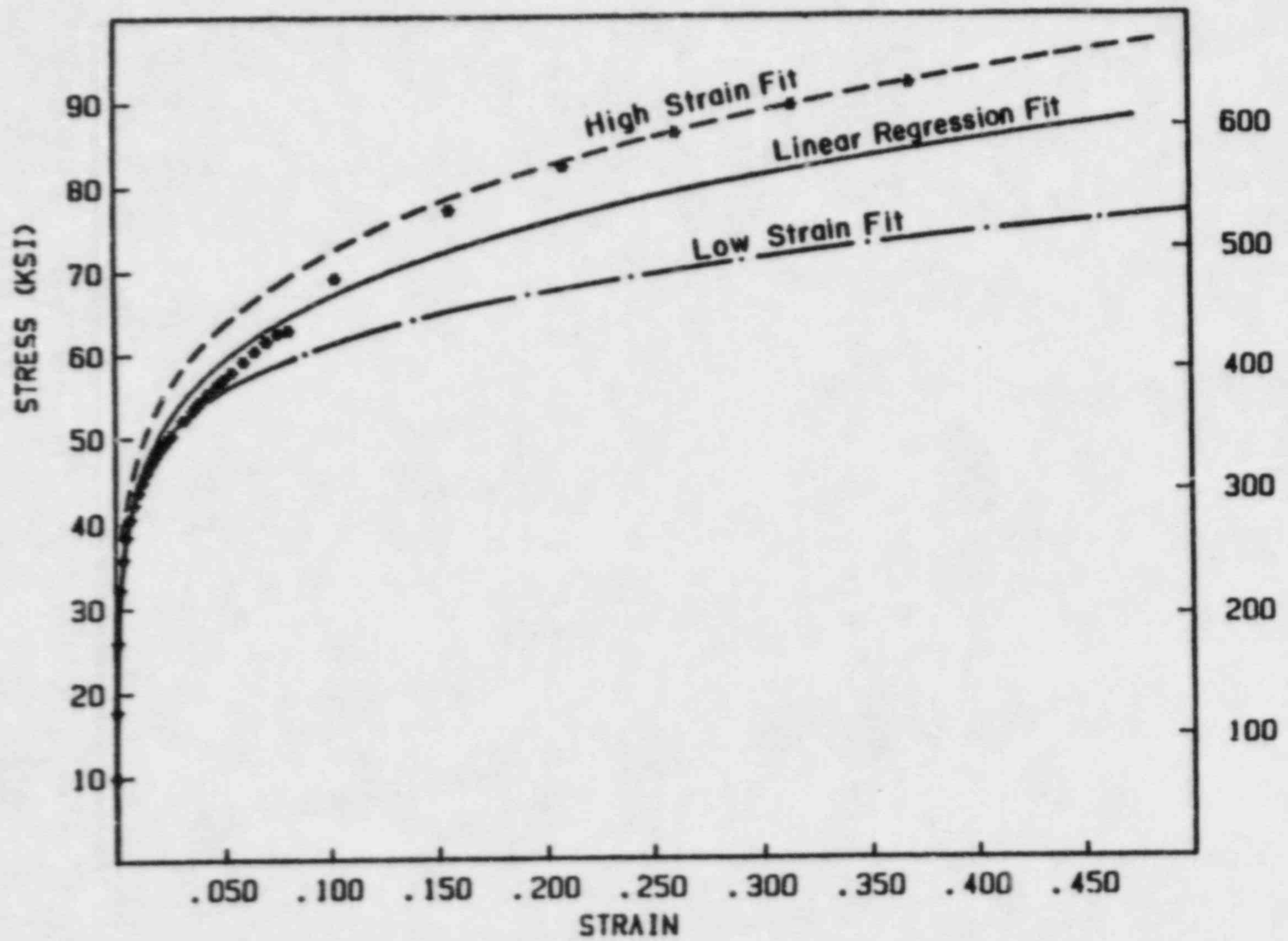
# PIPING FRACTURE

- DEVELOPMENT OF REPRESENTATIVE MATERIAL PROPERTY DATA

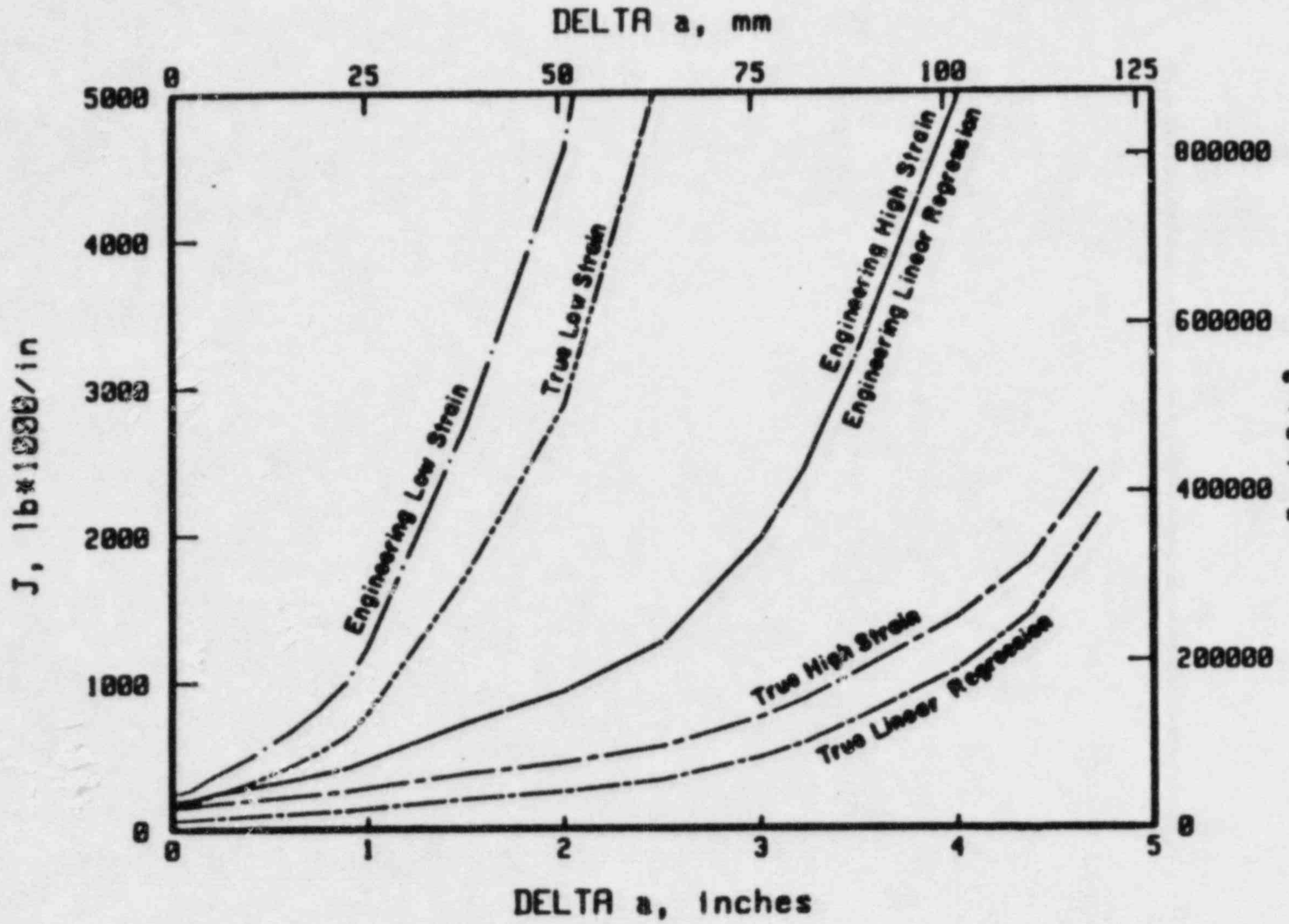
  - TENSILE TESTING
    TRUE STRESS - TRUE STRAIN
    - TEST METHODS
    - DATA ANALYSIS

  - FRACTURE TOUGHNESS TESTING
    APLICATION OF SPECIMEN DATA TO PIPE ANALYSIS
    - LARGE CRACK GROWTH FROM SMALL SPECIMEN

    SPECIMEN TYPE
    - CT - STANDARD VS LARGE PLAN FORM
    - FWFN (T)

