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NUCLEAR REGULATORY COMMISSION

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ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

(ACRS)

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MATERIALS SUBCOMMITTEE

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THURSDAY

AUGUST 21, 2014

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ROCKVILLE, MARYLAND

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The Subcommittee met at the Nuclear Regulatory Commission, Two White Flint North, Room T2B1, 11545 Rockville Pike, at 1:30 p.m., Ronald G. Ballinger, Chairman, presiding.

COMMITTEE MEMBERS:

RONALD G. BALLINGER, Subcommittee Chairman

DENNIS C. BLEY, Member

JOY REMPE, Member

PETER C. RICCARDELLA, Member

STEPHEN P. SCHULTZ, Member

GORDON R. SKILLMAN, Member

JOHN W. STETKAR, Member

ACRS CONSULTANT:

WILLIAM SHACK

DESIGNATED FEDERAL OFFICIAL:

CHRISTOPHER L. BROWN

ALSO PRESENT:

KENSAKU ARAI, Nuclear Regulation Authority Team

B. RICHARD BASS, ORNL

MICHAEL BENSON, RES

MICHAEL CASE, RES

TERRY DICKSON, ORNL

AMY FREED, Westinghouse

ERIC FOCHT, RES

RON GAMBLE, Sartrex Corporation

ROBERT HARDIES, NRR

ALSO PRESENT (CONTINUED)

TIM HARDIN, EPRI
MARK KIRK, RES
MARVIN LEWIS*
JAMES MEDOFF, NRR
SEUNG MIN, NRR
MARTHA MITCHELL, NRO
NATHAN PALM, EPRI
JEFF POEHLER, NRR
STACEY ROSENBERG, NRR
DAVE RUDLAND, RES
SIMON SHENG, NRR
PETER SNYDER, NRR
GARY STEVENS, NRR
BRIAN THOMAS, RES
ROB TREGONING, RES
ANEES UDYAWAR, Westinghouse

*Present via telephone

C-O-N-T-E-N-T-S

P R O C E E D I N G S

1:29 p.m.

CHAIRMAN BALLINGER: (presiding) Okay, can the meeting come to order, please?

This is a meeting of the Metallurgy and Reactor Fuel Subcommittee. I am Ron Ballinger, Chairman of the Subcommittee.

ACRS members in attendance are Pete Riccardella, Stephen Schultz, Dick Skillman, Dennis Bley, John Stetkar, Joy Rempe, and the August Mr. Bill Shack, Consultant.

Christopher Brown is the ACRS staff, Designated Federal Official for this meeting.

The purpose of this meeting is to receive a briefing from the staff on bifurcation -- I thought that was a medical term -- but, anyway, bifurcation of 10 CFR 50, Appendices G and H, rulemaking, and 10 CFR 50, Appendix G, research efforts, probabilistic evaluation of normal operations.

The Subcommittee will gather information, analyze relevant issues and facts, and formulate the position and action as appropriate for deliberation by the full Committee in September, on September 4th.

You didn't put that on there? We are not doing that? We are not doing anything.

(Laughter.)

Deliberate, okay.

The rules for participation in today's meeting have been announced as part of the notice of this meeting and previously published in The Federal Register on July 23rd, 2014. Is that true? Uh-hum. Okay.

A transcript of the meeting is being kept and will be made available as stated in The Federal Register notice. It is requested that speakers first identify themselves and speak with sufficient clarity and volume so they can be readily heard. Also, silence all iPhones and other electronic devices.

We have not received any request from members of the public to make oral statements or written comments.

There is a bridge line set up which will be in listen mode only, opened toward the end of the meeting.

We will now proceed with the meeting, and we call on Mike Case to give a brief introduction and introduce the presenters.

MR. CASE: Good afternoon, everyone. Thanks for the opportunity.

I am Mike Case. I am the Director of the

Division of Engineering in the Office of Research, at least for a few more days. I will be moving down into another office in Research, down to DSA.

Sometimes it is good to start with the obvious, as I call it. And so, I wanted to talk about the reactor pressure vessel, and it is big. It is expensive. It is difficult to replace. It grows old. And next to the cooling tower and maybe Homer Simpson, it is one of the most recognized iconic symbols of a nuclear power plant. And finally, it is very important to safety.

And so, given all those factors, what you find is that reactor pressure vessel issues have a lot of what I call emotional components. And what that means is, if there is an issue with the reactor pressure vessel, it is probably going to appear to be ten times to a hundred times worse to the general public.

So, when we reflect upon that -- and the Strategic Plan actually says this a lot more eloquently -- probably what my strategy is for the RPV is I don't want any problems to find me. And so, what that means is that I need to be out ahead of potential problems with the reactor pressure vessel. And so, that puts a lot more emphasis, I think, on research activities.

And so, the agency has actually been pretty good in the research area with reactor pressure vessels way back into the Tom Merliton days, and probably prior to that. So, we have always had a robust program. So, for the five or six years that I have been in Engineering, we have had a relatively-robust program in that area. You know, it probably averages about a million dollars a year, which is, if you look at that on the spreadsheet, that is probably a big program in the research area.

And Mark is probably wondering where his million dollars is. With sequestration and other budget restrictions recently, it is probably less than that now. But it is still a pretty robust program.

In many respects, it is like the steam generators, which is another component that has the same type of imprint to it, in that I don't have a problem spending money in order to make sure that problems don't occur.

And I really respect the NRR for having the wisdom to allow us to do that. But it is not sufficient just to build models about the reactor pressure vessel. It is how do you take that knowledge and how do you translate it into regulations or regulatory guidance, so that we can accumulate the safety value of the knowledge that we have gained and really, once we get it into one of those processes, it starts to engage the public and we start to build some of that confidence in the regulations that we have out there for this important component. So, it is good that we are hearing about reactor pressure vessel research today in the context of two rulemakings, you know, Appendix H and Appendix G.

