

1 UNITED STATES OF AMERICA  
2 NUCLEAR REGULATORY COMMISSION

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4 ADVISORY COMMITTEE ON REACTOR SAFEGUARDS (ACRS)

5 494TH MEETING

6 + + + + +

7 FRIDAY, JULY 12, 2002

8 + + + + +

9 ROCKVILLE, MARYLAND

10 The Committee met at the Nuclear  
11 Regulatory Commission, Two White Flint North, Room  
12 T2B3, 11545 Rockville Pike, at 8:30 a.m., Dr. George  
13 E. Apostolakis, Chairman, presiding.

14 COMMITTEE MEMBERS PRESENT:

15 GEORGE E. APOSTOLAKIS Chairman

16 MARIO V. BONACA Vice Chairman

17 THOMAS S. KRESS Member-at-Large

18 F. PETER FORD Member

19 GRAHAM M. LEITCH Member

20 DANA A. POWERS Member

21 VICTOR H. RANSOM Member

22 STEPHEN L. ROSEN Member

23 WILLIAM J. SHACK Member

24 JOHN D. SIEBER Member

25 GRAHAM B. WALLIS Member

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# NUCLEAR REGULATORY COMMISSION

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494th Meeting

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TROY

1 ALSO PRESENT:  
2 NILESH CHOKSKI, RES  
3 MARK KIRK, RES  
4 SHAH MALIK, RES  
5 MIKE MAYFIELD, RES  
6 THERESA VALENTINE, NRR  
7 RICHARD BASS, Oak Ridge National Laboratory  
8 TERRY DICKSON, Oak Ridge National Laboratory  
9 CLAUD PUGH, Oak Ridge National Laboratory  
10 PAUL WILLIAMS, Oak Ridge National Laboratory

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P-R-O-C-E-E-D-I-N-G-S

(8:30 a.m.\_

CHAIRMAN APOSTOLAKIS: The meeting will come to order. This is the 494th meeting of the Atomic Reactor Safeguards. During today's meeting, the Committee will consider the following: Application of the Probabilistic Fracture Mechanics Methodologies to Reactor Vessel Integrity Assessment; Proposed ACRS Reports; Future ACRS Activities; Reconciliation of ACRS Comments and Recommendations; Format and Content of the 2003 ACRS Report on the NRC Safety Research Program; and Proposed Papers for the Quadripartite Meeting.

This meeting is being conducted in accordance with the provisions of the Federal Advisory Committee Act. Mr. Sam Duraiswamy is the Designated Federal Official for the initial portion of the meeting.

We have received no written comments or requests for time to make oral statements from members of the public regarding today's session. A transcript of portions of the meeting is being kept and it is requested that the speakers use one of the microphones, identify themselves and speak with sufficient clarity and volume so that they can be

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1 readily heard.

2 As requested by Westinghouse, video  
3 teleconferencing arrangements have been made for  
4 Westinghouse to observe the meeting session of the  
5 application of the probabilistic fracture mechanics  
6 methodologies to reactor vessel integrity assessment.  
7 There is no one from Westinghouse -- oh, there is one.  
8 Okay. I'm sorry.

9 Do any of the Members wish to say  
10 anything?

11 (No response.)

12 Okay, so we can proceed with the  
13 application of probabilistic fracture mechanics and  
14 Dr. Ford will chair this part of the session.

15 MEMBER FORD: Thank you, Mr. Chairman.  
16 Probabilistic fracture mechanics, as you know, is  
17 central to some of the current problems that we are  
18 tackling primarily right now at PTS. Several others  
19 have asked for further information on this and  
20 calibration and validation of the current models and  
21 this is what we're going to hear about. This new  
22 letter is asked for. This is purely informational.

23 Mike, would you like to make a comment?

24 MR. MAYFIELD: Just very briefly. We've  
25 had the opportunity to brief the Committee a number of

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1 times on the higher tier aspects of the PTS  
2 reevaluation and we haven't had your questions and  
3 I've enjoyed interacting with Dr. Powers a number of  
4 times on the robustness of our vessel program and we  
5 appreciate the opportunity to come down and share with  
6 you some of the details and some of the historical  
7 basis for why we're pretty confident in the fracture  
8 calculations.

9 Mark Kirk is going to lead off the  
10 presentation and we'll go from there.

11 MR. KIRK: I'd like to invite my  
12 colleagues, Richard Bass and Claud Pugh and Shah Malik  
13 to come up because by the time I get to the fifth  
14 slide, I'm going to run out of steam. So need their  
15 help up here.

16 Well, Mike has given you the intros, so we  
17 know what we're talking about.

18 MEMBER POWERS: But see, when a vessel  
19 runs out of steam, it depressurizes and becomes safe.  
20 Is that the case here?

21 MR. KIRK: We'll discuss that in  
22 nauseating detail later.

23 (Slide change.)

24 As you know by the groans when you saw my  
25 lovely face up here this morning, we briefed many,

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1 many times over the past several years on  
2 probabilistic fracture mechanics techniques that are  
3 being used to assess the technical basis for updating  
4 the PTS rule.

5 Last time, you all requested that we  
6 provide additional background concerning both the  
7 appropriateness of using LEFM in such assessments and  
8 show you that LEFM is valid and applies to nuclear RPV  
9 assessment, in particular.

10 (Slide change.)

11 MR. KIRK: This just shows you an overall  
12 schematic of the PTS reevaluation process. You've  
13 seen this before. Start off -- oops. Shouldn't touch  
14 the screen. Never touch the screen.

15 We start off in the gray box on the left  
16 of your screen with our initial work. We first go  
17 back and forth between PRA and thermal hydraulics  
18 quite a bit trying to do the binning and see what  
19 sequences are significant. Finally we get -- or after  
20 that initial iteration we get out some transients, so  
21 we then pass on --

22 CHAIRMAN APOSTOLAKIS: We can't see almost  
23 half of the screen. Can you gentlemen move a little  
24 bit to the right and left. You don't have to move  
25 away, just move a little bit. I appreciate that.

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1 Thank you.

2 Thank you very much. I appreciate it.

3 MR. KIRK: All this schematic is  
4 attempting to show is that in the gray box, we do some  
5 initial iterations between PRA, HT and PFM to assess  
6 the combination of sequences and thermal hydraulic  
7 runs that we then take to characterize a particular  
8 plant. Once those are established, we go through a  
9 final run where we again go PRA to TH to PFM and  
10 finally come out with yearly frequency of through wall  
11 cracking.

12 MEMBER KRESS: Mark, do you have a group  
13 of expert panels to develop distributions for the  
14 things in the gray box for the inputs for the code?

15 MR. KIRK: The inputs for these, I mean,  
16 they come from a number of sources. In some cases,  
17 it's expert judgment. In some cases it's data. In  
18 some cases, it's well established models from the  
19 literature. And I think it's fair to say we've got a  
20 bit of both or a bit of all three in all three boxes.

21 (Slide change.)

22 MR. KIRK: Of course, this is just to  
23 orient us in terms of why we're here talking about  
24 PFM. Of course, the focus today is on PFM  
25 specifically and when we look at PFM we previously

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1 talked to you again in a great degree of detail about  
2 the uncertainty framework and now the diagram in the  
3 upper right hand side of the screen breaks out PFM  
4 into some of its component parts which again could be  
5 broken out yet further.

6 (Slide change.)

7 MR. KIRK: We've talked about the  
8 uncertainties in detail before, so I'm not going to go  
9 through that again because the focus of today's  
10 discussion is the deterministic calculations that lie  
11 at the heart of the FAVOR looping structure. I've  
12 shown you here again, a fairly high level schematic of  
13 what's going on in FAVOR. At the outer loop, we  
14 simulate vessels somewhere on the order of tens of  
15 thousands of vessels. Inside that is flaws and  
16 transients and time, the point in showing this being  
17 when you get to the very bottom of these Monte Carlo  
18 loops that in total, help us to simulate all the  
19 uncertainties. Down buried at the bottom there is a  
20 deterministic calculation and what we hope to show you  
21 by the end of the day is that that deterministic  
22 calculation is indeed an appropriate tool to use to  
23 assess RPV failure.

24 So with that --

25 CHAIRMAN APOSTOLAKIS: CPI is what?

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1 MR. KIRK: Conditional Probability of  
2 Initiation and Conditional Probability of Failure.

3 CHAIRMAN APOSTOLAKIS: Conditional  
4 Probability of Initiation, given what?

5 MR. KIRK: Conditioned that the transient  
6 has occurred.

7 CHAIRMAN APOSTOLAKIS: Okay.

8 MR. KIRK: There's yet again, to show it  
9 more generally, I suppose there would be yet again  
10 another outer loop or a post-processing box where what  
11 comes out of the FAVOR code itself are the conditional  
12 probabilities. Those are then combined later with the  
13 initiating event frequencies to get the yearly vessel  
14 failure frequencies.

15 MEMBER KRESS: And the failure frequency  
16 is defined as a through wall crack?

17 MR. KIRK: Right now it's defined as a  
18 through wall crack. That's right. But we calculate,  
19 the point being which gets back to our discussions of  
20 Wednesday, FAVOR calculates both initiation and  
21 failure. So we have the ability, of course, to look  
22 at both. But yes, right now, failure is defined as  
23 complete through wall crack.

24 CHAIRMAN APOSTOLAKIS: What does it mean  
25 is appropriate to predicting RPV failure?

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1 MR. KIRK: It does it right. That  
2 fracture mechanics predicts --

3 CHAIRMAN APOSTOLAKIS: You don't have any  
4 uncertainties there?

5 MR. KIRK: No. That's not to say that  
6 there aren't uncertainties, but within the range of  
7 uncertainties that are characteristic of the material  
8 of the data of however you want to look at it, we can  
9 predict the failure, let's say, of a reactor pressure  
10 vessel with a buried crack, just as well as we can  
11 predict the failure of a much more well-defined  
12 structure like a test specimen in a laboratory.

13 MEMBER POWERS: And because of that  
14 superior capability, we adequately researched the  
15 heavy section steel?

16 MR. KIRK: Wait for the last slide.

17 (Laughter.)

18 So we'll now go on to the presentations  
19 that will be made by our colleagues at Oak Ridge.  
20 Claud Pugh will do the first set of slides and then  
21 Richard Bass will do the second set of slides and then  
22 we'll wrap up. And I'll move out of the way.

23 MR. PUGH: I'm one who likes to stand on  
24 my feet.

25 CHAIRMAN APOSTOLAKIS: Can you please

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1 lower the mike a bit? The other one. Thank you very  
2 much.

3 MEMBER POWERS: Highly sensitive today.

4 CHAIRMAN APOSTOLAKIS: Enjoy this.

5 (Laughter.)

6 MEMBER KRESS: Dr. Pugh, how come you  
7 don't have an accent?

8 MR. PUGH: Well, it's funny, everyone else  
9 does in the room except you and me.

10 (Laughter.)

11 It's good to see you again, Tom.

12 For the record, my name is Claud Pugh. I  
13 recently retired last year from the Oak Ridge National  
14 Laboratory after some 33 plus years there. In my  
15 tenure there, included a number of years where I  
16 served as manager of the Heavy Section Steel  
17 Technology Program which is, of course, the primary  
18 pressure vessel technology program for the NRC and for  
19 the AEC prior to the NRC's creation and then in the  
20 last dozen years or so I served in a larger management  
21 capacity for NRC programs at Oak Ridge. So that's by  
22 way of kind of giving you an introduction of who I am  
23 and where I'm coming from.

24 I'd like to first made an observation that  
25 I think is very obvious and clear to all of us, that

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1 as we look at any technology, but in particular, today  
2 at the deterministic fracture mechanics technology  
3 applicable to the pressurized thermal shock issue,  
4 this is not a circumstance where the technology has  
5 been looked at in isolation, in particular, and only  
6 in particular to the PTS circumstances, but rather, it  
7 is a technology that is built upon all that has gone  
8 before it and then looked at in terms of either  
9 adapting, confirming or adding to as appropriate to  
10 the PTS scenario.