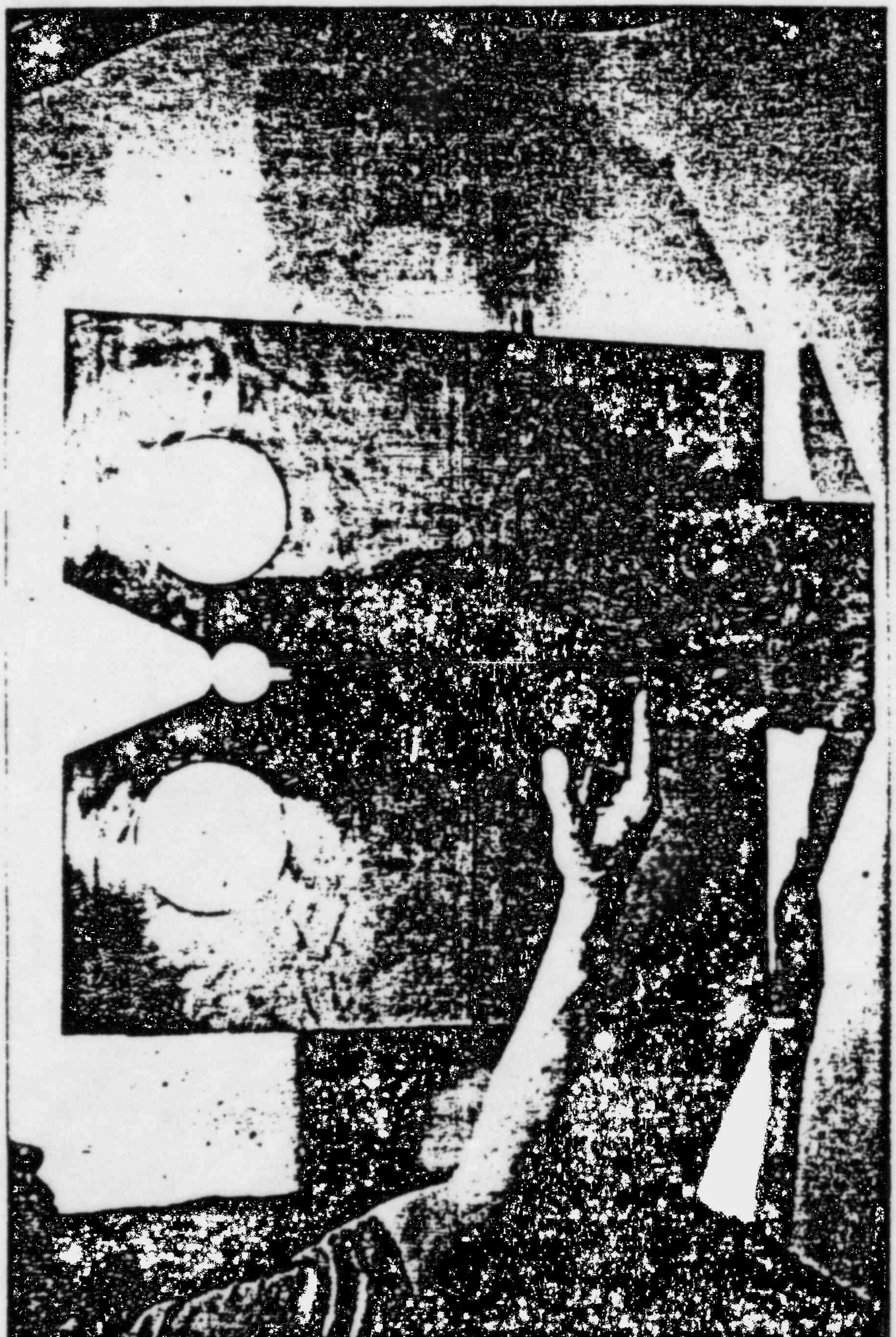


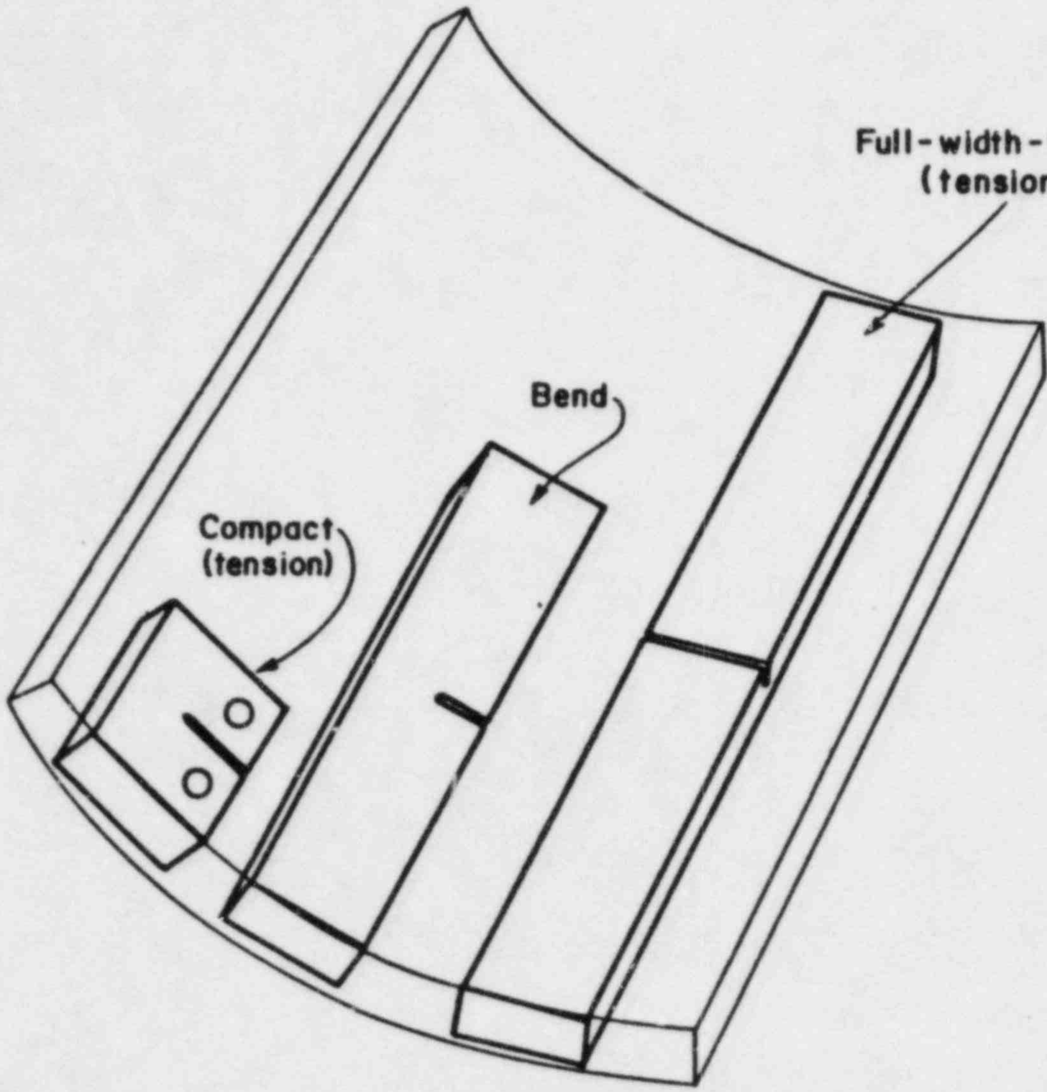
High Strain Fit
Linear Regression Fit
Low Strain Fit
STRESS (KSI)
90
80
70
60
50
40
30
20
10
STRESS (MPa)
600
500
400
300
200
100
.050
.100
.150
.200
.250
.300
.350
.400
.450
STRAIN




A8 (OD=16", t=1.03")