And then, finally, of course, we need your help. So, when you are working out ahead of problems, what you find is that what we want to produce in these rulemakings is largely based on the technical expertise that is presented in the rule. So, there is not operating experience with the budget problems that helps us move these regulatory products forward. It is really the strength of the technical credibility of what is being presented.

So, it is very important that our rulemakings and our guidance is based on good technical information. And that is really your role. You can help us make sure that we don't have gaps in our thoughts.

So, once again, I appreciate the help that you are going to give us today. And I think I am turning it over to Bob, right?

MR. HARDIES: Sure. Thanks, Mike.

For the record, I'm wondering where my million dollars is, too.

(Laughter.)

I am Bob Hardies. I am going to talk about bifurcation. That joke wasn't lost on me, whoever did that. And also, I am going to introduce Mark. After I introduce him, I am going to move out of the line of fire and allow him to go.

But I am going to cover bifurcation. To get to the end before I even begin, we did ask the Commission to direct us to proceed with rulemaking on Appendix H, and they did vote and decide to direct us to proceed with rulemaking on Appendix H.

And I was going to brief you on the memo that we sent them. You have got the memo and have seen it. And now you know the result of it.

I am going to start here with Title 10 of the Code of Federal Regulations in Appendix A and General Design Criteria 31, which says that the reactor coolant pressure boundary needs to be designed in a manner, so that when it is stressed under operating testing or maintenance or accident loads, that it doesn't behave in a non-brittle manner.

It also states that the probability of

rapidly propagating fractures shall be minimized. And it tells you to consider material properties, flaws, and stress, which means fracture mechanics. And then, it also tells you to consider irradiation.

And steel exhibits this ductile to brittle transition behavior. So, that needs to be managed. The way we accommodate General Design Criteria in 31 is through Appendix G of 10 CFR 50. And it basically provides the fracture toughness requirements for operating and hydrotesting, and by operating, it includes anticipated events. And it makes you limit the stored elastic strain energy in the reactor vessel, depending on how the reactor vessel fracture behavior is.

So, when it has got behavior that doesn't absorb much energy during fracture, you can't store much elastic energy in the vessel wall. And when the vessel is hot and tough and fracture behavior is such that it would absorb a lot of energy, you can store a lot more elastic energy in the reactor pressure wall. The only source of that elastic stress strain energy is pressure.

So, you end up getting a cookbook in Appendix G that correlates maximum allowable pressure with temperature where the transition toughness is what indexes that.

Criterion 31 also says you have to address irradiation. And the way we address irradiation is we index these pressure temperature limit curves in accordance with how much fluence went through the vessel, and those correlations come from shifts in Sharpe behavior from lots and lots of specimens, from lots of different materials irradiated to lots of fluences. And they are correlated with material chemistry and fluence and toughness shift. Those specimens come from the Appendix H programs and reactor vessel surveillance programs. They are all agglomerated and evaluated to create Regulatory Guide 199.

The Appendix H establishes surveillance programs for reactor pressure vessels. And it kind of does two things. It tells you what you have to have in a program, what kind of materials need to be there, what kind of specimens, how many specimens, how many capsules. So, it is the beginning of a surveillance program before a vessel starts up, and, then, an implementation phase. Once you have a vessel running, you occasionally pull a capsule, tear it open, and it tells you what temperatures to test, you know, to do the testing at. It tells you to keep broken specimens for later use.

And you learn things when you pull a surveillance capsule about irradiation of the vessel and about its embrittlement state that make you decide to change the order or the interval between the next withdrawal. So, part of Appendix H is evaluating changes to the withdraw schedule.

The way Appendix H tells you to do a surveillance program, it implements ASTM E185, the American Society for Testing of Materials Standard E185, which is surveillance programs.

The design portion of the surveillance program E185, it is done once for a vessel. It is done when the vessel is -- I am going to find this, unless it is gone. It is done, before the vessel shows up onsite, the design is done.

So, the current version of Appendix H directs plants to use the 1973, 1979, or 1982 version of ASTM E185. All operating vessels, their surveillance programs meet those additions of E185, including the ones that are being built now that are being ordered. They are ordered to have a surveillance program design that matches ASTM E185, the 1982 version.

And what we want to do when we update

Appendix H is update the allowable versions. So, for design of programs, it wouldn't apply to any vessels that exist right now or that are being built right now, because it only applies when you order a new vessel. So, this change won't impact any operating vessel for the design of the program.

For the conduct of the program, testing standards change; testing technology changes. I know since ASTM E185 '82 was developed, a lot of test standards have changed. I know that because, since then, Mark Kirk graduated from high school, went to college, graduated from college, and had a big, long career where he changed some test standards.

In 2002, ASTM split E185 into a design standard and a program conduct standard. The design standard, as I said, would only apply to future vessels. The conduct standard provides current testing techniques for people who are running operating plants, and to update it by 32 years of progress and standards technology is an appropriate thing to do.

There's a couple of other things this change would accomplish. The new version of E185 requires fracture toughness, specimens to be put into programs. All the new vessels, the new reactors are installing them anyway. They are doing it at their option, but they wouldn't be required to under the --

MEMBER RICCARDELLA: In addition to Sharpe or --

MR. HARDIES: Yes, in addition to Sharpe, both Sharpe and toughness specimens.

Also, E185 has you do a capsule very early in life, and we wouldn't do that now. We know a lot more about material radiation behavior. And frankly, it is a waste of money, a waste of time, a waste of resources, and a waste of radiation dose to workers to have them pull a capsule after one cycle with the modern steels.

MEMBER SKILLMAN: Was there any benefit to a low-fluence capsule?

MR. HARDIES: Early on, if you go back to the sixties and seventies when irradiation behavior wasn't so well-known or understood, any irradiation information was fickle.

MEMBER SKILLMAN: Today you are saying it has been overtaken by events? It really is not a value-added feature?