11 So what Richard Bass and I want to do in  
12 the forthcoming slides is to talk you through the big  
13 picture of what has gone before and what is today in  
14 terms of the deterministic aspect of the fracture  
15 mechanics technology that is applicable RPBs under PTS  
16 divisions.

17 MEMBER WALLIS: In this context, is this  
18 a standard technology that's throughout all  
19 industries, or did you have to develop special things  
20 for this purpose?

21 MR. PUGH: Basically, the answer is the  
22 latter. There are very definitely specific aspects  
23 that are peculiar and specific to reactor pressure  
24 vessels. In fact, about four comments from now you'll  
25 see one of those come forward.

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1 CHAIRMAN APOSTOLAKIS: But probabilistic  
2 fracture mechanics is used widely, isn't it?

3 MR. PUGH: As Mark said earlier,  
4 probabilistic fracture mechanics entails the  
5 performance of a multitude, a large multitude of  
6 deterministic fracture mechanics analyses. So what  
7 we're focusing on this morning, as I understand it, is  
8 the question of the applicability and the validation  
9 of the applicability of linear elastic fracture  
10 mechanics to the deterministic aspect of the PFM  
11 analyses for PTS conditions.

12 MR. KIRK: Let me jump in.

13 MR. PUGH: Yes.

14 MR. KIRK: The probabilistic fracture  
15 mechanics is widely used in a number of industries and  
16 the underlying linear elastic fracture mechanics was  
17 not developed specifically for nuclear applications.  
18 But there are unique aspects for nuclear pressure  
19 vessels, that over time we've had to address. But the  
20 root technology is not unique to this application and  
21 the probabilistic techniques are widely used in a  
22 number of industries.

23 (Slide change.)

24 MR. PUGH: Yes. Well put. So this is  
25 just saying that we're going to look at -- trying to

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1 give you a picture of the systematic and evolutionary  
2 nature of the development over the last two plus  
3 decades or three decades, really.

4 As the nuclear power enterprise developed  
5 in the 1960s, it was widely recognized by a lot of  
6 people that indeed the circumstances -- well, first of  
7 all, that the fracture mechanics technology was rather  
8 young in itself and most of the work in developing it  
9 and validating it were for situations such as  
10 aerospace applications and particularly like rocket  
11 motor casings which were high strength steel with low  
12 ductility and very thin sections. Here, we had a  
13 circumstance developing of very thick sections of  
14 relatively low strength in terms of yield strength  
15 material, but very ductile materials. So the  
16 questions were how applicability is that fracture  
17 mechanics technology that was already being developed  
18 to the circumstances that had not yet been validated  
19 as to being applicable --

20 MEMBER WALLIS: When you said linear  
21 elastic, aren't you beyond this linear elastic range?  
22 You have to show you're not or something.

23 MR. PUGH: Kind of hold the thought as we  
24 work through some of this and hopefully the picture  
25 will come as to the interface and the transition

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1 between regions.

2 MEMBER WALLIS: Okay, thank you.

3 MR. PUGH: So let's say this was widely  
4 recognized, but perhaps to give the motivation and  
5 impetus to actually creating a program to investigate  
6 it, there was a certain body called the ACRS which you  
7 may be familiar with, wrote a letter on November 25,  
8 1965 to the then AEC and they cast the question more  
9 or less in this sense sort of the suggestion, the  
10 recommendation saying industry in the U.S. AEC should  
11 give detailed attention to RPV integrity assessment  
12 methods to support the then existing position that RPV  
13 failure is incredible.

14 MEMBER KRESS: Was that letter signed by  
15 Bill Manley?

16 MR. PUGH: I don't think, so Tom.  
17 Actually, I was thinking last night who did sign it  
18 and -- no, this is pre-Tom. 1965. Whoever was the  
19 Chairman then. I don't think it was Bill Manley.

20 MEMBER KRESS: He was Chairman in the  
21 1980s.

22 MR. PUGH: This was in 1965 during the AEC  
23 time. And they suggested including assessment of  
24 stress analysis, development of inspection methods,  
25 improving means for evaluating factors that could

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1 affect propagating flaws during the RPV service life.

2 So this gave the AEC then the basis for  
3 rallying all stakeholders, all interests together to  
4 the table to develop a plan where the AEC being the  
5 entity that had the funding to underwrite a plan once  
6 it was agreed upon and deemed a viable plan.

7 So indeed, they sent forward with  
8 stakeholders, from vendors, from universities, from  
9 just essentially every person involved, every entity  
10 involved, ASME and tremendous voluntary efforts came  
11 to the table under the auspices of the Pressure Vessel  
12 Research Committee. From this came, after a long  
13 intense year of planning, a detailed plan,  
14 multi-year plan for pursuing the fundamental  
15 questions of the applicability of fracture mechanic to  
16 thick wall reactor pressure vessels.

17 And the AEC then looked to Oak Ridge to do  
18 the centralized management of this effort. I say it  
19 that way because Oak Ridge certainly played an  
20 important technical role, but also there was a lot of  
21 subcontract participants, Battelle, BMW, Westinghouse  
22 and in those was a very strong participant and  
23 contributor.

24 But the very first step in executing the  
25 plan was the development of a state-of-the-art

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1 technology report and the report is cited here,  
2 NSIC-21, technologies for steel pressure vessels in  
3 water cooled nuclear reactors and you see it was quite  
4 a tome and truly it was a state-of-the-art document  
5 that served a good purpose for many years going  
6 forward. That plan included looking at the  
7 fundamental fracture properties of reactor pressure  
8 vessel steels. It looked at an incremental step-wise  
9 fashion of once that you something about the  
10 characteristics of the fracture, what are the models,  
11 what are the properties to gain to quantify the  
12 models, what are the analysis methods to use, how do  
13 you validate them and they had three stages of  
14 structural or pressure vessel experiments, basically,  
15 laboratory science, intermediate vessels and full  
16 scale. That was the plan.

17 First priority, I said, was establishing  
18 basic fracture techniques. Large scale testing was  
19 testing to it. And the models and properties were  
20 integral to the overall plan.

21 MEMBER KRESS: Are you going to explain  
22 what the thing is in the picture?

23 MR. PUGH: That is a pressure vessel from  
24 a 1100 megawatt plant, 1100 megawatt unit built at  
25 Combustion Engineering. We bought and shipped this to

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1 Oak Ridge as part of the work that we did there and  
2 one of the conditions on buying it, actually DOE  
3 bought it. One of the conditions of buying it, we  
4 were not supposed to be given the identity to it. but  
5 when you look at the outlet nozzles and having flats  
6 for supports you have a pretty strong indication of  
7 who may have made it.

8 MEMBER KRESS: That's the vessel used by  
9 PNL to determine the flaw size and distribution?

10 MR. PUGH: PNL did a detailed mapping of  
11 the flaw distribution inside this vessel.

12 MEMBER KRESS: One of our questions is if  
13 you've got one vessel and you look at the flaw size  
14 and distribution, how representative is that of the  
15 fleet of vessels that are out there?

16 MR. PUGH: There have been inspections of  
17 segments of other vessels. Of course, I'm sure as you  
18 know, Salem vessel being one, all of which creates a  
19 database. There is non-nuclear vessel data. All  
20 nuclear vessels were inspected prior to going into  
21 service, so there is some data from pre-service  
22 inspections, all of which gives a database which we,  
23 I'm sure, would always like to think we'd like to have  
24 a larger one. But it's the best it's ever been.

25 MEMBER RANSOM: How small is the

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1 probability of failure to be accepted as incredible?

2 (Laughter.)

3 MR. PUGH: Ah. May I pass on that  
4 question?

5 Quantitatively? Of course,  $10^{-6}$  has been  
6 used in recent studies, so I guess if I were to give  
7 an answer I would relate it to that.

8 MEMBER RANSOM: Less than  $10^{-6}$  --

9 MR. PUGH: Would be considered in the  
10 range of incredible, yes. You remember, I'm speaking  
11 here historically, in the context of 1960s when PRA  
12 and dose type analyses were not quantitatively being  
13 looked at. It was more qualitative.

14 Could you demonstrate a degree of  
15 difference between the actual circumstance and failure  
16 of the operation and failure that would give you a  
17 feeling that the margin is well sufficient as to not  
18 to lead to failure?

19 By the way, Tom, that picture was on there  
20 just for --

21 MEMBER KRESS: Just to make it look good.

22 MR. PUGH: Just to dress it up a bit.  
23 That's what a real vessel looks like and that's a  
24 fellow we work with.

25 In the beginning, then executing the plan,

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1 emphasis was placed on understanding the fracture  
2 characteristics of the material and properties that  
3 went with that. The AEC, ORNL procured over 500,000  
4 tons of reference test material, typically 12-inch  
5 thick plates of A508 and A533 steel primarily.

6 A large number of exploratory and property  
7 experiments were done in those early days to (a) to  
8 start out with the question does this kind of material  
9 like the high strength, low ductility material show a  
10 transition from brittle to the transition to the  
11 ductile regime.

12 Those are some of the first experiments  
13 done, not just on small laboratory specimens, but on  
14 tensile specimens up to 12 inches thick being  
15 prototypical of pressure vessels. And so that  
16 question turned out to be yes. They went forward,  
17 deciding well, what kind of specimen do you measure  
18 properties with? A whole host of specimens were  
19 looked at and in the end it was settled on the compact  
20 tension specimen which then led to the acceptance of  
21 the trial ASTM standard E-399 for fracture testing, so  
22 this program and its exploratory work and its round  
23 robin led to that being settled upon as the fracture  
24 mechanic specimen of use.

25 (Slide change.)

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1 MR. PUGH: Looking at the properties,  
2 there were a number of variables though that could  
3 influence them, in particular, of course, we all know  
4 temperature, the toughness versus temperature are kind  
5 of dependent. But also rate has a very pronounced  
6 influence. After a lot of studies and dynamic  
7 effects, it was concluded that the crack arrest  
8 toughness represented a very reasonable lower bound to  
9 the dynamic fracture toughness data.

10 MEMBER WALLIS: You said load rate had a  
11 big influence?

12 MR. PUGH: Yes. The higher the rate, the  
13 lower the --

14 MEMBER WALLIS: Within what sort of range  
15 of speeds, which what sort of time frame are you  
16 talking about for an influence?

17 MR. PUGH: As I just said, kind of the  
18 limiting case that was considered to be the arrest  
19 toughness.

20 MEMBER WALLIS: But you're talking about  
21 fractions of a second, presumably. You're not talking  
22 about long periods -- you're talking about short  
23 blows?

24 MR. PUGH: Something like split Hopkins  
25 bar has been used, for example, giving strain rates of

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1 10<sup>-5</sup>. I mean 10<sup>5</sup> per second. Very fast rates.

2 MEMBER WALLIS: Very fast rates.

3 MR. PUGH: Yes. But what one looks for is  
4 asymptotic behavior of the rate dependence which seems  
5 to be there approaching that of the crack arrest  
6 values.

7 So tremendous progress was made during  
8 those years in generating data. Westinghouse played  
9 a very important role in that testing specimens up to  
10 12 T. I should have emphasized that within this, it  
11 was adopted that plain strained fracture mechanics was  
12 to be the reference as in the vessels, if you had a  
13 flaw, it was going to have a lot of constraint. So  
14 they looked for a specimen that would exhibit plain  
15 strained conditions on the crack front.

16 As temperature goes up to maintain the  
17 plain strained conditions, you have to have larger and  
18 larger specimens, so many of these data, many are  
19 called out here but to get up into this region here of  
20 like 200 MP<sub>A</sub> meters toughness required 12 inch thick,  
21 that meant like 24 inch square specimen. Huge  
22 specimens. And Westinghouse, for example, tested a  
23 lot of those for us.