Battelle
Columbus Laboratories



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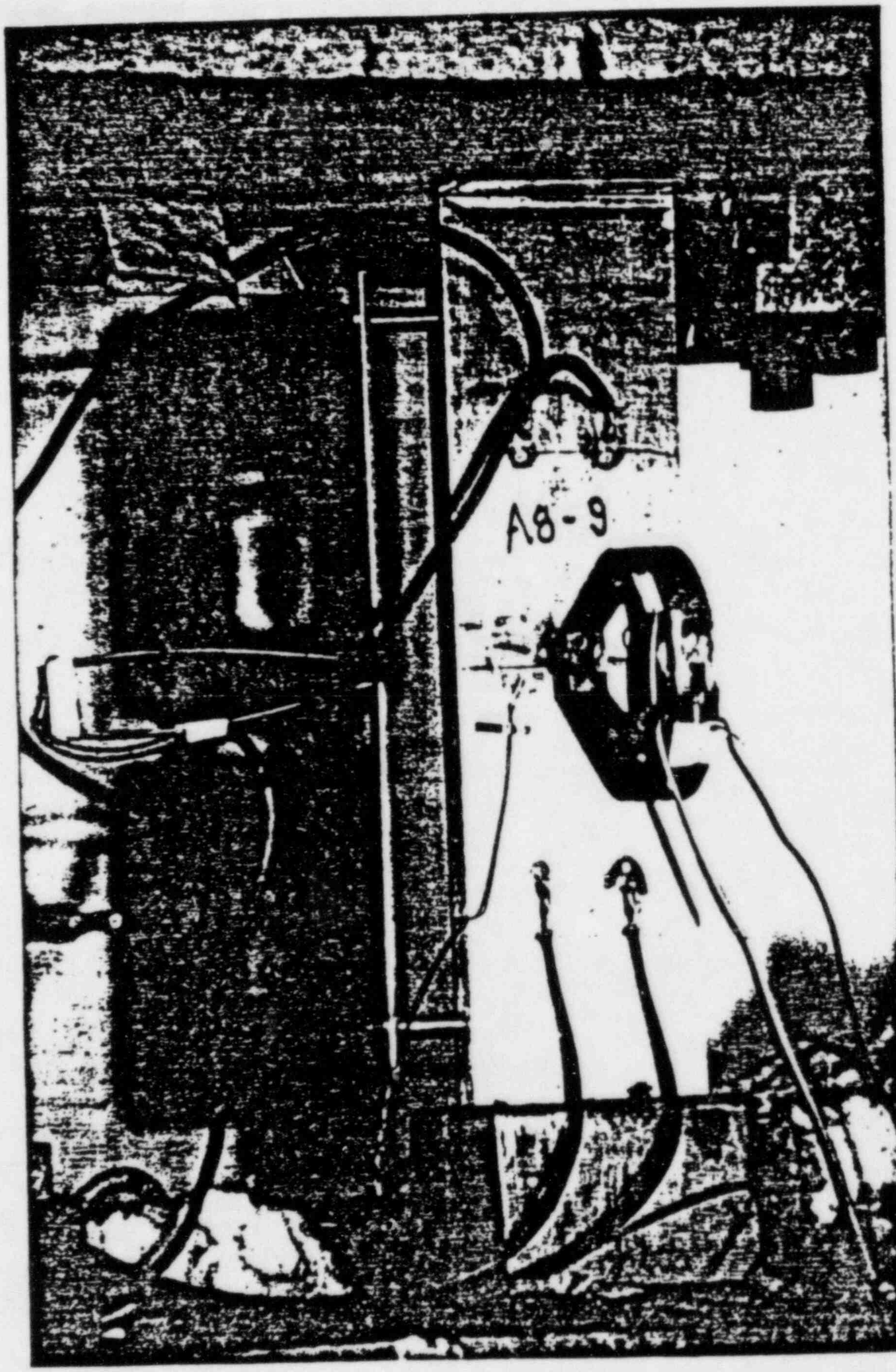
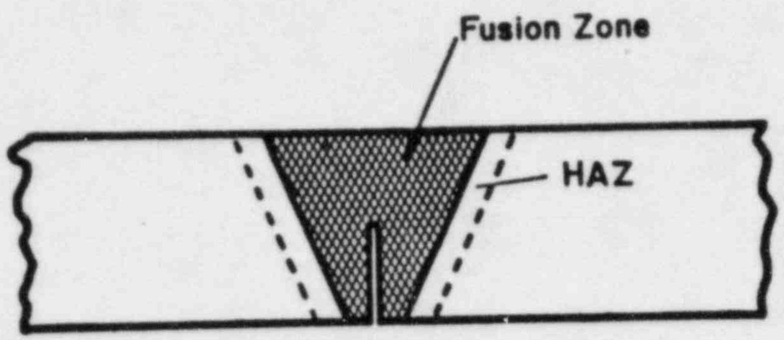
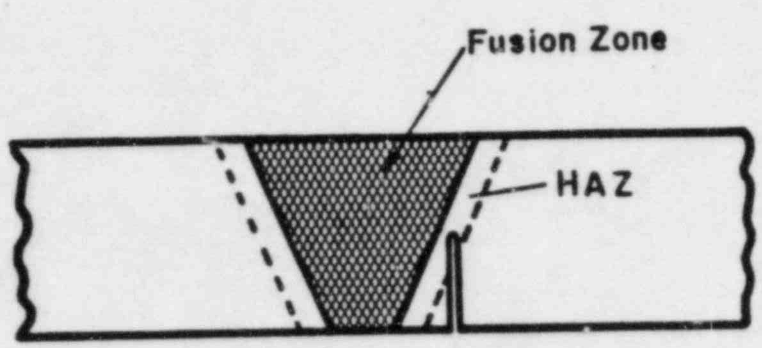

A8-9




(a) Weld Specimen




(b) HAZ Specimen

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## PIPING FRACTURE

- NRC HAS FUNDED 49 PIPE FRACTURE EXPERIMENTS
  - BCL 30
  - DTNSRDC 19
- CURRENT WORK PLANS INCLUDE AN ADDITIONAL 45 PIPE EXPERIMENTS
- BCL HAS DOCUMENTED 39 PIPE FRACTURE EXPERIMENTS FROM OTHER LABS (EXCLUDING DTNSRDC)
- PIPE FRACTURE DATA RECORD BOOK BEING PREPARED