MR. HARDIES: Right.

MEMBER SKILLMAN: I understand. Okay. Thanks. Thank you.

MR. HARDIES: E2215, which is the one for conduct of programs, provides some guidance on how to take a program that is for a vessel that was originally designed to have a 40-year surveillance program, and it provides guidance on how to change it to a 60-year or an 80-year program. And that is useful guidance.

And finally, E185 has eliminated the need to include heat-affected zone specimens, and they don't provide very much useful information. I think we are going to consider eliminating the requirement for existing programs to test those specimens when we change Appendix H.

Also, that first line up there, we would like to be clever in how we do Appendix H, so that we can actually get future changes to the ASTM standard edition accomplished by changing 50.55(a), which is the codes and standards rule, rather than having to wait 30 years, in 30-year chunks, to try changing Appendix H.

The last thing I want to bring up is there is a requirement, once you pull a capsule, to test it within 12 months. In the seventies, some plants would leave them in the pool for a while. There was some urgency to get data because it wasn't well understood. The radiation happened a little quicker than had been anticipated. And so, it was put in the rule, this

12-month requirement.

There is now enough information that we don't really need people to provide the information within 12 months. And there are very good reasons why 12 months is too short of a time. There's contracting difficulties. There's more players involved in the handling of a capsule now. And some of these capsules have much higher fluence, and they have to sit in the pool and decay a little bit, so that the shipping containers have adequately-low dose rates to meet Department of Transportation external surface dose measurements.

So, the industry has asked us to extend this. They send us extension requests. We review them. We grant them. And all of that involves resources that are better spent on higher-priority things.

Appendix G and Appendix H were bundled several years ago. When they are bundled, the staff can do a prioritization of rulemaking. The staff did and prioritized it high and began working on them.

Appendix G you are going to hear about. This technical basis isn't ready, but it has been 32 years since last time the ASTM standard -- or it is 32 years out of date. So, we wanted to proceed with rulemaking on Appendix H. Mike Case talked us into it.

And so, the way you do that is you ask the Commission to direct you to do that. We did; they did. And so, we are going to proceed on rulemaking. That is the end of the bifurcation problems. I can retire.

And I have covered most of the next one because -- if I go the right direction -- we know what Appendix G is now. We have covered all of this.

And I am going to go to General Design Criteria 31 again and note that the second criteria it said was that you minimize the probability of rapidly-propagating fracture. In the middle of the nineties to the middle to late 2000s, NRR asked Research to do some probabilistic fracture mechanics analysis of pressured thermal shock events. They did. They developed the FAVOR code. Mark will go into that a lot today. And it was used to develop the technical basis for issuing the alternate PTS rule.

Near the end of that it became apparent to us that we could apply that same methodology for other reactor vessel integrity issues or subjects, like heatup and cooldown. So, NRR wrote a user need and asked Research to evaluate Appendix G, evaluate risk-informing Appendix G.

And Research developed a modification to the FAVOR code. Industry has been a partner on reactor vessel integrity research or a collaborator for many years, and they took the FAVOR code and did enough analyses to come up with a risk-informed alternative to Appendix G that was published in MRP-250, which is the Materials Reliability Program, Report 250.

And that was incorporated into the ASME code in 2011 as an alternative to the Appendix G that is in the ASME code. At that point we needed to do confirmatory research. So, Research looked at it and evaluated it, and the failure frequencies of the risk-informed approach were higher than we expected, higher than Research expected, higher than anyone expected.

The failure frequencies for the current Appendix G were higher than anyone expected, and the risk was coming from small flaws rather than the large flaws, which is very counterintuitive. A big flaw in a stress structure should, of course, be more risky than a little, tiny flaw in a stress structure. And because it was counterintuitive, we have been pouring some work to understanding the results, and that is where we are now.

We did do enough of a scoping study to determine there is no immediate safety issue, no immediate need to have plants change the way they are operating, and we are working to understand the results. In the meantime, Appendix G is kind of on hold.

At that point, I am going to turn it over to Mark Kirk, who will describe the results in much more detail.

MR. KIRK: Are there any questions at this point before Bob gets away?

Thank you.

Okay. So, the next part of the briefing concerns the research efforts that Bob alluded to. We started in 2007 looking at Appendix G requirements for normal operation. I am the sole guy who is sitting up here, which means that I was not clever enough to walk away.

But there are many other contributory or guilty parties, depending on how you like to talk about it. I think all of them are in the room today, all except for Paul Williams. Gary Stevens, Eric Focht, Mike Benson, who many of you on ACRS. He used to work here. He is now a pleasure working with us. And John Kusnick. And then, at Oak Ridge, of course, Terry Dickson, Richard Bass, and Paul Williams as developers of the FAVOR code.

So, as an outline of what I would like to cover in the next several hours is give you a little bit of background and objective. Bob has started that on the Appendix G project in general.

And for those of you who didn't suffer through the alternative PTS rule, Bill can take a break at that point. We will talk a little bit about the probabilistic fracture mechanics code FAVOR, which is going to be our primary tool in doing this assessment.

I will, then, talk about what were identified on your agenda as Technical Issues 1 and 2 together, this being the shallow interdiameter surface-breaking falls in the context of the FAVOR cladding model.

And then, I think there is probably a much-needed break, at least I hope.

And then, we will talk about Technical Issue No. 3, which is boiling water reactor leak test. I should say, as Bob has already alluded to, the main focus of this presentation is to describe to you, and hopefully, get your good comments and feedback on this question of shallow surface breaking falls in the cladding, because that is really the thing that is driving our results. Everything else is a sideshow after that.

So, the discussion of the boiling water reactor leak test is but one example of the challenges that are presented when we consider this particular class of flaws.

In case I drift off into geek-speak, you have a secret decoder ring sitting at your pillow-side. We talk about conditional probabilities of crack initiation and failure. Those are probabilities calculated by FAVOR, conditioned on the loading event actually having occurred.