24 All that data was -- is the basis for the  
25 K<sub>IR</sub> curve that is still in the ASME code today.

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1 You'll find those data reported in Welling Research  
2 Council Bulletin 175. You may have heard the  
3 terminology, \$1 million curve? Now a \$1 million curve  
4 today may not be that much, but in 1965 that was a big  
5 effort.

6 MEMBER KRESS: Is that the curve that you  
7 have on the thing or did it go through the mean?

8 MR. PUGH: This was intended to be a lower  
9 bound.

10 MEMBER KRESS: It was a lower bound.

11 MR. PUGH: Yes.

12 MEMBER KRESS: Okay.

13 MR. PUGH: The ASME curve, it is lower  
14 bound, not only of the fracture toughness, but of the  
15 arrest toughness, initiation and arrest toughness.

16 MEMBER FORD: Claud, you mentioned earlier  
17 on this condition of probability for crack initiation  
18 as being one criterion. Surely, the K value for crack  
19 initiation from a pre-existing flaw will be plain  
20 stressed conditions or could be. Therefore, your  
21 methodology would be very conservative? Is my  
22 rationale right?

23 MR. PUGH: It's an excellent question and  
24 I'm about two slides hence. I'm going to show you an  
25 example of the answer to that.

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1           Your conclusion is correct, generally, but  
2           on that one variable, namely the constraint variable,  
3           but I'm going to have a very good example popping up  
4           here in about two slides that will show that.

5           MEMBER KRESS: This may be a question to  
6           Mark, but you're no longer using this lower bound?  
7           You've actually gone to the best estimate?

8           MR. KIRK: MR. KIRK: That's correct. I  
9           mean the data, well, the curve that's shown here is  
10          the lower bound  $K_{LR}$  curve. There's also a lower bound  
11          initiation curve. Those are the ASME design curves  
12          that are used. They're still used by the NRC and the  
13          nuclear licensees in calculating heat up and cool down  
14          limits. And in fact, those lower bound curves are the  
15          curves that were used in the early 1980s to establish  
16          a current PTS rule. That was a long background. The  
17          answer to your question is yes. Now we take that  
18          whole distribution of data and use it.

19          MEMBER KRESS: Yes, you get a substantial  
20          distribution.

21          MR. KIRK: So we use it -- what we do is  
22          we sample from that distribution and we draw values  
23          out so we capture the uncertainty that you see  
24          depicted on that plot, yeah.

25          MR. PUGH: Thank you for asking that

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1 question, Tom, because I am commingling the evolution  
2 of the total technology on fracture prevention with  
3 what we know about fracture mechanics, so we do try to  
4 make the distinction as we go along with the two.

5 MEMBER WALLIS: These variations are  
6 because the steels are different or because the flaws  
7 are different?

8 MR. KIRK: The variations are just simply  
9 inherent to the material. I could show you what on  
10 the previous slide that's the result of about 12  
11 different materials that makes the plates in welds and  
12 forgings. I could take one material and if you'll  
13 forgive the phrase, test the hell out of it, and I see  
14 exactly the same variation.

15 MEMBER WALLIS: This is because the --

16 MR. KIRK: Because the material is  
17 inhomogeneous at a micro scale.

18 MEMBER WALLIS: It had a different history  
19 or had --

20 MR. KIRK: No, no, no. It's just the  
21 local inhomogeneity of the material along the crack  
22 front. You could test -- if I took a plate of  
23 material the size of this conference table and cut it  
24 up into big, small specimens, you pick --

25 MEMBER WALLIS: You'd get different

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1 answers for these specimens?

2 MR. KIRK: Tested all under precisely  
3 controlled conditions and you would see that  
4 variability. And so that's -- that's a classic  
5 aleatory variability and we capture that appropriately  
6 in FAVOR.

7 MEMBER POWERS: Mark, if I doubled the  
8 number of tests on a single material or multiple  
9 materials, either way, would I see large numbers of  
10 points below the solid curve that you've drawn in  
11 there?

12 MR. KIRK: No.

13 MEMBER POWERS: Why can you say that so  
14 confidently?

15 MR. KIRK: Because since that curve has  
16 about 175 points --

17 MEMBER POWERS: About 350.

18 MR. KIRK: And the years since, I go up to  
19 my desk, since I'm a data geek, I collect these  
20 things. We have a database now well in excess of  
21 4,000 points and no point has ever -- except on the  
22 lower shelf where it wasn't ever meant to be a bound,  
23 but in the transition region, I'm sorry, I'm pointing  
24 at the screen again. In the transition region, where  
25 Claud is pointing, which is where the action is for

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1 RPV failure, no curve has ever transgressed the line  
2 and that's --

3 MEMBER POWERS: I see a point that  
4 transgresses the line right there.

5 MR. KIRK: No. Go up a ways. There you  
6 go. As we discussed on -- as Mike discussed on  
7 Wednesday, when we were talking about the risk goal,  
8 one of the  
9 -- if we had a completely risk-based rule, you might  
10 be able to reach the conclusion that you could operate  
11 the reactor vessel safely on the lower shelf.

12 MEMBER WALLIS: What's the lower shelf  
13 mean?

14 MR. KIRK: That's the lowest fracture  
15 toughness you can get.

16 MEMBER WALLIS: That's what you mean by  
17 lower shelf?

18 MR. KIRK: That's what I mean by lower  
19 shelf, yes.

20 MR. MAYFIELD: This is Mike Mayfield.  
21 When you plot Charpy energy versus temperature, there  
22 is a transition from a lower plateau region to an  
23 upper plateau region in energy and that lower region  
24 is typically characterized as the lower shelf. It  
25 comes below the nil ductility transition temperature

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1 for the material. So when we talk about lower shelf,  
2 upper shelf and transition, we typically are referring  
3 to regions on the Charpy energy versus temperature  
4 curve.

5 MR. KIRK: In any event, there are other -  
6 - the point I was trying to get to is there are  
7 certainly good engineering reasons why even if your  
8 risk numbers told you you could, you wouldn't allow a  
9 structure with as high a failure consequence as our  
10 nuclear RPV to operate down in this region.

11 But in answer to Dr. Powers' question, the  
12 substantial testing that's occurred in the ensuing  
13 years has generated a database well in excess of, I  
14 think, 4,000 to 5,000 data points. None of them has  
15 ever crossed an  $RT_{NDT}$  indexed  $K_{1C}$  or  $K_{1R}$  curve which is  
16 simply a testament to the conservatism that is built  
17 in to the current ASME rules.

18 MEMBER POWERS: Well, the one point that  
19 does should be banned and burned and otherwise  
20 castigated.

21 MR. KIRK: When I say none has ever  
22 crossed, remember I put the caveat on in the  
23 transition region.

24 MEMBER POWERS: Well, it looks like it's  
25 pretty close to the transition region.

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1 MEMBER SHACK: He's up there with a  
2 triangle rippling data.

3 MR. KIRK: That's on the curve. That sets  
4 the curve.

5 MR. PUGH: And recall, this is the \$1  
6 million curve which is not necessarily the  $K_{1R}$  curve,  
7 that is in the code.

8 MEMBER POWERS: You tell me that there is  
9 a point that is exactly on the curve, that's what's  
10 said and I will never ever, no matter what I do find  
11 a point that falls below that curve. You are a man of  
12 faith.

13 (Laughter.)

14 CHAIRMAN APOSTOLAKIS: He said he hasn't  
15 seen -- right, Mark?

16 MR. KIRK: Yes.

17 CHAIRMAN APOSTOLAKIS: Are you also saying  
18 you will never see it?

19 MR. KIRK: I would not expect to see it.

20 MEMBER WALLIS: It would be incredible.

21 MR. KIRK: It would be incredible -- okay,  
22 the --

23 CHAIRMAN APOSTOLAKIS: It's really, really  
24 unlikely.

25 MR. KIRK: It's really, really unlikely.

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1 I mean nonparametrically if you've got a database of  
2 5,000 database, no, what are the odds? But equally,  
3 we understand making strictly a data argument because  
4 it was a database question, but we understand why the  
5 curve is there. We understand why we can collapse  
6 multiple curves together, using an indexed temperature  
7 approach and we also understand the conservatism  
8 that's inherent to the  $RT_{NDT}$  index temperature which is  
9 if you go to establish  $RT_{NDT}$  based on nil ductility  
10 temperature tests and Charpy tests, the only way you  
11 can run the procedure forces you to overestimate the  
12 parameter. And that was done intentionally in the  
13 early days to make sure we were working with a  
14 bounding curve.

15 MEMBER WALLIS: What does NDT mean?

16 MR. KIRK: The nil ductility transition is  
17 defined in ASTM E 208 as the temperature in which you  
18 go from a break to a no break condition in a nil  
19 ductility test which is a 5/8ths thick by about 6  
20 inches long, 2 inches wide specimen with a brittle  
21 weld bead put on top.

22 MEMBER WALLIS: Well, of course, that's a  
23 fairly complicated thing.

24 MR. KIRK: Oh yes, it is. But it's an  
25 order of merit --

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1 MEMBER WALLIS: I thought it meant normal  
2 daytime temperature or something like that.

3 MR. KIRK: No.

4 MEMBER ROSEN: You see, the logical  
5 inconsistency with your remarks in response to Dr.  
6 Powers is that the day before you had that test which  
7 gave you that point right on the line, you would have  
8 said that there's no chance of having any test like  
9 the one you were about to get the next day.

10 CHAIRMAN APOSTOLAKIS: He said that point  
11 defined the curve, that's different.

12 MEMBER ROSEN: He's also said that nothing  
13 can be to the right of that. And I'm just pointing  
14 out, that's what you would have said on the day before  
15 --

16 MR. KIRK: That's true. So perhaps I'll  
17 revise my comments for the record that subsequent  
18 testing of thousands and thousands of specimens has  
19 revealed nothing below that curve.

20 MEMBER KRESS: And if it did, why would  
21 you care?

22 CHAIRMAN APOSTOLAKIS: And frankly, I've  
23 heard enough about this curve.

24 (Laughter.)

25 MEMBER POWERS: Well, George, I'm sorry,

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1 I just have to know.

2 CHAIRMAN APOSTOLAKIS: You want more?

3 MEMBER POWERS: When I didn't have that  
4 point I would have used the little black square to fix  
5 the curve.

6 MR. MAYFIELD: Mark, let me. There's a  
7 bit of perspective to not lose here. The curve and  
8 the  $K_{1R}$  curve that's discussed in the fourth bullet on  
9 that slide is the lower bound -- was intended to be  
10 the lower bound curve to crack initiation, dynamic  
11 crack initiation and crack arrest toughness. It was  
12 intended as the lower bound to all of those  
13 conditions.

14 The data that we are using comes, in the  
15 analysis, comes from two aspects. One is essentially  
16 static -- it's very slow loading, crack initiation.  
17 That's the  $K_{1C}$  curve that Mark has talked about before  
18 and those data, because these materials are loading  
19 rate sensitive, those data tend to be well above that  
20 curve.

21 The lower data points that you're seeing,  
22 tend to come from either dynamic initiation or crack  
23 arrest tests which -- that's a very rapidly moving  
24 crack. Those tend to be the lower -- tend to be the  
25 lowest of the data. So there's a mixture of data that

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1 went into defining the  $K_{1R}$  curve.

2 When you go back and segregate the data  
3 between the two types you're really interested in,  
4 initiation and arrest, there are separate curves for  
5 those data types and the uncertainty associated with  
6 those gets rolled in. I think we need to be a little  
7 careful in drawing too many conclusions about whether  
8 the curve does or doesn't bound all the data because  
9 we're really interested in the application in  
10 segregating the data.

11 MR. KIRK: One perhaps final point is I  
12 think it's good to get back to Dr. Kress' comment  
13 earlier that now we're using a probability  
14 distribution through all this data which gets us away  
15 from, as is obvious here, the very difficult question  
16 of establishing an absolute lower bound. We take into  
17 account the inherent variability that's there and  
18 that's included in the calculation.

19 MEMBER KRESS: I think Dana's question  
20 bears on that because you have to set a distribution  
21 to sample from and how you set that distribution  
22 depends on what form you assume it takes. Do you  
23 sample vertically? Do you fix the temperature and  
24 sample vertically?