# PIPING FRACTURE

- FRACTURE BEHAVIOR OF FLAWED PIPE
  - PIPE SIZES
    - o 4 IN. TO 42 IN.
    - o 37 IN. OD X 3.25 IN. WALL
    - o 28 IN. OD X 0.875 IN. WALL
  - MATERIALS
    - o STAINLESS STEEL & WELDS (TIG, SAW, SMAW)
    - o CAST STAINLESS STEEL & WELDS
    - o INCONEL
    - o CARBON STEEL & WELDS
  - LOADING TYPE
    - o TENSION
    - o BENDING
    - o TENSION & BENDING
    - o EFFECT OF SYSTEM COMPLIANCE

# PIPING FRACTURE

- ANALYSIS METHODS
  - ELASTIC-PLASTIC FRACTURE MECHANICS
  - STRENGTH OF MATERIALS

# PIPING FRACTURE

- ELASTIC-PLASTIC FRACTURE MECHANICS

  - MUST HAVE VALID FORMULATION FOR J

    - o TWO TYPES - PREDICTIVE VS NON-PREDICTIVE

NON-PREDICTIVE

- $\eta$-FACTOR APPROACH FROM BCL
- MUST HAVE P-$\delta$ CURVE

PREDICTIVE

- GE ESTIMATION SCHEME
- PARIS & TADA
- NRC-NRR
- FINITE ELEMENT

# PIPING FRACTURE

- ELASTIC-PLASTIC FRACTURE MECHANICS

  - GE ESTIMATION SCHEME

    - O CONSERVATIVE PREDICTIONS
    - O MORE CONSERVATIVE FOR STAINLESS STEELS THAN FOR CARBON STEELS

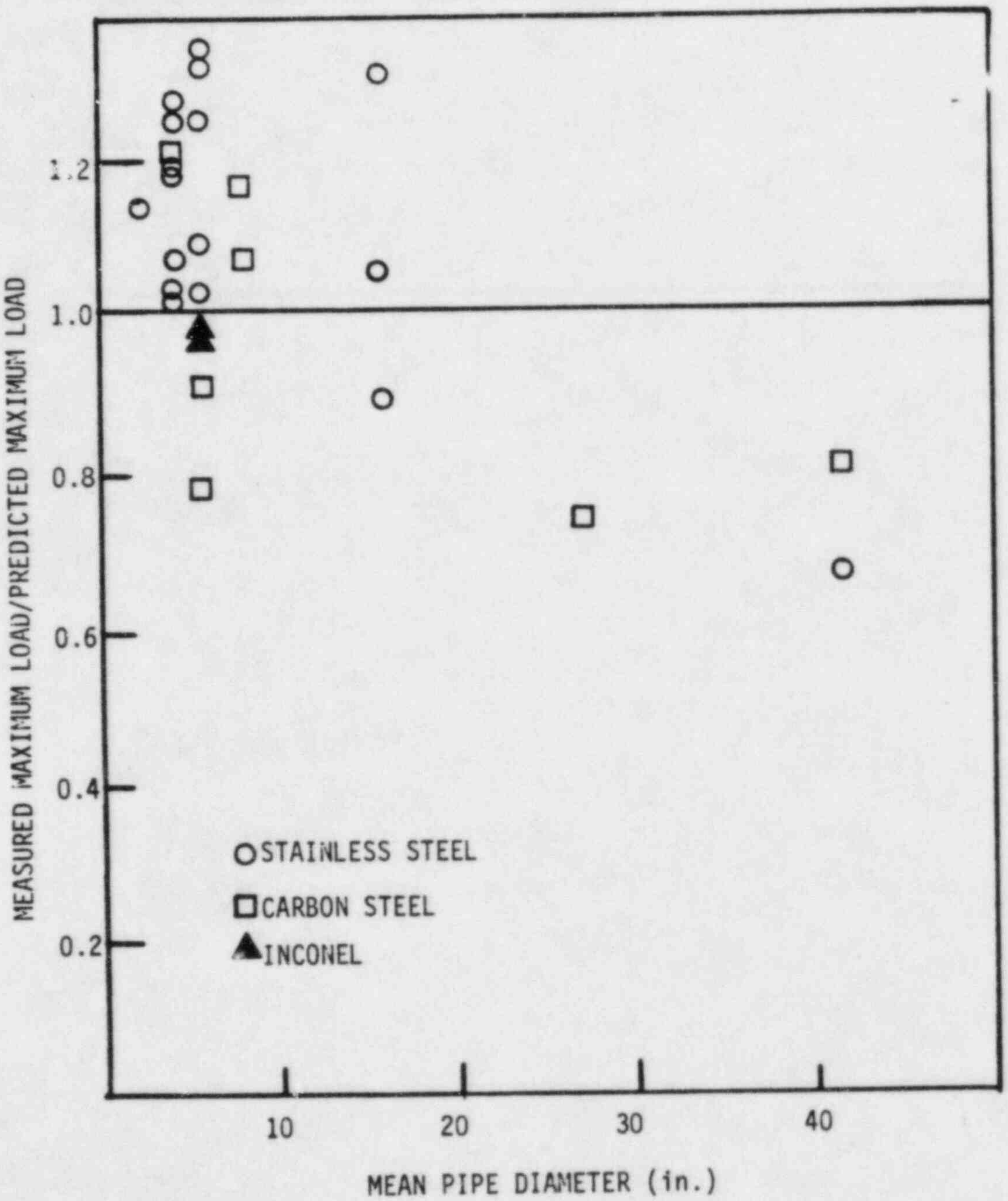
  - NRC-NRR SCHEME

    - O CONSERVATIVE PREDICTIONS FOR STAINLESS STEEL
    - O SLIGHTLY NON-CONSERVATIVE PREDICTIONS FOR CARBON STEEL
    - O AT NRR REQUEST, BCL WORKING WITH NRR TO TEST METHOD AND DOCUMENT