If you were to, then, weight them in terms of the probability of that loading event having occurred, they would become the through-wall cracking frequency.

P-T, of course, means pressure temperature limits, as calculated by the ASME code. And then, there are two subsets of those. ASME current means P-T limits calculated, I will say, the way we have always done; whereas, the risk-informed alternative is the new proposed way. It was developed in MRP-250 and codified in the 2011 version of the code. And I will have a graphic that explains better, I hope, what the differences between those two limits are.

So, a little bit of background on the Appendix G project. Bob covered most of this. We were requested to look at this in 2007 by our colleagues in NRR.

What we are looking at in total are all the provisions of 10 CFR 50, Appendix G, which incorporates ASME Section 100, Appendix G, by reference. So, that effectively makes ASME Section 11, Appendix G, part of federal law unless conditioned or excluded by 10 CFR 5055(a). And hopefully, that is the end of the legalistic-type comments I have to make.

The joint provisions of what I will abbreviate is Code of Federal Regulations G and ASME, Appendix G. I don't know how they both became G.

MEMBER RICCARDELLA: That was intentional.

(Laughter.)

MR. KIRK: Okay.

MEMBER RICCARDELLA: To avoid confusion.

(Laughter.)

MR. KIRK: I have learned something. Our pressure temperature limits for normal operation, which include normal heatup, cooldown, and leak test, and that is where we are going to be focused on today. That is the discussion.

However, the totality of this project, which hopefully we will get another chance to talk this

Committee on, includes other requirements like minimum temperature requirements of the flange, limits on Sharpe upper shelf, and so on.

In the fullness of time, once we get this detail wrung out, our project addresses all of these. And hopefully, we will be talking to you about them at some future date.

So, again, the risk-informed alternative was developed by the industry and documented in a Technical Report published in 2009. The industry was using the FAVOR model as its representation of the reactor pressure vessel. So, very similar to our assessment approach.

In 2011, those recommendations were adopted by the ASME code. And now, what we are talking today at least in part is the staff's evaluation of some of those recommendations.

Again, I said this. We are focusing on the part of the model that is the most important, where "most important" means giving us the highest-calculated failure probabilities. And we are using operating pressure leak tests as just one example of the impact of the shallow through-cladding falls and, also, to give you a comparison of the current provisions of ASME to risk-informed ASME.

So, finally, a graph, thank goodness. So, our evaluation approach to P-T limits, our model of the RPV is the probabilistic fracture mechanics code FAVOR, which stands for Fracture Analysis of Vessels, Oak Ridge.

This is the same code, well, I should say this is the same code that was used, reviewed and approved for use in the PTS re-evaluation effort that eventually gave rise to 10 CFR 50.61(a). It has since been augmented. At the time of the PTS re-evaluation, which was mid-2000s, it only dealt with cooldowns. Now it has been augmented to address heatups, and it has also been augmented to address boiling water reactors, which, of course, have a different radius-to-thickness ratio than Ps. So, we needed to include other influence calculations. But, basically, the failure model, the same ideas hold.

So, our weighting conditions are twofold, and I think that is shown by illustration. Let's just focus on the cooldown. So, following the ASME Appendix G limits, you are allowed to have a cooldown up to 100 degrees Fahrenheit per hour. And then, you plug that temperature and time into the ASME equations, which have a structural factor on the membrane load and assume a quarter t flaw. And that allows you to calculate the maximum allowable pressure as a function of time.

And this diagram illustrates the effect of the risk-informed alternative that is now itself part of the ASME code, which is -- I will leave out the mathematics. That is in the reports, if you are interested. But the net effect of the risk-informed revision or alternative relative to current practice is it requires a drop from full operating pressure at an earlier in transient, but allows higher pressures at the end of the transient. Obviously, at the end of the cooldown, you need to be down to atmospheric pressure. You are going to have a hard time unbolting the head. These changes were of interest to the industry in terms of increasing operability.

What we are doing in this analysis is our loading follows these P-T limits, as established by the Code of Federal Regulations and ASME Appendix G. So, when I talk about an assessment of the current approach or the risk-informed approach, that is something that is dropping at a linear cooling rate and is following this pressure curve.

This is something we recognized at the beginning, and you will see it a little bit later. If we overlay on these graphs an actual operational cooldown or heatup, you will find out they don't hug the curve. They don't really come anywhere close to it, except down here in the low temperature regime, but they are also protected by LTOP in that regime.

So, we recognized that following these limit curves was a conservative approach. But we did it for two reasons. One was we believed, based on the rather large changes that we were able to adopt in the PTS embrittlement limits, and since these are much less-aggressive transients than anything in PTS, we thought, well, we can have this small amount of conservatism in there. Well, I shouldn't say "small". We can have this conservatism in there without unduly affecting the practicality of our results.

And also, it is kind of logical in that, if we are evaluating, what we wanted to do is to evaluate a change from the current approach to the risk-informed approach, it is kind of natural I think to evaluate cooldowns along the limits that are permitted by those two approaches.

Also, I will note this is exactly the same approach that was used by the industry in its evaluation. They again assumed cooldowns or heatups along these limits curves.

What we found out is things are a little bit more complicated than that. Following this approach, we got, as Bob alluded to, higher CPIs and CPFs than expected. And so, one of the things we will share with you today is also a modeling of cooldowns along actual and plant procedural loadings. So, you can see the effect of following something closer to what really happens versus that which is allowed.

MEMBER RICCARDELLA: Mark, a couple of questions.

MR. KIRK: Yes.

MEMBER RICCARDELLA: Refresh my memory on LTOP.

MR. KIRK: The LTOP requirement is that there be systems in place to ensure that the P-T limits are respected. So, the words say you need to stay below the curve.