25 MR. KIRK: Yes, we do and the form that

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1 the distribution takes can be established by data. It  
2 can also be established by physics and it's indeed a  
3 happy circumstance that the physical expectation, the  
4 distributional form that you expect physically is well  
5 substantiated by the data.

6 MEMBER KRESS: Is it log normal?

7 MR. KIRK: It's Weibull.

8 MEMBER KRESS: Weibull.

9 MR. KIRK: Yes.

10 MEMBER POWERS: So that's why we can't  
11 have points below the curve.

12 MR. KIRK: That's right.

13 MEMBER POWERS: I took from Mike's comment  
14 that the way to get points below the curve was to  
15 increase the rate of loading.

16 MR. MAYFIELD: Dana, this curve was drawn  
17 by a guy with a French curve and he didn't know how to  
18 use it. This is not a statistical figure. Okay? And  
19 he tried to pin his curve to the lowest data point he  
20 had at that point.

21 When you look at the curve that's in the  
22 ASME code, this  $K_{1R}$  curve, you'll actually find a cusp  
23 in it and so that the gentleman that didn't know how  
24 to use this French curve to create a smooth curve,  
25 that has propagated its way up until the last four or

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1 five years when the ASME finally made a change. So I  
2 don't want you to leave this discussion with the  
3 impression that there's great high science or  
4 mathematics behind that particular representation.  
5 The work that Mark and company have done subsequently,  
6 to move away from this sort of historic plot is, in  
7 fact, much better science and I think we're drawing  
8 far too much significance to this particular plot.

9 CHAIRMAN APOSTOLAKIS: So it's Weibull  
10 vertically?

11 MR. KIRK: Yes, that's correct.

12 CHAIRMAN APOSTOLAKIS: And what is the  
13 probability? Do you remember roughly of the point  
14 falling below the curve?

15 MR. KIRK: I'm sorry, I don't understand.  
16 I know this sounds stupid, but I don't understand the  
17 question.

18 CHAIRMAN APOSTOLAKIS: Isn't there a  
19 probability that if I pick a temperature, there will  
20 be a point below the curve now, as soon as you have a  
21 distribution?

22 MR. KIRK: Yes, but the Weibull, it's a  
23 three parameter Weibull. It has an absolute cutoff,  
24 yes.

25 CHAIRMAN APOSTOLAKIS: And the absolute

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1 cutoff coincides with this curve?

2 MR. KIRK: No. As Mike said, we have a  
3 Weibull distribution that's been statistically fit to  
4 not only these data, but also the data that have been  
5 developed since then. That curve has an absolute  
6 lower bound since it's a three parameter Weibull.  
7 It's agreement or disagreement with this particular  
8 curve, which as Mike said was hand-drawn, would be a  
9 complete circumstance.

10 This is a historical design curve.

11 MEMBER FORD: If I could suggest that  
12 we've used up half our time.

13 CHAIRMAN APOSTOLAKIS: That's what I  
14 think.

15 MEMBER WALLIS: But still, this NDT, is it  
16 ductile to the right or the left of this point, zero  
17 point? There's a nil ductility transition?

18 MR. KIRK: It's more ductile to the right.

19 MEMBER WALLIS: I would expect it to be  
20 more ductile to the -- the region of interest, there  
21 is ductility.

22 MR. KIRK: Yes.

23 MR. PUGH: Perhaps I can shed some  
24 additional light on that type of question as we look  
25 at the next two or three slides.

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1           Remembering the earlier technology was  
2 directed at fracture prevention, not fracture  
3 prediction in the applied sense of the ASME code, so  
4 that's one of the reasons of this type approach to it  
5 earlier.

6           We are going to look at real quickly,  
7 hopefully three, large scale sets of experiments for  
8 purposes of validating the applicability of the  
9 fracture mechanics technology which is based on  
10 uniaxial specimens. So obviously, the application is  
11 multiaxial conditions of pressure loading being  
12 multiaxial at the very outset, plus any other factors  
13 that come to bear.

14           MEMBER WALLIS: This is nonirradiated  
15 steel?

16           MR. PUGH: All of these experiments run --  
17 RPB steel, but nonirradiated, yes sir. Very typical  
18 of steel though.

19           I'll speak very briefly about intermediate  
20 vessel tests. If you would, Mark, please?

21           These were experiments conducted on one  
22 meter diameter by 6-inch thick walled specimens with  
23 axial flaws, the very deep ITB7. One happened to be  
24 portrayed here in this schematic. Most of them had  
25 like a quarter to a half thickness in the flaw. Ten

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1 such vessels were procured. Like I say, they're 8508  
2 Class 2 steel, RPB steel. You recall I said that  
3 early plan included a full scale testing phase. It  
4 was concluded in the early to mid-1970s. That was  
5 just too cost prohibitive to pursue, so the added  
6 importance was taken on by this set of ITB experiments  
7 to demonstrate the transferability of the fracture  
8 mechanics developed in the laboratory and even in  
9 these large plain strain fracture uniaxial specimens  
10 would transfer to a constraint situation prototypical  
11 of the vessel.

12 MEMBER KRESS: This flaw you show on here  
13 is on the outside of the vessel.

14 MR. PUGH: That is correct.

15 MEMBER KRESS: Can you explain the  
16 rationale behind that?

17 MR. PUGH: The constraint and loading  
18 conditions are essentially the same as if it were on  
19 the inside. You have the pressure loading, which is  
20 still the 2 to 1 pressure loading. You have in the  
21 case later, we'll look at it, thermal stresses, the  
22 case of the crack front is loaded in the same way as  
23 if it were internal and it was much easier to work, of  
24 course, experimentally with the external flaw.

25 MR. BASS: This is Richard Bass from Oak

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1 Ridge National Laboratory. I just want to reiterate  
2 a great deal of analytical effort went into evaluating  
3 these vessels with the flaws on the exterior surface,  
4 via-a-vis the IPV laws on the intersurface to assure  
5 that we had stress fields, fracture toughness fields  
6 and gradients in these vessels that were also  
7 correspondent to RPVs.

8 MEMBER KRESS: This didn't have to be a  
9 cylinder, did it?

10 MR. BASS: Pardon me?

11 MEMBER KRESS: The only reason you made it  
12 a real cylinder is so you could pressurize the inside  
13 of it?

14 MR. BASS: Yes.

15 MEMBER KRESS: It could have been a flat  
16 plate for all you cared, if you could provide the  
17 loading.

18 MR. BASS: I don't know that we would have  
19 wanted to use a flat plate in this case.

20 MR. PUGH: Certainly in subsequent  
21 experiments where we looked at thermal shock,  
22 definitely would not have wanted a flat plate because  
23 of certain inertia and bending effects that develop in  
24 the arc of the cylinder.

25 MEMBER SHACK: It probably would be hard

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1 to stress state the flat plate too.

2 MR. PUGH: You're probably thinking about  
3 a set of experiments that was done in Japan once upon  
4 a time, thermal shock.

5 MEMBER SHACK: You did do some sort of  
6 trick with the heat treatment to embrittle this  
7 material.

8 MR. PUGH: Not on these. These are  
9 prototypical. This is a detail. There are two sets.  
10 One of them was normalizing temper and the other was  
11 tempered to impact the fracture properties slightly.

12 MEMBER SHACK: This is a relatively  
13 bicuspus material. This is like the --

14 MR. PUGH: Yes, this is like the real  
15 stuff.

16 MEMBER SHACK: The real stuff.

17 MR. PUGH: Absolutely. Now there was one  
18 experiment run on a lower per shelf weld that was  
19 absolutely tailored to study the fracture properties  
20 of the lower shelf weld in one of these vessels. That  
21 was ITV-8(a), but no, the basic principle was to use  
22 the real pressure vessel conditions to validate the  
23 fracture behavior and the ability to predict that  
24 fracture behavior.

25 (Slide change.)

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1 MR. PUGH: So if we look at the next  
2 slide, we'll see that here is a schematic of this  
3 Charpy curve, Dr. Wallis, that Mike was describing  
4 earlier, the lower shelf, transition region, upper  
5 shelf.

6 Operating conditions of reactor pressure  
7 vessel is up here on the upper shelf. Should you have  
8 the thermal shock circumstance, you have the injection  
9 of the coolant, then you're progressing back down in  
10 this region. So this is the region of real interest  
11 to the fracture behavior to the PTS issue is in the  
12 lower to mid transition range. So we're going to  
13 focus right here on this slide on these, what looks to  
14 be three experiments, I mean four experiments.  
15 Actually, this 8(a) had two initiation and arrests, so  
16 there will be five points plotted over here of failure  
17 pressure versus predicted failure pressure. Here's  
18 the one-one line. You see these four line up very  
19 nicely.

20 Peter, I don't remember if it was you a  
21 while ago or Dr. Rosen, asked the question about what  
22 if you did not have this constraint to yield the plain  
23 strained conditions. This test here is ITV-9. This  
24 is a nozzle experiment. There was a flaw in the inner  
25 corner of the nozzle and this -- I don't know if you

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1 can see it or not, but this is what a vessel with a  
2 nozzle looked like.

3 With a flaw in that inner corner of the  
4 nozzle, you absolutely do not have the constraint  
5 conditions. You lose much or most of your constraint,  
6 so in answer to the question do you elevate or  
7 decrease the fracture, apparent fracture toughness in  
8 that circumstance? You increase it. This is why this  
9 point is well above here in terms of the actual  
10 failure pressure, well above what LEFM would have  
11 predicted.

12 MEMBER POWERS: Let me ask a question.

13 MR. PUGH: Yes sir.

14 MEMBER POWERS: Converting of units, I'm  
15 never very confident about these things with pressure,  
16 but 100 mega Pascals corresponds to, I think, 14,000  
17 psi. Is that correct?

18 MR. PUGH: 6.895 over whatever is the  
19 conversion.

20 MEMBER POWERS: So roughly 14,000 psi.

21 MR. PUGH: Yes.

22 MEMBER POWERS: Which of our pressure  
23 vessels in the United States, reactors, 14,000 psi?

24 MR. PUGH: Tthe design pressure for this  
25 vessel is 9 point something mega Pascals or is it ksi?

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1 MR. BASS: 9.75 ksi.

2 MR. PUGH: 9.75 ksi. It is the design  
3 pressure for the ITV that's equivalent to a full RPV  
4 under 2250 psi.

5 MEMBER POWERS: So there's some scaling  
6 that's been done here to decide that what you think  
7 the critical flaw, stress field that the critical flaw  
8 will be to mimic what it is in the much bigger  
9 pressure vessel?

10 MR. PUGH: Yes sir.

11 MEMBER POWERS: It's an element of faith  
12 involved in going from here to the actual pressure  
13 vessel.

14 MR. PUGH: But with detailed stress  
15 analysis, I think one can feel that it is well  
16 simulated.

17 MEMBER SHACK: Which is why they scaled  
18 this test from a Charpy compact test specimen to this  
19 vessel.

20 MR. PUGH: Yes.

21 MEMBER SHACK: You verified the scaling to  
22 that extent.

23 MR. PUGH: Yes. You recall the original  
24 plan had in it full scale testing that would have  
25 validated perhaps the nth increment of scaling, but it

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1 was just too expensive to take on.

2 MR. MAYFIELD: Dana, I think the other  
3 point that's worth making is there's been a lot of  
4 work done in showing that this fracture toughness  
5 parameter and that the stress near the crack tip is  
6 what controls. You just need to do something that  
7 looks like a cylinder to get the stress state to be  
8 similar?

9 MEMBER POWERS: I don't have any trouble  
10 of scaling this up. I think you've left out an  
11 element in the presentation of discussing that  
12 scaling.

13 MR. MAYFIELD: Fair enough.

14 MEMBER POWERS: It's not so important for  
15 the presentation, but in making the case for the PTS  
16 when you use this information to say this elastic  
17 fracture mechanics is a valued technology for doing  
18 your PTS analysis and verified, you're going to have  
19 to put that step in.