# PIPING FRACTURE

- STRENGTH OF MATERIALS
  - BASIC CONCEPT:

    PLASTIC COLLAPSE OF THE CRACKED CROSS-SECTION IS THE FAILURE MODE

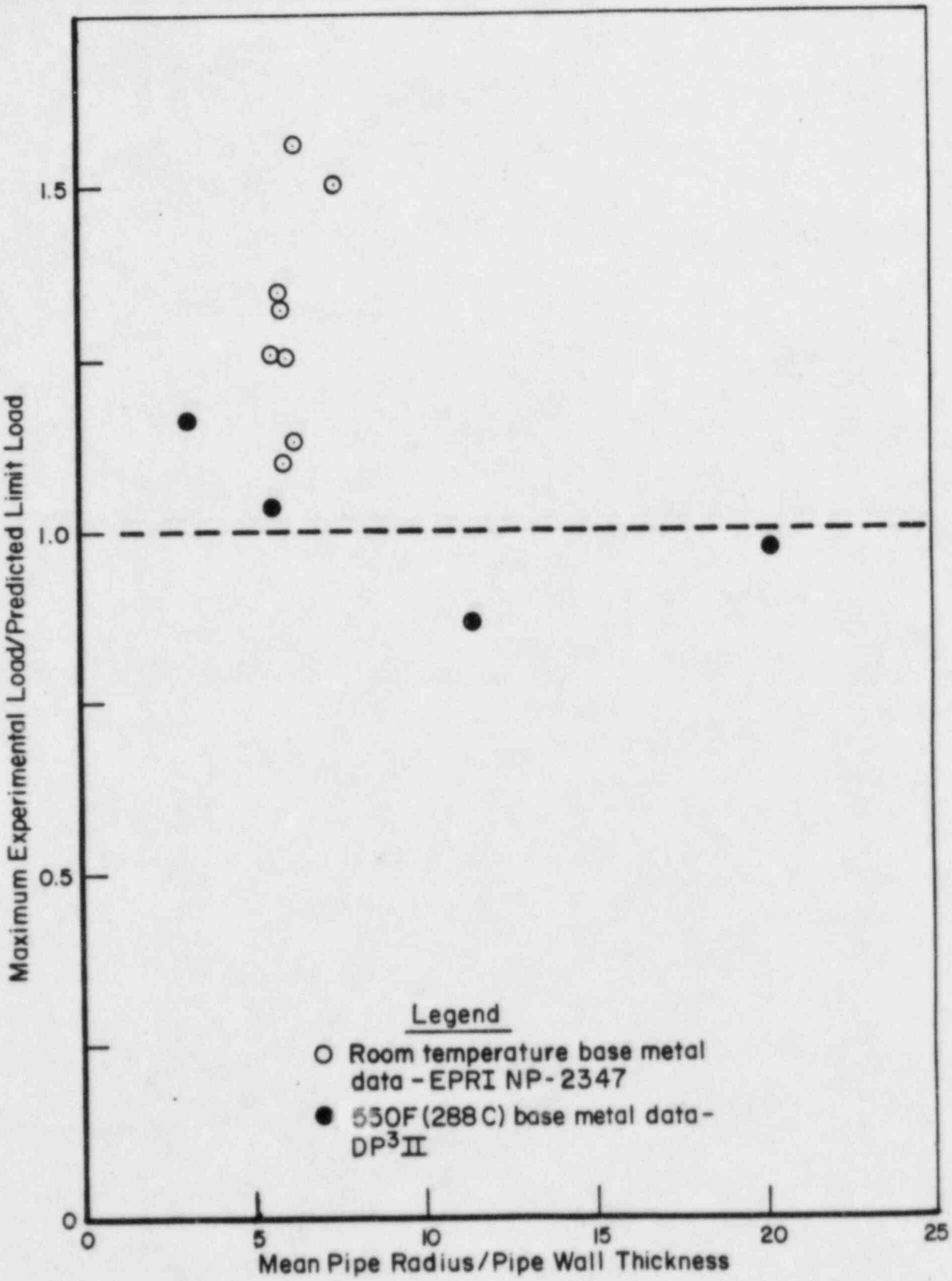


MEASURED MAXIMUM LOAD/PREDICTED MAXIMUM LOAD
1.2
1.0
0.8
0.6
0.4
0.2
STAINLESS STEEL
CARBON STEEL
INCONEL
10
20
30
40
MEAN PIPE DIAMETER (in.)