Now you are more familiar with the actual implementation of that than I am. You need to account for valve errors and all sorts of things. So, the actual setpoints may be considerably lower than the P-T limits curve, especially in a single setpoint valve.

But the only written requirement that gets weaved into the regulation is you just need to have a physical system there to make sure that these curves are respected.

MEMBER RICCARDELLA: LTOP is Low

Temperature over Pressure Protection?

MR. KIRK: Right.

MEMBER RICCARDELLA: Right?

MR. KIRK: So, there is generally an LTOP-enabled temperature that says you have to turn on that system once your RCS temperature goes below a certain value.

MEMBER RICCARDELLA: And did you say that when the industry did their analysis for the risk-informed approach, they used FAVOR as well?

MR. KIRK: They used FAVOR, yes. So, we are both using the same computational model. The only significant difference is in our assumptions about the flaw population.

In the industry approach, they used the population of embedded flaws. They only used the population of embedded flaws that was developed as part of the PTS reevaluation project. So, that is lots and lots, in any given simulated thousands of rather smallish flows, but none of them breaking the surface of the vessel, all of them fully embedded in the ferritic steel.

In our assessment, we wanted to stay completely consistent with the PTS evaluation. So, we did that population of embedded flaws and, also, this population of shallow-surface breaking flaws, which we will be discussing in detail.

CONSULTANT SHACK: And both of those populations come from 6817?

MR. KIRK: Correct. Those are both --

CONSULTANT SHACK: That hasn't changed?

MR. KIRK: No. No. And 6817, for those of you that don't know, is the basis document developed for us by PNNL with advice from an international panel of experts as to what should be in those flaw distributions. And I will talk a little bit about that.

MEMBER BLEY: Mark, before you go ahead, you don't have to answer me now, but when you talk about favor, a couple of things I would like you to try to point out as you go through it.

My familiarity with that dates back to when the PTS work was going on, and I was involved in some of the work on human modeling --

MR. KIRK: Uh-hum.

MEMBER BLEY: -- and on the thermohydraulics.

MR. KIRK: Right.

MEMBER BLEY: FAVOR was being developed to support that work --

MR. KIRK: Right.

MEMBER BLEY: -- or modified.

MR. KIRK: Right.

MEMBER BLEY: And I remember one thing that troubled me a little bit at the time, and it was what seemed to be a real strong sensitivity to what appeared to be minor changes in timing or temperature that led to very wildly-different predictions of the likelihood of failure.

And the other thing I don't remember seeing addressed was uncertainties in -- I think with respect to flaws you think you are taking a conservative position, as I am looking at the uncertainties in that. Correct me if I am wrong on that.

And then, kind of associated with what seems to be a sensitivity to small changes would be, is there any approach to try to deal with the uncertainties that are within the model as the development continues and to the point it is now?

So, if you can address those as you go forward or --

MR. KIRK: Okay. I think I would like to take them on now because --

MEMBER BLEY: Okay.

MR. KIRK: -- otherwise I am likely to

forget them.

And I am not sure exactly what you are referring to, if it came out of the HRA, or whatever. In terms of sensitivities to small changes, in some cases they exist. I will say I have personally wrung it out enough in my mind to say they are in an errant part of the model and, moreover, they are accurate.

MEMBER BLEY: Okay, that is what I was getting at.

CONSULTANT SHACK: There are more of them today.

MR. KIRK: And you will see even more of them. I will highlight one example of that today, based on that.

In terms of the uncertainties, what we have done is -- well, we will talk about the flaw model as an example. The flaw model was developed -- I am going to try to go ahead to a slide, so I have something meaningful to talk to.

I don't know where it is. There it is. I am on slide 33, and we will go back to it.

The flaw model was developed based on a number of different inputs, destructive and non-destructive evaluation of the sections taken from the PV rub vessel, welding simulations using the

PRODIGAL code, some exams done at Bettis Laboratories, and expert elicitation done by Debbie Jackson and Lee Abramson in the early 2000s.

All of that got mushed together into what Bill was referring to, which is NUREG/CR-6817, which gives the model to be used in FAVOR. Now we are focusing on the shallow cladding flaws here, but this accounts probabilistically for distributions in-depth, aspect ratio, flaw size, and so on.

As we went through this, there was an attempt to be -- if this doesn't make your head hurt -- both realistic and conservative at the same time, which is to say, if we felt like we had good information, we tried to be realistic and sample against it. However, when we ran up against situations, as you inevitably do, where there wasn't adequate information, we tried to be conservative.

The net effect of this, again, using flaws as an example, is in any given vessel that is simulated in FAVOR, it is simulated to have thousands of embedded flaws. However, when you go out and do a vessel exam -- and I will use my most current reference, which is the exam of the Palisades vessel, which was just submitted to the staff for review under 5061(a), I don't have the exact count in my head, but they didn't find thousands of flaws in or near their beltline welds. They found more like dozens.

So, that is one example of where the process we went through trying to be both realistic and conservative, if you bounce it up against a datapoint from an actual operating plant, you get a sense of where we are.

There are lots of other areas in the model where uncertainties, what I would say is uncertainties are dealt with everywhere in FAVOR. Each and every input, each and every submodel has been independent assessed for its uncertainties.

In some cases, like say the distribution of fracture toughness data, where the uncertainties were large and we just knew or we knew through sensitivity studies that they would be significant, they are explicitly modeled through statistical distributions --

MEMBER BLEY: For parameter uncertainties?

MR. KIRK: Those are parameter uncertainties.

MEMBER BLEY: Are there places where you have addressed any areas where you have uncertainty in the models, where you are not sure you have got the right model?

MR. KIRK: Not quantitatively.

MEMBER BLEY: Okay.

MR. KIRK: A good example of that would be the attenuation function through the vessel wall. We know there is a model uncertainty there. There are other models predicting many different things. We are using a conservative model.

MEMBER BLEY: Conservative in the sense of?