20 MR. PUGH: The next slide will have  
21 something relevant to that step coming up.

22 MR. BASS: Richard Bass at RNL. I have  
23 the analysis that you're talking about on my desk at  
24 Oak Ridge and I'll be glad to provide that.

25 MR. PUGH: It's more important that they

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1 provide it in their ETS.

2 MR. MAYFIELD: If the Committee is  
3 interested, we can certainly provide the information,  
4 but I think the point is well taken to make sure, as  
5 we document what we're doing, that we lay that basis.

6 MEMBER POWERS: This is a crucial part.  
7 And it's important not to leave out what is a crucial  
8 step and in thermal hydraulics land, they spend an  
9 enormous amount of time discussing that scaling and I  
10 think you'd be remiss to gloss it over. I mean it's  
11 very familiar to you, but it's not very familiar to  
12 some of your critics.

13 MR. MAYFIELD: And there's a very good  
14 story to that.

15 MEMBER POWERS: I bet there is.

16 MEMBER FORD: Claud, you mentioned that  
17 those five data points come from the -- towards the  
18 lower shelf area.

19 MR. PUGH: This is the four which is the -  
20 -

21 MEMBER FORD: The five, rather.

22 MR. PUGH: Right here. And they are down.

23 MEMBER FORD: If you had done the tests on  
24 the specimens on the upper shelf region, you would  
25 presumably start to deviate from that one to one line

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1 towards the upper part of it.

2 Do you and -- does that, in fact, happen?

3 MR. PUGH: Yes. The short answer is yes.

4 MEMBER FORD: And so therefore the use of  
5 the fracture mechanics is not necessarily fickle to  
6 low fluence stations. Now I recognize --

7 MR. PUGH: No, that's the wrong  
8 conclusion, I think.

9 MEMBER FORD: Less irradiated pressure  
10 vessels. Am I going the wrong way?

11 MR. MAYFIELD: No, you're going the  
12 correct way. And in fact, we've had some situations.  
13 Claud mentioned this low upper shelf energy weld that  
14 we tested. That was one of the motivations for us  
15 developing the elastic plastic fracture effort and  
16 applying, in fact, Jim Rice's J analysis and  
17 subsequently the development of the JR curve, so  
18 there's a lot of that work that goes into doing an  
19 analysis for a fully ductile condition.

20 MEMBER FORD: The reason I asked the  
21 question --

22 MR. PUGH: I understand better your  
23 question now, where you're coming from.

24 MEMBER FORD: You show a good correlation  
25 for lower shelf, i.e., embrittled conditions. When

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1 you go to fully ductile conditions, i.e., beginning of  
2 life, then this must fail to a certain extent, unless  
3 you use --

4 MR. PUGH: In the sense of being accurate  
5 in your prediction of failure, you will be ever more  
6 increasingly conservative.

7 MEMBER FORD: Correct.

8 MEMBER RANSOM: I understand the vessels  
9 are fabricated using axial welds from rolled plate?

10 MR. PUGH: Most of them are.

11 MEMBER RANSOM: How do you know that the  
12 data you're using is characteristic of what's in the  
13 weld region?

14 MR. PUGH: Well, because this is a weld,  
15 that's a weld and some of the other experiments are  
16 involved with welds.

17 MEMBER RANSOM: The previous curve you  
18 gave though is for homogeneous material.

19 MR. PUGH: Data have been collected on  
20 weld material as well.

21 MR. MAYFIELD: In ferretic material, the  
22 welds, the forgings, the plates, they all show the  
23 same characteristics in transition, same  
24 characteristic temperature.

25 The things that change will be the index

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1 temperature, where that curve is on the temperature  
2 axis. But all the other characteristics of the curve  
3 remain the same.

4 MR. PUGH: But I'm glad you asked the  
5 question, Dr. Ransom, because some of these are  
6 absolutely weld material, even in these ITVs.

7 I realize our time is getting away from  
8 us.

9 CHAIRMAN APOSTOLAKIS: Yes, we really have  
10 to finish at 10.

11 MR. PUGH: If one looks, then at an  
12 application of the ASME approach for these ITVs and  
13 looks at a ratio of the load factor, that is, say the  
14 failure pressure versus design pressure, ASME design  
15 pressure, these are roughly the -- they're not  
16 roughly, these are the ratios. There are roughly  
17 three for all cases, except this one and this is at  
18 nozzle -- excuse me, this is that very deep flaw was  
19 80 some percent way through the wall to begin with.

20 If you apply to a full-scale reactor  
21 vessel, then the same technology, these are designed  
22 failure  
23 -- these are fracture failure curves for a full  
24 reactor pressure vessel under like 2250 psi. Based on  
25 the stress design limits, here's the operating

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1 condition. Here's the design level. Here is the  
2 fracture mechanics for the quarter T analysis allowed  
3 by the ASME code. Quarter T would be like 2 point  
4 something depth. Compare it to this curve and you'll  
5 see like a factor of three safety factor that exists  
6 in applying the ASME code versus failure curves. So  
7 you're talking about that lower bound curve, etcetera.  
8 That's not the end of the story in terms of being  
9 conservative when applying ASME code.

10 MEMBER WALLIS: What's the parameter on  
11 these curves, is it inches?

12 MR. PUGH: Those are flaw depth.

13 MEMBER WALLIS: Flaw depth, okay.

14 MR. PUGH: So even with flaws much deeper  
15 than ASME code quarter T, still we see tremendous  
16 margin before one gets to a predictive failure  
17 condition.

18 After this set of experiments is done, the  
19 question -- not done, but during their performance, a  
20 question came up about thermal shock with the most  
21 severe condition thought to be a large break LOCA  
22 where one would have a loss of pressure, but a very  
23 extreme thermal shock. So the set of experiments  
24 using a vessel something like this where -- not  
25 something -- this is a vessel, 6 inches thick, 1 meter

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1 diameter, dunked in liquid nitrogen from a temperature  
2 of about 280 degree C to give the thermal shock.

3 This type of experiment gave the through  
4 the wall variation as one would anticipate in reactor  
5 pressure vessel for stresses. This is through the  
6 wall versus the --

7 MEMBER WALLIS: Did you get film balling  
8 at the liquid nitrogen?

9 MR. PUGH: Interesting you should ask  
10 that. A tremendous effort went into developing a  
11 coating that would --

12 MEMBER WALLIS: Would nucleate.

13 MR. PUGH: Would nucleate, yes. It was a  
14 rubber cement process that Dick Sheverton actually got  
15 the genesis idea from some people in France and worked  
16 on it, a very high priority topic to perform these  
17 experiments, yes sir.

18 As a flaw exists in a particular place in  
19 the wall during the thermal shock, though as the  
20 thermal shock passes, the stresses and stress  
21 intensity on that flaw will peak and start down and it  
22 may not reach the critical value of  $K_{Ic}$  until later,  
23 namely when it's cooled, and this can give rise to  
24 something called warm pre-stressing, which will  
25 inhibit the initiation of the flaw in certain sense,

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1 especially for deep cracks in thermal shock  
2 conditions.

3 So these experiments were to examine  
4 behavior under thermal shock, one prestressing,  
5 whether or not arrest would occur in a rising K field  
6 or above the ASME limit.

7 As a qualitative example which was  
8 actually done quantitatively, TSE-5, it was predicted  
9 that three crack initiation arrest events would occur  
10 in this one thermal shock. It was predicted that  
11 since the initial flaw was a tenth of the way through,  
12 that it would go to halfway through if (1)  
13 prestressing occurred on the third event. If it did  
14 not, it would go to .7. You can see from the cross  
15 section going from the inner radius to the outer  
16 radius of this cross section, indeed, three jumps  
17 occurred and propagated to .8.

18 MEMBER FORD: Would you mind just going  
19 back to the previous graph. This is a question that  
20 came up when we -- I forgot which one it was, one of  
21 the reviews. What is the data to support that fluence  
22 distribution or is it calculated?

23 It seems to me to be very important in  
24 terms of whether the crack arrests or not.

25 MR. PUGH: Certainly, the toughness

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1 through the wall depends upon the fluence through the  
2 wall and I'd rather defer the question to Mike.

3 MR. MAYFIELD: It's a calculated fluence.  
4 There have been some experimental activities looking  
5 to benchmark the calculations. There's something of  
6 a raging debate that probably that Dr. Bonaca is in a  
7 better position to describe than I am. There's some  
8 raging debate among the purists about whether the  
9 attenuation function that we have incorporated in this  
10 which is a power law attention, as to whether that  
11 really is technically sound or not. The experimental  
12 data that we -- what limited experimental data there  
13 are, looking at through wall attenuation suggests that  
14 it's reasonable. It may not be precisely correct, but  
15 it's within the uncertainty of the experimental data.  
16 It seems to work fairly well.

17 MEMBER FORD: I think we asked the  
18 question, but I can't remember the answer as to what  
19 the effect of that uncertainty of that fluence  
20 distribution would be on your resulting calculations.  
21 Is it a huge swinger?

22 MR. KIRK: Since most of the flaws that  
23 play a significant role in PTS are very close to the  
24 inner surface, because that's where the thermal shock  
25 is the greatest. The differences between -- as Mike

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1 said, there's a debate as to how fast the exponential  
2 fall off is, but since most of the flaws that get you  
3 occur within say 10 percent of the thickness between  
4 the inner wall and 10 percent of the way in, the  
5 differences between those two attenuation functions is  
6 really pretty small.

7 MR. MAYFIELD: I think the other thing I  
8 would say is that the uncertainty in the calculated  
9 fluence at the vessel, the inner surface, far  
10 dominates the uncertainty of the through wall, the  
11 uncertainty associated with through wall attenuation.

12 MEMBER FORD: And there's more data to  
13 back up that early -- presumably more fluence data --

14 MR. MAYFIELD: Data to support the  
15 discrete ordinants of code approaches than calculating  
16 the inner surface.

17 MR. KIRK: Where you may wish to re-raise  
18 this question, where it, in fact, is very significant,  
19 is when we get to talking about heat up and cool down  
20 limits because they're controlled by notional flaws  
21 that are a quarter T thick, both on the inner diameter  
22 and outer diameter. So you've got to attenuate to all  
23 the way to three quarter T in a heat up or cool down  
24 calculation and there, the differences between the  
25 functions that are advocated by one group of experts

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1 versus another is indeed very significant, but for  
2 PTS, since the flaws that are important are on the  
3 inside and like Mike said, the greater uncertainty is  
4 on the inner wall flunce, it's not that huge a  
5 factor.

6 MEMBER SHACK: But wouldn't it have a more  
7 significant effect on your conditional probability of  
8 failure. I can understand your argument for the  
9 conditional probability --

10 MR. KIRK: That's correct. Yes. Yes,  
11 that's correct.

12 (Slide change.)

13 MR. PUGH: Just one last slide, I believe,  
14 that I'd like to show you briefly and that is if you  
15 look at the -- in this presentation at least on this  
16 slide, four of the TSE experiments, if you look at the  
17 calculated initiation values and the calculated crack  
18 arrest values, some of this -- the experiments were  
19 multiple initiation and arrest; initiation and arrest.  
20 You can see that the data fall in a good trend with  
21 that from small specimen data. These are  
22 approximately upper and lower bound for small specimen  
23 data and you see the initiation values follow the  
24 trend very well and so do the arrest values.

25 All the work, of course, that these two

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1 sets of experiments represent, it was like 15 years of  
2 work. We really can't do it much justice here in 30  
3 minutes or less, but hopefully I've given you a little  
4 snapshot to show you that the validity and the  
5 applicability for operating conditions in the case of  
6 ITVs and an accident condition in case of a large  
7 break LOCA, the results of these experiments suggest  
8 LEFM is applicable to fracture prevention and in  
9 toughness prediction.