IWB-3640

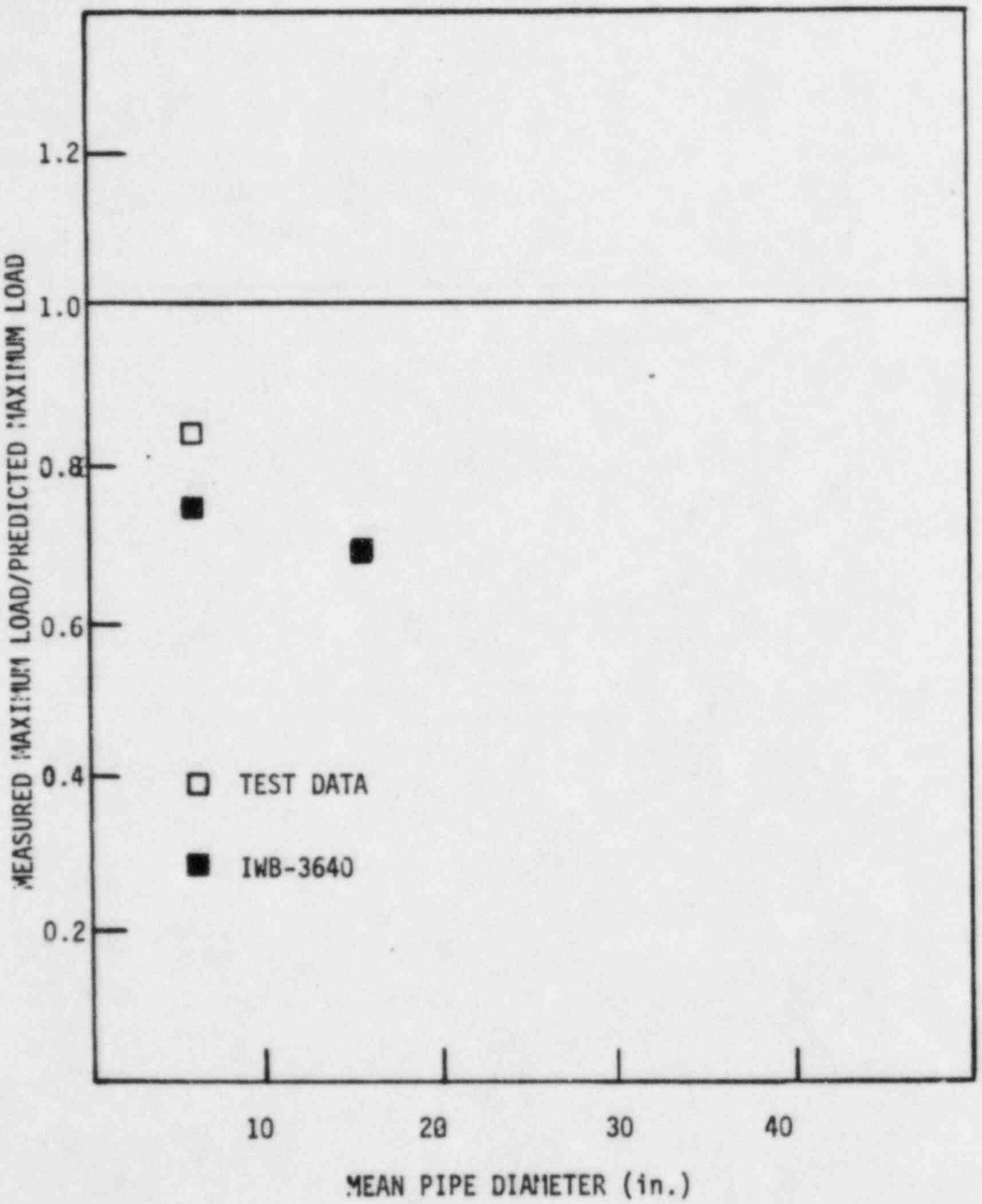
EVALUATION PROCEDURES AND ACCEPTANCE CRITERIA FOR AUSTENITIC PIPING

- METHOD FOR DETERMINING ACCEPTABLE FLAW SIZES
- ASSUMES PLASTIC COLLAPSE OF THE CRACKED CROSS-SECTION
- APPLICABLE TO:
  - AUSTENITIC PIPE $\geq$ NPS 4
  - AUSTENITIC PIPE FITTINGS
  - AUSTENITIC WELD MATERIALS
  - CAST AUSTENITIC MATERIALS ($<$20 FN)
  - SMYS $<$ 45 KSI
  - CODE ACCEPTED MATERIALS


Maximum Experimental Load/Predicted Limit Load
1.5
1.0
0.5
0
0
5
10
15
20
25
Mean Pipe Radius/Pipe Wall Thickness
Legend
Room temperature base metal data - EPRI NP-2347
550F (288 C) base metal data - DP$^3$II

# IWB-3640

- EARLY CONTROVERSY CONCERNING LOW TOUGHNESS WELDS
- TASK GROUP DEVELOPED METHOD TO HANDLE WELDS
  - LOAD MULTIPLIERS INCLUDED FOR FLUX WELDS (SAW & SMAW)
  - NO LOAD MULTIPLIER FOR NON-FLUX WELDS (TIG, ETC.)
- NRC RESEARCH ADDRESSING BOTH FLUX AND NON-FLUX WELDS