MR. KIRK: Conservative in that it doesn't attenuate as much as other models do.

MEMBER BLEY: Okay.

MR. KIRK: As I would think we --

MEMBER BLEY: This is like the other areas where you haven't directly addressed the uncertainty; you have tried to put some bound on it and be conservative?

MR. KIRK: Yes. Right.

MEMBER BLEY: Okay.

MR. KIRK: What I would say, we have looked under every rock and tried to do the best job possible. Where we can, we have incorporated it quantitatively in the model.

MEMBER BLEY: I think you are dealing with what I wanted. The first part at the time, I saw these sensitivities to small changes, nobody had a good answer to why things were jumping around.

MR. KIRK: Uh-hum.

MEMBER BLEY: But you have really dug into it, and you are pretty confident in the models now, that they are doing what you want them to do? There is not glitch in the code.

MR. KIRK: Right. As an example, I mean, just as one example -- we will get to Bill's example -- is the lower bound of the fracture toughness distribution, it has a zero percentile. And if you go to the physics of cleavage fracture, there is a zero percentile. You can get at that.

So, say you do an analysis at 10 EFPY. If all the KFY values are below that zero percentile, you have got zero failure probability. You rachet it up a little. You go from zero to 10 to the minus 9. That is still a small number, but it is a huge percentage change.

So, yes, there are -- I'll use Bob's words again -- there are bifurcations in the model, and we believe them to be real.

MEMBER RICCARDELLA: What about residual stresses? Are they in there deterministically or --

MR. KIRK: Residuals?

MEMBER RICCARDELLA: -- or are they --

MR. KIRK: Residual stresses are in there -- I don't like the word "deterministically". So, I am going to say there is one residual stress profile. It is not sampled.

MEMBER RICCARDELLA: That seems like a big uncertainty.

MR. KIRK: Yes.

MEMBER RICCARDELLA: In similarly, the clad to base metal residual stress?

MR. KIRK: Well, we will get to that. With regards to weld residual stresses, I mean, they have got to go through yield. It turns out in any of our analysis they haven't made a big difference in the calculated failure probabilities.

MEMBER RICCARDELLA: Well, you mean they have to go through YIELD? I mean, they are cross-weld heat-treated. They are less than YIELD, aren't they?

MR. KIRK: Yes, and that is what we are using in the model.

MEMBER RICCARDELLA: Okay.

MR. KIRK: In terms of the clad residual stresses, they are also tied up in the coefficient of thermal expansion mismatch.

MEMBER RICCARDELLA: Right.

MR. KIRK: That is a physical property. That doesn't vary much at all.

MEMBER RICCARDELLA: Oh, no, I will bet there is a big uncertainty in that. I know you took it from a test. You took data from a test of stress-free temperature.

MR. KIRK: Uh-hum.

MEMBER RICCARDELLA: But I will bet there is variability in that parameter.

MR. KIRK: I think we are maybe getting a little ahead of ourselves. In the PTS work we didn't focus a lot on the cladding model and the shallow flaws, simply because they didn't contribute a lot. You don't look too hard at things that don't contribute.

What we will get to here is we now understand much better why they didn't contribute in PTS, why they are contributing here. And so, the various aspects of that model are now being subjected to a lot more scrutiny along some of the lines you are getting at.

So, just a little history of FAVOR. It goes back quite a ways. The FAVOR code first was named FAVOR in 1995, but it finds its origins in PFM codes dating back to the integrated PTS studies of the eighties and Yankee Rowe of the 1990s. In the timeframe of 1999 to 2005, there were significant developments toward the PTS project; as I have tried to reflect, a very thorough evaluation of all models; coding for both aleatory and epistemic uncertainties, incorporation of warm pre-stress.

Since 2009, we have expanded it to address, as I said, BWRs and heatups. And 2012 is the most recent release, and I think you can expect to see another release in 2015.

In terms of review and V&V, again, throughout the PTS reevaluation project, it felt like every time I turned around there was a review. There were thorough internal reviews of the code and all its models, including those done by our colleagues in our industry. There were thorough reviews by this group. There was explicit V&V, as published in NUREG-1795, and there was also review by six external experts that we explicitly contracted with and paid to review our work. And that is all documented in Appendix B of NUREG-1806. And they found some things that they found lacking in the code, and we updated the code to address those things.

Since that time, since the expansion of FAVOR to address BWRs and heatup, it has again been

V&Ved by Southwest Research Institute. And also, I will just note in passing that, along the way, papers providing benchmarking of the K solutions to ABAQUS, which we consider the gold standard, have been published throughout the years to make sure those are correct.

Just a very high-level view of FAVOR, what we are going to be talking about mostly is what happens in the middle part, the FAVPFM or Probabilistic Fracture Mechanics module. There is also a load generator that puts the transients into FAVOR in a post-processor that multiplies them by event frequencies on the way out. But those two parts, by and large, were not used. Those were developed and are an inherent part of the PTS evaluation. They weren't really used here because on the front end, as I indicated, the loading follows the allowed P-T limit. So, it is a much simpler loading case than this library of cooldowns that we had for PTS.

And at the other end, there is no event frequency weighting. There could be. There might need to be. But that is not a part of the briefing today.

So, mostly, we are in the middle in the PFM module that, given a load input and embrittlement conditions with distributions, of course, and flaw conditions calculates conditional probabilities of crack initiation and conditional probabilities of vessel failure.

Just internally to the code -- and if people are interested in details, there are folks on the side who can do much better than me -- it is a pretty brute-force PFM code. There is no important sampling. It is just a Monte Carlo simulation inside a nested loop structure. So, on the outside we simulate RPVs. Then, we go through flaws, transients. We don't use that here because we have essentially got one transient to run. We go through the time of the transient. And then, at each time in the transient you are calculating, does the crack initiate, does the crack initiate, does the crack initiate?