10 MEMBER WALLIS: It suggests to me that  
11 something is different about the French work from the  
12 other work. When you say follow the trend, that's a  
13 very gross statement. If you actually look at the  
14 data from one lab, the trend is not obvious. The  
15 gross way, you're within your bounds.

16 MR. MAYFIELD: You're talking about the  
17 French data?

18 MEMBER WALLIS: All the others, any other  
19 data. I don't want to prolong this, but you said  
20 follow the trend. To get a trend, you really need to  
21 look at one lapsed data or something other than saying  
22 it's within some statistical --

23 MR. BASS: This is Richard Bass from ORNL.  
24 I'll make a comment on the French data. That's been  
25 a topic of discussion for at least 20 years and it's

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1 our feeling that there's doubt about the actual  
2 temperatures that were made, the data that was  
3 gathered in those experiments.

4 MEMBER WALLIS: So we should throw it out?

5 MR. BASS: The French, that's their data  
6 and that's what they provide. It's not our place to  
7 throw it out. We can --

8 MEMBER WALLIS: You put uncertainty bounds  
9 on the temperature?

10 MR. BASS: Yes.

11 MR. MAYFIELD: Richard, as Dr. Apostolakis  
12 said, we just need to make sure we hit 10 o'clock.

13 CHAIRMAN APOSTOLAKIS: No, 10:15.

14 MR. MAYFIELD: 10:15.

15 (Slide change.)

16 MR. BASS: In keeping within the rules, my  
17 name is Richard Bass, Oak Ridge National Laboratory.  
18 And I am the current manager of the Heavy Section  
19 Steel Technology Program and I want to spend the  
20 remaining time of our presentation focusing on the  
21 third set of large scale experiments that were carried  
22 out in the 1980s at ORNL. These are the so-called  
23 pressurized thermal shock experiments. And again,  
24 these experiments were performed to confirm and  
25 develop a fracture analysis methodology.

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1           The particular feature that we introduced  
2           in these experiments is subjecting these flawed  
3           vessels to a coordinated thermal shock and internal  
4           pressure loading. You see in the plot on the right  
5           hand side here, the loading factors of not only the  
6           temperature that we investigated in the original  
7           thermal shock experiments, but now we introduce a  
8           coordinated pressure transient that apply to the inner  
9           surface of these vessels.

10           The objective here is to again to  
11           coordinate these loading factors so as to produce a  
12           desired evolution of crack driving forces on the flaws  
13           of interest that we've installed in the vessel. In  
14           this particular case, we see an example of a transient  
15           where we have increasing K, crack driving force on the  
16           shallow flaw which then reaches the maximum, the flaw,  
17           the tirade of change of K crack driving force on a  
18           shallow flaw which then reaches the maximum. The flaw  
19           -- the tirade of change of K then becomes negative.  
20           We say that this flaw then is subjected to simple warm  
21           prestressing and warm prestressing was a particular  
22           effect that we wanted to investigate in both the first  
23           and second pressurized thermal shock experiments.

24           Also, we wanted to look at the -- get a  
25           better understanding of the nature of cleavage crack

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1 arrests at temperatures near or above onset what we  
2 discussed previously here as the Charpy, the onset of  
3 the ductile upper shelf.

4 The PTSE-2 experiment addressed low upper  
5 shelf energy steel. We're not going to have time to  
6 talk about that this morning. We're going to focus on  
7 these first two elements that were studied in the  
8 PTSE-1 experiment.

9 In both of these experiments, we had long  
10 surface cracks that were inserted into the ITV  
11 vessels, pictures which you've already seen. Shallow  
12 flaws subjected to this coordinated loading conditions  
13 to achieve specific objectives and we'll look at what  
14 those objectives were shortly and of course, one of  
15 the elements that we're very interested in here this  
16 morning is the features of LEFM that were used to  
17 design these experiments and also to analyze them.  
18 And specifically, we did a good deal of small specimen  
19 fracture toughness testing that we used to construct  
20 our fracture test as models. That's the essence of  
21 the LEFM approach. And then we used the -- applied  
22 our methodology to design the loading conditions which  
23 are properties and so forth to achieve these  
24 objectives and our particular tools in doing that, in  
25 this -- these two experiments performed in the 1980s,

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1 the so-called OCA code and OCA was a precursor to the  
2 FAVOR code. FAVOR and OCA still used basically the  
3 same methodology for doing deterministic structural  
4 and fracture mechanics calculations.

5 So we'll look briefly at some results from  
6 OCA in analysis of these experiments and also touch on  
7 application of the current FAVOR code to, in essence,  
8 demonstrate that we still get the same answers. Next  
9 slide.

10 (Slide change.)

11 MR. BASS: Okay, this is the vessel.  
12 We've seen pictures of this before. Again, we've got  
13 a wall thickness of about 6 inches, 148 millimeters  
14 and the vessel is long enough to give us this  
15 constraint condition that -- plain strain/constraint  
16 condition that we're looking for in our test specimen  
17 that we can then transfer or use to evaluate our  
18 methodology that we can then transfer to the RPV.

19 Again, you see here, we have a flaw in the  
20 outer surface. In the PTSE-1 experiment, the first  
21 experiment that we're going to focus on, the flaw was  
22 12.2 millimeters in depth here on the outer surface,  
23 one meter in length.

24 The photograph on the right hand side, you  
25 see this test vessel is being lowered in what we call

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1 a shroud or an outer test vessel. That outer vessel  
2 serves two purposes. First of all, to heat the  
3 specimen up to the test temperature of approximately  
4 290 degree Celsius operating temperature for an RPV;  
5 and then since this was then connected into a large  
6 thermal hydraulics test loop, the outer vessel served  
7 as a shroud and we had about a one-half inch gap  
8 between the outer shroud and the inner surface here  
9 that would then allow us to thermally shock the outer  
10 surface of the vessel and the flaw with a fluid  
11 temperature that varied anywhere from say 15 degrees  
12 Celsius down to minus 29 Celsius.

13 We started out in the first transient of  
14 this experiment using water because we thought we  
15 could get away with avoiding the hassles that go along  
16 with using a refrigerant, but the second and third  
17 transience necessitated we use a mixture of methanol  
18 and water so that we could lower the coolant  
19 temperature and achieve a more severe thermal shock.

20 That's the essence of the experimental set  
21 up that we used in this program.

22 MEMBER ROSEN: How do you make the flaw  
23 and how do you know that it's representative of the  
24 real flaws in service?

25 MR. BASS: Well, a lot of work over the

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1 years has gone into that and this was a well-developed  
2 methodology. We used an embrittling weld technique  
3 that was then hydrogen charged, a little bath around  
4 this thing and put a potential across it of sulfuric  
5 acid that spontaneously generates a very sharp flaw.  
6 Of course, there was a lot of research that went into  
7 this, trials and so forth. By the time we got around  
8 the mid-1980s of doing these experiments, this was a  
9 very well-developed methodology.

10 I think we're ready to go to the next  
11 slide.

12 (Slide change.)

13 MR. BASS: Okay, this --

14 MR. MAYFIELD: Richard, could I say one  
15 thing?

16 MR. BASS: Sure.

17 MR. MAYFIELD: The second part of your  
18 question was about how are these representative of  
19 what flaws are in vessels in service. By and large,  
20 we don't think these flaws are in vessels. This was  
21 a test condition designed to give us -- to support  
22 this particular analysis. We don't really think there  
23 are 10 percent wall, deep cracks that run for  
24 extensive lengths along the vessel surface.

25 MEMBER ROSEN: Yes, I know that, but I was

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1 just asking really about the morphology of the crack.

2 MR. BASS: I took your question to mean  
3 about the sharpness of the crack and of course, in  
4 this technique you get a very sharp crack. That  
5 certainly would be -- a representative say a sharp  
6 defect in a weld or between clad weld interface, that  
7 kind of thing.

8 This is a diagram here that illustrates  
9 the applied K factor, the crack driving force as well  
10 as the crack initiation toughness and the crack arrest  
11 toughness for this material. This is really a  
12 schematic. This is not something from an actual test.  
13 The purpose of this particular slide is to describe  
14 the planned transient in this experiment and then  
15 compare that with what actually happened.

16 The original plan called for doing this  
17 experiment in a single transient, but failing the  
18 objective of achieving all of these in a single  
19 transient, then we would do a backup second and third  
20 transient, but we want to give this a first shot of  
21 let's see if we can do it all in one effort. That  
22 actually did not work out. We actually ended up doing  
23 an experiment in three transients. But we'll get to  
24 that shortly.

25 The objective in this PTSE-1 experiment

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1 was to load the crack, this shallow crack with the  
2 thermal shock up to Point A here where the crack  
3 becomes critical. We would then experience, observe  
4 a cleavage initiation of the flaw. It would then  
5 arrest at the crack arrest toughness curve at a deeper  
6 point in the wall. We would continue loading this  
7 flaw. It would then go into a mode of warm  
8 prestressing here, prestressing where the  $K_{Ic}$  is  
9 negative. And the crack will not initiate when  $K_{Ic}$   
10 is negative in cleavage.

11 The crack becomes critical here and it  
12 crosses again the  $K_{Ic}$  curve at this deeper point. It  
13 becomes critical at this point, but it does not  
14 initiate because of warm prestressing. We apply  
15 pressure loading here to alleviate the one  
16 prestressing, reload and at some point, F here, we  
17 want to achieve a cleavage reinitiation and then drive  
18 the crack very deeply into the -- say up to 40 percent  
19 of the way through the wall of the vessel, 30 percent  
20 or so to -- and get a cleavage arrest at a temperature  
21 that corresponds to the Charpy upper shelf of this  
22 material.

23 Those were the objectives in the transient  
24 and if we go to the next slide we'll see what actually  
25 happened.

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1 (Slide change.)

2 MR. BASS: This particular diagram on the  
3 left plots again the applied  $K_I$  loading of the flaw.  
4 The  $K_{Ic}$  fracture toughness and the  $K_{IA}$  toughness for  
5 this material as a function of crack tip temperature.  
6 We do this -- this is a very popular curve or type of  
7 curve to use in depicting these analyses because we  
8 can draw the  $K_{Ic}$  and the  $K_{IA}$  curves, fixed, on the plot  
9 for the crack tip. And then look at the evolution of  
10 the transient loading applied to the flaw and compare  
11 it with these fracture toughness curves. Remember,  
12 these are our -- we haven't talked about this before,  
13 but these are our predictions from small specimen  
14 testing. We went out and did a lot of testing of 1T  
15 specimens. We did size corrections of the 1T  
16 specimens and we developed a lower bound fracture  
17 toughness curve to that data. That's the  $K_{Ic}$  curve  
18 you see here.

19 We did similar testing of small specimens  
20 for  $K_{IA}$  crack arrest and we developed a median curve  
21 that you see here to that crack arrest data which was  
22 also size adjusted. These are very small specimens.  
23 We wanted to adjust them to a plain strain constraint  
24 condition we used in methodology developed by George  
25 Erwin long ago to do that.

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1                   And then let's talk about what happened in  
2 the actual test in these three transients. The first  
3 transient we see here is A. This is the original flaw  
4 of 12 millimeter depth. OAW is .08. The time is  
5 moving to the left here. The crack tip is cooling  
6 from the thermal shock and we see that the crack first  
7 becomes critical at this point where the applied curve  
8 crosses the  $K_{Ic}$  curve, fracture toughness curve.

9                   At this particular point, due to several  
10 factors, the flaw is just going into warm  
11 prestressing. You can see the K dot becomes slightly  
12 negative as it hits this point and consequently as we  
13 move in here with the one prestressed flaw, we do not  
14 get an initiation to recover from that warm prestress  
15 effect. You require more loading of the flaw which we  
16 did not have in this pressure transient. Consequently  
17 we have here a highly critical crack which did not  
18 initiate. The ratio of the applied K to the  $K_{Ic}$  here  
19 is on the order of 2. So this is really an  
20 unambiguous testimony to the effects of warm  
21 prestressing.