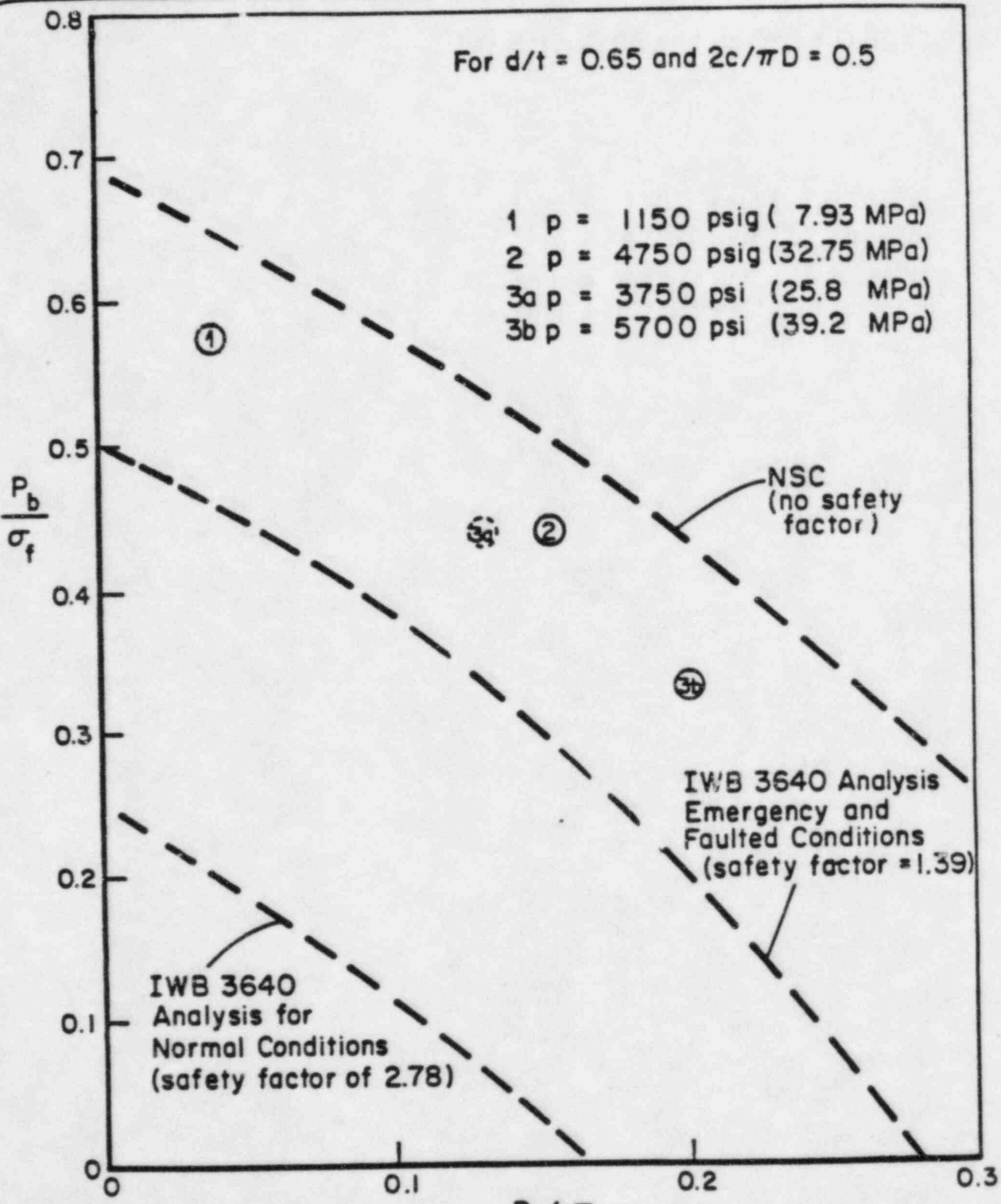
MEASURED MAXIMUM LOAD/PREDICTED MAXIMUM LOAD
1.2
1.0
0.8
0.6
0.4
0.2
TEST DATA
IWB-3640
10
20
30
40
MEAN PIPE DIAMETER (in.)

# IWB-3640

- CODE SECTION USED TO ANALYZE WELD OVERLAY REPAIRS
- WOR MENTIONED BUT NO EXPLICIT RULES ARE GIVEN IN CODE
- NRC RESEARCH HAS EVALUATED TYPICAL WOR
  - IWB-3640 TYPE ANALYSIS

    9% NON-CONSERVATIVE IF FULL WOR THICKNESS USED

    36% CONSERVATIVE IF ONLY PIPE WALL THICKNESS USED


For d/t = 0.65 and 2c/πD = 0.5
1 p = 1150 psig ( 7.93 MPa)
2 p = 4750 psig (32.75 MPa)
3a p = 3750 psi (25.8 MPa)
3b p = 5700 psi (39.2 MPa)
NSC (no safety factor)
IWB 3640 Analysis Emergency and Faulted Conditions (safety factor = 1.39)
IWB 3640 Analysis for Normal Conditions (safety factor of 2.78)
P_b / σ_f
P_m / σ_f
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
1
2
3a
3b

M-6/85-FA-4

## CONTINUING RESEARCH PLAN

- DEGRADED PIPING PROGRAM
  - WILL CONTINUE FOR ANOTHER 1½ YEARS
  - NRC HAS 2 ONE YEAR OPTIONS
  - CONTINUATION WORK
    - o LARGER D AND T
    - o WELDS
    - o MORE MATERIALS
- DTNSRDC
  - CURRENTLY DEFINING NEW PROGRAM
  - WELDS WILL PLAY A KEY ROLE
  - CONSIDERING COOPERATIVE EFFORT WITH USNA ON DYNAMIC LOADING

# INTERNATIONAL PIPING INTEGRITY RESEARCH GROUP
# (IPIRG)

A CONSORTIUM OF FREE-WORLD COUNTRIES FORMED FOR THE PURPOSE OF FUNDING RESEARCH ON THE INTEGRITY OF NUCLEAR PIPING.

# OBJECTIVE

TO DEVELOP, IMPROVE AND VERIFY ENGINEERING METHODS FOR ASSESSING THE INTEGRITY OF NUCLEAR POWER PLANT PIPING CONTAINING DEFECTS.

- SUPPLEMENTS AND STRENGTHENS BASIS FOR CURRENT REGULATORY ACTIONS
- PROVIDES DIRECT INPUT TO LBB TECHNOLOGY AS A REPLACEMENT TO THE DEGB AS A DESIGN BASIS

## LEAK-BEFORE-BREAK

- Piping Research Effort Focuses on LBB
- Research to Date Supports the Regulatory Positions
- Future Research Will Seek to Provide Basis for Selecting Replacement to DEGB