If the crack initiates, then you run a simulation of does the crack arrest, does the crack arrest, does the crack arrest? At that time, if it arrests, you go back into the initiation loop and continue.

This diagram -- and again, we can get into whatever level of detail you want, but I have stripped out all the details -- shows you the major modules in FAVOR. There is a flaw distribution module, a neutronics model that does both the distribution of fluences around the vessel. I have taken account of the different distances from the core and, also, the extenuation through the vessel wall.

Then, you have got the crack initiation and through-wall cracking model, which addresses both crack arrest and the possibility of ligament failure by ductile overload.

We have already talked about uncertainties. In all cases we have looked at them. We have decided explicitly how to treat them. A lot of them are modeled explicitly, numerically. Some are represented as constants. In some cases, because we believe them to be less significant, like the vessel is imperfectly round. It is not the same radius all the way around. That is not modeled. It probably won't be modeled.

Conversely, the welding residual stresses are also modeled as a one-size-fits-all distribution. That might be modeled in the future. We will see.

And also, like I said, there are areas where, if we didn't feel like we had enough data to construct a credibility stochastic model, we adopted a conservatives model.

MEMBER BLEY: Thinking back to what you

showed us about the PTS runs and what you are doing here, in the PTS the plant is doing something. It puts you through a thermal cycle over time.

MR. KIRK: Right, right.

MEMBER BLEY: And you can see what is happening over time. Here you are using the pressure temperature limit curves.

MR. KIRK: Uh-hum.

MEMBER BLEY: Do you apply that instantly? Or it seems to me that what happens depends on rates in approaching and exceeding those curves. So, how do you handle that?

MR. KIRK: Well, we follow, in most of our analysis, we follow a linear ramp cooldown.

MEMBER BLEY: Okay.

MR. KIRK: A hundred degrees Fahrenheit per hour is the maximum allowed cooldown. We have also done 75 and 50.

MEMBER BLEY: Okay. So, that curve is on the linear --

MR. KIRK: Is accounted for, yes.

MEMBER BLEY: Okay. Fair enough.

MR. KIRK: Yes, yes.

MEMBER SKILLMAN: So, Mark, how do you handle the steamline break where you cool down much faster than 100 degree Fahrenheit an hour?

MR. KIRK: We cool down much faster than 100 degrees Fahrenheit per hour. But that is not a part of this analysis.

In PTS, we did steamline breaks. We did large-break LOCA, small-break LOCA, and in all cases I think we followed the advice of Dennis Bley.

MEMBER SKILLMAN: On some things.

MR. KIRK: On some things.

(Laughter.)

MEMBER SKILLMAN: But they also looked at you are injecting cold water. You get mixing. So, the thermohydraulics guys did a lot of analysis to see --

MR. KIRK: Right, right.

MEMBER SKILLMAN: -- if you get mixing. What if you don't get mixing? And each of those possible timelines got set over to the --

MR. KIRK: The transients for PTS, which included steamline break and many, many other things, were much more complex than what we are modeling here.

MEMBER SKILLMAN: I see. Thank you.

MR. KIRK: Yes.

MEMBER SKILLMAN: Thanks.

MEMBER BLEY: The last question along the line I started. It would seem to be in real-world transients that are driven not by a ramp, if you get arrest, it might be possible, if the transient changes nature, that you could reinitiate the crack.

MR. KIRK: Yes.

MEMBER BLEY: But here I don't think that arises, or does it?

MR. KIRK: It depends on, well, I have got one picture of a transient from a plant record, and it has got a repressurization. So, given adequate K, it could. I mean, that is not -- I am not sure I want to say it is typical or not. I am not plan ops guy.

But, yes, sometimes --

MEMBER BLEY: But it is primarily just run against assumed cooldown rates and --

MR. KIRK: Yes.

MEMBER BLEY: -- and heatup rates?

MR. KIRK: Yes.

MEMBER BLEY: Rather than looking at those kinds of situations that --

MR. KIRK: As I alluded to, our initial cut at this is we are going to do something simple and, admittedly, conservative or bounding. I realize those words have different interpretations to different people. So, I don't like to throw them around, but I do.

What we thought was we would do that and we would calculate probabilities that were very low, and it would be easy. It turns out for the shallow surface breaking flow we are not calculating that. So, we will kind of get onto that.

CONSULTANT SHACK: Are you going to tell us what you got when you did the whole distribution?

MR. KIRK: Uh-hum. Of embedded flaws?

CONSULTANT SHACK: Embedded.

MR. KIRK: Yes.

CONSULTANT SHACK: And surface-breaking flaws?

MR. KIRK: Right.

CONSULTANT SHACK: I mean, I know what the results were when you don't have the surfaces-breaking flaws from MRP-250.

MR. KIRK: Right.

CONSULTANT SHACK: But I haven't seen anywhere where somebody computed a number.

MR. KIRK: It's here. It is coming up. Yes.

CONSULTANT SHACK: Where do you go?

MEMBER SKILLMAN: Mark, would you go back to 29 just for a second?

MR. KIRK: No, there you don't go.

(Laughter.)

MEMBER SKILLMAN: A crazy question, but I have got to ask it. Most of the time we read left to the right, upper left to lower right. This is right to left. Is there any significance to that.

MR. KIRK: I was in an alternative universe when I --

MEMBER SKILLMAN: Okay. That's fine. I was just curious.

MR. KIRK: No, no.

MEMBER SKILLMAN: Thank you. That's all I had. Thanks. Thank you.

CONSULTANT SHACK: Now it bothers me.

(Laughter.)

MR. KIRK: Okay. So, Bill, here is a result just for a spectrum of surface-breaking flaws with different crack depth-to-thickness ratios.

CONSULTANT SHACK: Yes, you showed me that one. What I am more worried about is the absolute probability. This is conditional in having one of those flaws.