22                   The applied load achieves the -- it  
23 exceeds the fracture test by a factor of 2.

24                   Well, recognizing that we had a warm  
25 prestress crack and we didn't have quite enough

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1 loading power at this particular point in our planned  
2 pressure transient to get an initiation, we went back.  
3 We cranked up the -- basically doubled the pressure  
4 level in the cylinder and we lowered the coolant  
5 temperature to introduce a more severe thermal shock.  
6 That's the B transient here and you can see it does  
7 not initiate at the  $K_{Ic}$  curve. We get a little bit  
8 supercritical with the crack. We then did get a  
9 cleavage initiation. It jumped to an OAW.165, about  
10 24 millimeters in depth. The thermal shock,  
11 pressurized thermal shock continues. We're continuing  
12 to increase the load. The flaw became critical again  
13 at this particular point, just crossing the line, the  
14  $K_{Ic}$  curve here we then go into warm prestressing phase  
15 again without an initiation.

16 LEFM would have predicted an initiation,  
17 of course, at this point, but just across the line  
18 there was no initiation.

19 Again, this was a very strong  
20 demonstration of the effects of warm prestressing in  
21 this PTS event. You see here we have then an applied  
22 K value which well exceeds the  $K_{Ic}$  fracture toughness,  
23 but K dot is negative, you're going to get an  
24 initiation of the crack.

25 The last experiment we simply cranked up,

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1 ratcheted up the pressure up to a little more, dropped  
2 the coolant temperature a little bit more and we got  
3 an initiation here pretty much on the line, the  
4 intersection with the  $K_{1C}$  curve and the arrest point  
5 here at a crack  $F$  about 41 millimeters, very close to  
6 the small specimen  $K_{1A}$  curve. And finally the system  
7 runs out of gas at this point here.

8           So we achieved all of the objectives here.  
9 We wanted to investigate the warm prestressing. We  
10 had two very strong examples of that here in the A and  
11 B transients. We were able to drive the crack here  
12 into temperature regime that was on the Charpy upper  
13 shelf of material and get a very high crack arrest  
14 value.

15           MEMBER FORD: When you say it ran out of  
16 steam, you mean you couldn't apply any more pressure  
17 to the system to push up --

18           MR. BASS: That's correct. Yes, the  
19 pressure -- our accumulator just didn't have anything  
20 left to -- and we would not have wanted to do that  
21 anyway. We had planned to -- I didn't mean to imply  
22 that we were trying to get to the line again. We  
23 wanted to preserve the fracture surfaces which meant  
24 that we did not want to burst the vessel. We were  
25 very happy with the arrest where it was.

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1 MEMBER WALLIS: So it's pretty good in  
2 view of the uncertainties you have in  $K_{1A}$  and  $K_{1C}$ .

3 MR. BASS: That's the story here and this  
4 is really -- this is the punch line here. And this  
5 whole story about pressurized thermal shock and  
6 applications of LEFM and the methodology, you're  
7 looking at it right here. And just in a few words  
8 we've got the  $K_{1C}$  curve that was generated from small  
9 specimen data.

10 MEMBER WALLIS: That's the best estimate,  
11  $K_{1C}$  is that what that is?

12 MR. BASS: No, that's the lower bound.

13 MEMBER WALLIS: Oh, lower bound.

14 MR. BASS: It's the lower bound to the  
15 size of just this data from small specimens for this  
16 particular material and the  $K_{1A}$  curve that you see  
17 here, this is again --

18 MEMBER WALLIS: That's why it can cross  
19 and not do it because you've got --

20 MR. BASS: It's a lower band. We've got  
21 a long flaw. You've got a lot of opportunities for  
22 sampling of defects along that flaw, so you would  
23 expect to get -- you hope to get very close to the  
24 line and in effect, we see that we did achieve that  
25 objective of getting initiations very close to the

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1 smallest specimen predicted curve, and likewise, with  
2 the  $K_{1A}$  curve. This is unretouched curves and data.  
3 This is the median toughness curve for the  $K_{1A}$  small  
4 specimen data. Again, it's adjusted for size effects.

5 Also, down here you'll see this is the  
6 ASME section 11  $K_{1C}$  and  $K_{1A}$  curves and you can see that  
7 these are very conservative in predictions. As a  
8 matter of fact, we did a code analysis on this  
9 experiment and the code analysis said that we would  
10 fail the vessel in three crack jumps, 40 seconds into  
11 the transient. Obviously, that did not occur.

12 MEMBER POWERS: The code curves, the  
13 conservative ones are the product of reflection by a  
14 large number of people thinking about a large number  
15 of things. Why did they make them so much more  
16 conservative than your curves that have been --

17 MR. BASS: Oh, we're -- remember, we were  
18 trying to conduct a particular experiment here.

19 MEMBER POWERS: I understand what you're  
20 doing --

21 MR. BASS: We're not --

22 MEMBER POWERS: I'm not asking about what  
23 you're doing. I'm asking about what the code people  
24 are thinking.

25 MR. BASS: I wasn't there. I can't tell

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1 you.

2 MR. MAYFIELD: I'm sorry, I didn't hear  
3 the question clearly.

4 MEMBER POWERS: What I'm asking is, Mike,  
5 you've got some data curves where your particular  
6 experiment, your curves are -- the code curves are  
7 substantially more conservative and I'm wondering what  
8 was the thinking of the ASME Committee that moved  
9 those curves in this conservative direction.

10 MR. MAYFIELD: Okay, the approach that the  
11 code has taken is to develop generic fracture  
12 toughness curves and then to try and index those to a  
13 particular material based on the nil ductility  
14 temperature and some adjustment from there.

15 So their intention was to develop a  
16 conservative generic curve so that when you picked  
17 what was believed to be the limiting material in the  
18 vessel and index the curves to account for the  
19 embrittlement of that limiting material, you still  
20 have a conservative representation.

21 They were not trying to do best estimates.  
22 That's where this lower bound concept came from.  
23 There's a lot of concern and I think a number of us on  
24 the staff share the concern about the level of  
25 conservatism in those ASME curves and the approach

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1 taken. But the underlying piece of it was to develop  
2 generic curves so that you didn't have to have exactly  
3 the right material from each pressure vessel and you  
4 could still account for a lot of the variation in  
5 material.

6 MEMBER POWERS: So what you're saying is  
7 the shift that's manifest in this figure is  
8 capricious. It's not in response to any particular  
9 phenomenological thing that they're worried about.

10 MR. MAYFIELD: That's correct.

11 MR. BASS: The plot on the right hand side  
12 shows the plot of the --

13 MEMBER ROSEN: I didn't understand what  
14 you said about what the ASME code would have  
15 predicted. You said a code predicted it would have  
16 failed --

17 MR. BASS: If you do a code analysis, what  
18 it would -- what the code analysis showed was that the  
19 crack would propagate in three jumps and would  
20 penetrate the wall and fail the vessel. I'm sorry.

21 MEMBER ROSEN: Okay.

22 MR. BASS: The plot on the right hand side  
23 is the crack arrest plot of the arrest toughness data  
24 versus -- now this is normalized temperature relative  
25 to  $RT_{NDT}$ . And again, we've got the two values here

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1 from our PTSE-1 experiment and some other data  
2 generated from various sources: Japanese data, the  
3 thermal shock experiments that Claud has discussed  
4 recently, and again, we've got the French TSE data  
5 that's in an area of its own down here. And finally,  
6 a wide plate -- the first wide plate experiment that  
7 we did here at NVS back in the 1980s.

8 A couple of things about this plot. First  
9 of all, this  $K_{1A}$  curve is from the PTSE-1 small  
10 specimen data here. And you see, as we look at it, we  
11 think that's a pretty good representation of these  
12 large scale experiments when you reference them to the  
13  $RT_{NDT}$ .

14 One other thing I did not point out here  
15 is that one of the landmark pieces of data that came  
16 out of PTSE-1 was that we calculated or measured, I  
17 should say, a very high crack arrest value here,  
18 roughly 300 MPA root meters which is well above this  
19 implied upper bound in the ASME Section 11 curve of  
20 220 MPA root meters. We demonstrated that in a thick  
21 section, highly constrained thick section that we  
22 could generate a very high arrest toughness value here  
23 without any sign of intervention of stable or unstable  
24 tearing to muddy the picture here.

25 And also, you will see down here that this

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1 is well above the onset of the Charpy upper shelf here  
2 by about -- for the PTSE-1 material by about 30  
3 degrees Calvin.

4 Next slide.

5 (Slide change.)

6 MR. BASS: This particular slide gives an  
7 example of a recent analysis that we carried out at  
8 ORNL where we went back and used the current FAVOR  
9 version of FAVOR code to analyze the first two  
10 transients, A and B. We're only showing the transient  
11 B here and we find again that we get basically the  
12 same solutions that we generated back in the 1980s  
13 with OCA and we would expect to do that. We're using  
14 basically the same methodologies. And if your input  
15 is the same, the output should be the same and sure  
16 enough it was.

17 On the left hand side here, we see  $K_1$ ,  $K_{1C}$ ,  
18  $K_{1A}$ . Again, you've seen the curves versus the crack  
19 tip temperature. This is what we call the classic  
20 LEFM model, classic LEFM prediction. When you hit  $K_1$   
21 equal to  $K_{1C}$ , you forecast the crack propagation,  
22 arrest the  $K_{1A}$  curve. This prediction is something  
23 like 19.2 millimeters. Actually, in the experiment,  
24 the flaw initiated a little bit later in the transient  
25 and it jumped a little bit deeper, as a consequence to

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1 about 24 millimeters. Again, we would have predicted  
2 initiation here. It did not reinitiate at this  
3 particular point, so we did not see that in this  
4 second transient.

5 These are the actual calculations over  
6 here.

7 MEMBER WALLIS: Did FAVOR predict  
8 reinitiating or not? You don't show that.

9 MR. BASS: Well, yes, FAVOR would -- FAVOR  
10 is -- FAVOR is classic LEFM, so it would -- we would  
11 predict a reinitiation at this point.

12 MEMBER WALLIS: You don't show it.

13 MR. BASS: Well, we didn't get it in the  
14 experiment. This is the analysis of the actual  
15 experimental data over here with FAVOR. This is what  
16 would have been predicted.

17 You see that we did not get the second  
18 jump.

19 MEMBER WALLIS: Is that because of your  
20 uncertainty in the temperature turnaround or --

21 MR. BASS: Well, it has to do with the  
22 nature of cleavage fracture. Cleavage at a given  
23 temperature is a distribution and we think a Weibull  
24 distribution in our models now. And, of course, where  
25 -- you can't anticipate that you're going to initiate

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1 at the earliest possible -- the lowest possible value  
2 in a methodology here where you're looking at a  
3 distribution of possible toughnesses.

4 MEMBER WALLIS: There's also the K dot  
5 that you've got to take into account.

6 MR. BASS: K dot here, yes, after this  
7 point. The current version of FAVOR and I don't know  
8 if I should even mention this, does not currently  
9 incorporate warm prestressing, but Mark, do you want  
10 to say anything about that?

11 MR. KIRK: The next version probably will.

12 MEMBER WALLIS: I would think it should.  
13 It seems to be a significant defect.

14 MR. KIRK: Yes.

15 MR. BASS: Let's move on to the last of  
16 the technical slides here.

17 (Slide change.)

18 MEMBER WALLIS: It's wonderful to see some  
19 data for once. It's a technical discussion one could  
20 follow more or less.

21 MR. BASS: This is our view of the world  
22 summarized here insofar as the applicability of LEFM,  
23 FAVOR, OCA and so forth to the assessment of RPV  
24 integrity under pressurized thermal shock. We saw in  
25 these tests that we did achieve cleavage fracture in

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1 these large scale tests and an important element here  
2 is that they were consistent with the small specimen  
3 data.

4 Another really important element that came  
5 out of these tests was the warm prestressing evidence.  
6 Clearly, warm prestressing is a reality. It's there  
7 and very effective in certain types of transients.

8 And in our punchline here the observed  
9 cleavage-crack behavior in these thick-section  
10 experiments has been well described by the LEFM  
11 methodology and that methodology is embodied in the  
12 current version of the FAVOR code and it is  
13 historically consistent with all of the other  
14 calculations that we made in these large scale  
15 experiments.

16 MEMBER KRESS: If you were to put warm  
17 prestressing into FAVOR, you would just simply say if  
18 you ran into the negative thing you just stop the  
19 crack there?

20 MR. KIRK: You wouldn't, as Richard said,  
21 you wouldn't allow the crack to reinitiate like -- if  
22 I can point -- you wouldn't allow the crack to  
23 reinitiate on the downward slope whereas now -- well  
24 --

25 MEMBER KRESS: So you have a problem here

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1       though with -- even if you had warm prestressing in  
2       FAVOR, you would have hit  $K_{1c}$  and would have thought  
3       you would have initiated there.

4               MR. KIRK: In the current weld you need to  
5       be -- it's a little bit more complicated than that  
6       because in the current version of FAVOR, because we're  
7       treating the uncertainty in both  $K_{1c}$  and  $K_{1A}$  as  
8       aleatory --

9               MEMBER KRESS: So it depends on which  
10       sample you --

11              MR. KIRK: It never really initiates.  
12       You've got a probability of initiation. You've got a  
13       probability of failure, but suffice it to say right  
14       now -- where is the pointer? I have got to point and  
15       talk into this thing. Right now, in FAVOR, we count  
16       the probability of -- we allow a crack to initiate in  
17       this area. So we're essentially counting up that  
18       probability whereas we shouldn't be. The reason, warm  
19       prestressing has been around for a long, long time.  
20       In fact, it was around, well recognized and well  
21       researched when SECY-82-0465 was published and the  
22       original basis for this rule was established.

23              It wasn't included in the calculations  
24       then, not because anybody on the staff didn't believe  
25       the physics of the situation, but because at that

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1 stage we were using what were called idealized thermal  
2 hydraulic transients. So instead of having all of the  
3 bumps and squiggles of a real thermal hydraulic  
4 transient, they were idealized as exponential fallouts  
5 so the concern was that you might believe, based on  
6 the idealized transient that warm prestressing had  
7 occurred when, in fact, in the real transient it  
8 wouldn't have.

9 We've revisited this recently and in fact,  
10 warm prestressing is next on our list of things to add  
11 in and what we anticipate it will do is stop a lot of  
12 cracks from going all the way through the wall.

13 MEMBER KRESS: Yes, it's conservative to  
14 not --

15 MR. KIRK: Yes, indeed. It's conservative  
16 to not put it in.

17 MR. MAYFIELD: Let me add one other  
18 consideration. As Mark noted, these were idealized  
19 transients. And the concern was that the operator  
20 might intervene, particularly when you've got primary  
21 fluid escaping somehow through a break or whatever.  
22 The operator might intervene, isolate the break and  
23 then a lot of the system would tend to repressurize  
24 which negates the warm prestressing effect.

25 The one thing that we've done that I think

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1 is a significant improvement now is to bring in  
2 operator actions explicitly. So now you can go back  
3 and within the vagaries of that analysis. You can now  
4 go back and include whether you will or won't  
5 repressurize the system. Before, with the idealized  
6 transients, without really having something you could  
7 track, it just didn't seem to be a good idea to  
8 include warm prestress.

9 MR. KIRK: Are there any more questions  
10 regarding the technical part of the presentation?

11 (Slide change.)

12 MR. KIRK: Okay, then to summarize and of  
13 course, the Committee is, as always, free to draw its  
14 own conclusions. We believe that the NRC research  
15 programs have established both the calculational  
16 methodologies and the empirical data needed to enable  
17 our assessments of RPV fracture resistance for both  
18 routine loading conditions and most importantly, in  
19 this context, accident conditions using LEFM.

20 We have shown that LEFM predictions of  
21 both crack initiation and crack arrest and of course  
22 the combination of them would leave to vessel failure  
23 or not agree well with the results of prototypic large  
24 scale RPV experiments and consequently suggest that  
25 LEFM is indeed an appropriate methodology for use in

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1 assessments of RPV fracture resistance.

2 (Slide change.)

3 MR. KIRK: The logical conclusion from  
4 that is to turn off the funding spigot. However, in  
5 our day to day operations the staff is routinely  
6 motivated to take this yet a bit further. We've got -  
7 - there are both regulatory and commercial motivations  
8 to not stop here.

9 On the regulatory side, the licensees are  
10 now fairly routinely making exemption requests to our  
11 current LEFM based methodologies and they're even  
12 queuing up to make exemption requests to a modified  
13 PTS rule that we haven't even got in place yet. We  
14 have no systematic way to deal with those. The  
15 easiest example which I think several members of the  
16 Committee are familiar with is the licensees have  
17 routinely come in with request to use the master curve  
18 which is an EPFM based methodology. Right now, we're  
19 dealing with that on a case by case basis and right  
20 now we don't really have any systematic way in place  
21 to assess the appropriateness of those applications --

22 MEMBER ROSEN: What's their underlying  
23 motivation?

24 MR. KIRK: Their underlying motivation is  
25 down in the bottom, is that in a deregulated -- or

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1 rather, in a regulated energy environment, they were  
2 paid on a dollar per kilowatt hour basis. They were  
3 paid based on capacity. So they had a plan sitting  
4 there. They were paid based on whether they could  
5 generate.

6 Now they're in competition with everybody  
7 else, so they're motivated to do things with their  
8 reactors that they never would before. For example,  
9 one of the things that we said on Wednesday, 10 CFR  
10 50.61 says that if you're in danger of crossing the  
11 line for the PTS rule, you're obligated to install  
12 flux reduction which reduces the number of neutrons  
13 going through the steel, reduces the embrittlement  
14 rate.

15 Lots and lots of plants have flux  
16 reduction. Of course, you pay a penalty for that in  
17 production. The Beaver Valley nuclear plant which is,  
18 I believe, per current regulations, .5 degree  
19 Fahrenheit from the current screening limit, has flux  
20 reduction in place, but believes, based on the use of  
21 new technologies, namely the master curve, that they  
22 can justify removal of that flux production, increase  
23 their productivity, increase their profitability and  
24 still stay below the regulatory screening limits.  
25 Removing flux reduction is simply something that

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1 nobody would ever have thought of or even considering  
2 putting up NRR in a regulated environment. Also,  
3 other motivators are that some plants that aren't as  
4 close to the line as .5 degrees Fahrenheit, have to  
5 make significant economic decisions like whether to  
6 replace the steam generators. In order to make that  
7 economically feasible, they have to show to their  
8 business people that those, the cost of those  
9 generators can be amortized over 20 to 30 years. If  
10 you've got a plant that's sitting within 5 degrees  
11 Fahrenheit of the current screening limit which some  
12 are, and they need to buy a new steam generator, and  
13 they've only got 10 years left in their current  
14 license, the business people will say unless you can  
15 show us that we're not at risk at bumping up against  
16 this thing that we understand is called the PTS Rule,  
17 we're going to shut you down. So they have  
18 significant economic motivation to use available  
19 technology which right now we've done and this gets  
20 over to our activities. The gentlemen who have been  
21 so helpful in making this presentation have been  
22 contractors for us for years, developing elastic  
23 plastic fracture mechanics methodologies.

24 We right now have on the shelf, I'd say  
25 probably 85 to 90 percent of the research that's

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1 needed to have a systematic elastic plastic fracture  
2 mechanics evaluation methodology. What we're engaged  
3 in right now in the current HSST project is what we've  
4 called FAVOR<sup>EP</sup> development which simply means an  
5 elastic plastic version of FAVOR which would enable  
6 what when in place will enable the staff to do  
7 systematic and rigorous reviews of licensees' requests  
8 that right now --

9 MEMBER POWERS: Can I ask the question?  
10 If the economic incentive all lies on the part of the  
11 industry, why don't they pay for this next 10 percent  
12 that has to be done? You said you had 80 to 90  
13 percent. Why don't they pay for the 10 to 20 percent?

14 MR. KIRK: Taking it from the industry's  
15 perspective which --

16 MR. MAYFIELD: Let's not speak for the  
17 industry.

18 MR. KIRK: Okay.

19 MR. MAYFIELD: Okay?

20 MR. KIRK: Okay.

21 MR. MAYFIELD: The reason the staff does  
22 these things is to provide the staff an independent  
23 capability to perform these kinds of analyses. And  
24 mixing the industry perspective in with this, to take  
25 money from their pocket or to take their code gets to

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1 be problematic because we still need an independent  
2 capability. This is an area where the staff does have  
3 significant expertise through staff capabilities and  
4 contractor capabilities.

5 We routinely go through this and ask  
6 ourselves the same question, when is enough enough?  
7 We believe that this next piece is justified and  
8 supportable and to support staff capabilities.

9 MEMBER POWERS: Believe it or not, so do  
10 I.

11 MR. MAYFIELD: But that's the why. We  
12 think that's something the staff needs to do.

13 One other point I'd like to make as we  
14 close, Dana, is that we've talked a number of times  
15 and you and I have had some enjoyable banter about  
16 whether we should or shouldn't continue this program.  
17 The fact is the budget for pressure vessel related  
18 activities has declined significantly over the years.  
19 We can agree or agree to disagree on whether it's gone  
20 low enough, but the fact that when we were doing the  
21 kinds of large scale experiments that have been  
22 discussed this morning, we were up what \$7 or \$8  
23 million for the combined pressure vessel testing and  
24 embrittlement activities. That has declined  
25 significantly. We can certainly provide the Committee

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1 or come back and talk to you about what that's looked  
2 like over the last few years, if you're interested.  
3 But I wouldn't want to leave the impression that the  
4 funding level today is anywhere near where it was in  
5 the 1980s when we were doing this kind of work, 1970s  
6 and 1980s.

7 MEMBER FORD: Are there any other last  
8 minute questions? Mark and --

9 MEMBER SIEBER: Yes, I'm curious about one  
10 thing you said when you were discussing the economics  
11 of flux reduction. Flux reduction is a low leakage  
12 loading pattern which basically has a peak to average  
13 that's pretty substantial. The hot fuel is in the  
14 middle of the core and thrice burned fuel is on the  
15 outside edge. And that gives you less fluence to the  
16 vessel walls.

17 When you say there's an economic incentive  
18 to abandon that kind of loading pattern, I presume  
19 that what you're saying is if you want to do a power  
20 uprate, you would try to flatten the flux which would  
21 place fresh assemblies more on the outside. That has  
22 a fuel cost penalty. It does have a rating advantage.

23 Is that basically what you were saying?

24 MR. KIRK: Yes, that's it and to be fair,  
25 in discussions I've had with various licensees,

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1 different operations seem to take a different view of  
2 whether flux reduction is an economic penalty or not.  
3 Certainly, some plans do, but to be fair, we should  
4 also say that other plans don't.

5 MEMBER SIEBER: Well, at the current  
6 license power at Beaver Valley, it can run 100 percent  
7 power with a flux reduction core. And a flux  
8 reduction core is cheaper from the standpoint of  
9 dollars spent than one that has flux flattening.

10 I used to be the fuel guy there.

11 MEMBER FORD: Before handing it back to  
12 you, George, I'd like to thank very much everybody for  
13 coming and we have been informed and I really  
14 appreciate it. Thank you.

15 CHAIRMAN APOSTOLAKIS: Thank you, Peter.

16 We'll recess until 10:35.

17 (Off the record.)

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This is to certify that the attached proceedings before the United States Nuclear Regulatory Commission in the matter of:

Name of Proceeding: 494<sup>th</sup> Meeting Advisory  
Committee on Reactor  
Safeguards Materials

Docket Number: N/A

Location: Rockville, Maryland

were held as herein appears, and that this is the original transcript thereof for the file of the United States Nuclear Regulatory Commission taken by me and, thereafter reduced to typewriting by me or under the direction of the court reporting company, and that the transcript is a true and accurate record of the foregoing proceedings.

  
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