MR. KIRK: No, no, no. No, no. This is conditional --

MEMBER SKILLMAN: On having the transient.

MR. KIRK: This is conditional on -- okay, maybe this is subject to interpretation. So, I will tell you what this is.

Based on NUREG/CR -- you remembered the number, and I didn't.

CONSULTANT SHACK: 6817.

MR. KIRK: 6817. 6817 tells us that, based on all of that destructive and non-destructive evaluation, the PRODIGAL runs and the expert opinion, that the best advice we could get at that time -- and I also point out there has not been a lot of development since then, so it might still be the best advice, is we should be simulating .0037 surface-breaking flaws per square foot of ID real estate. That doesn't sound like a lot, but when you consider the amount of ID real estate in a PWR, or a BWR, you get between two and four flaws.

CONSULTANT SHACK: Per vessel?

MR. KIRK: Per vessel.

CONSULTANT SHACK: Uh-hum.

MR. KIRK: So, this is reflecting, I think, in this particular vessel it was two flaws. So, that is two flaws per vessel. But the other thing you need to realize is those flaws aren't ceded preferentially at the worst location. Every time

FAVOR runs it says, oh, here's my two faults for this vessel; throw them at the wall.

Well, you know the fluence distribution inside a reactor. Most of those areas are essentially unembrittled. So, a lot of times those two flaws go to a spot where there is adequate toughness, no failure probability whatsoever.

MEMBER RICCARDELLA: And not always in a weld, right?

MR. KIRK: Not always in a weld, no. No.

MEMBER RICCARDELLA: Rarely in a well, right?

MR. KIRK: I mean, this is now -- PWR Plant A is codeword for a weld-limited plant. So, in this plant, only about 2 percent of the ID area has any significant embrittlement at all. Most of it is banal.

So, two flaws per vessel based on .037 per square foot of ID area, randomly ceded into each vessel. Do the FAVOR runs until you converge, and that is the CPF you've got.

So, I am going to say all models can be improved, and we all recognize that. But I am going to say it is conditional only on having that transient occur.

CONSULTANT SHACK: Okay. I didn't

understand how you did that calculation.

MR. KIRK: Yes. Yes. And so, what we see -- and this is sort of a launch point -- is I think Bob said, well, it is counterintuitive to think that this big flaw that is two inches deep could have a lower failure probability than this itty-bitty flaw.

MEMBER RICCARDELLA: But if you did the analysis right, on the big flaw you would look at K at all the points along this cracked surface. And when you got close to the cladding, you would have a higher K. You know, the analysis of the big flaw only considers the deepest point, right?

MR. KIRK: That's correct. That is correct.

MEMBER RICCARDELLA: So, it is really an artifact of the big flaw analysis --

MR. KIRK: Well, I mean, yes, we talk about this, that the small, shallow flaws, or as one of my colleagues in the industry has called it, an inconveniently-sized flaw, which is a name I like, yes, given this model calculated that way, calculating only the K at the deepest point, you get a higher failure probability.

Maybe the more significant thing is just simply the number. We are in the 10-to-the-minus-4 or

10-to-the-minus-3 region. Whereas, we weren't anywhere close there in PTS. So, we said, again, this part of the model now needs some more investigation to see if we believe it.

MEMBER RICCARDELLA: The guidance that you were using for the shallow flaw distribution --

MR. KIRK: Uh-hum.

MEMBER RICCARDELLA: -- they say surface-breaking, but were they all touching on the low alloy steel like this is?

MR. KIRK: Yes. Yes. What the guidance was was that, in fact, in the destructive examinations -- it is probably too far to go to that -- in the destructive examinations of the PV rough vessel, which was primarily the basis for the .0037 value, they looked at 47 square feet of cladding. In that 47 square feet of cladding, they did not find a flaw that fully penetrated the cladding. They found one that was about a third of the way through, one that was about two-thirds of the way through.

But now, here is where the expert judgment part comes in. The judgment was, okay, 47 square feet, that is my table and your table, but relative to the ID area of a PWR or a BWR, that is about 2 percent. Relative to all the cladding in the fleet, that is like

.05 percent.

The judgment was, based on that group at that time and that evidence, that wasn't sufficient information for them to say no through-clad flaws ever. So, they took that information, combined with others, and I am simplifying -- we really need to go to the report -- to say, to give us the guidance that we should have .0037 or, basically, two flaws per vessel.

MEMBER RICCARDELLA: Okay. That is a pretty big extrapolation, what he is saying.

(Laughter.)

CONSULTANT SHACK: Well, now that flaw distribution is dependent on depth. So, you get different depths. You know, they predict flaws that just come up to the surface and shallower flaws. I mean, it is --

MR. KIRK: So, we are not simulating the shallower ones --

CONSULTANT SHACK: Right.

MR. KIRK: -- because they are all in stainless steel?

CONSULTANT SHACK: In stainless steel. I mean, so he has set the depth so that he only looks at that.

MEMBER RICCARDELLA: I understand, but in the particular vessel you analyzed to get this data, you had none of those --

CONSULTANT SHACK: Well, I mean, they --

MEMBER RICCARDELLA: -- in the 47 square feet that you measured, yes.

CONSULTANT SHACK: They had expert judgment because they did PRODIGAL simulations, which gave them even lower numbers. So, I think they would argue that that number is conservative, I believe.

MR. KIRK: Well, like I answered in answer to Dr. Bley's question, the intent is, when you don't have enough information, be conservative. The slippery slope issue I think we have got. Quite frankly, at the time I argued against, I personally argued against including any surface-breaking flaws. And I was told no by the experts, no by this Committee, and no by the international committee.

CONSULTANT SHACK: But you convinced the MRP.

MR. KIRK: Well, I'm going to send out a job app.

(Laughter.)

Anyway --

CONSULTANT SHACK: I am just saying I think, if we wish to reassess that -- and that is a perfectly legitimate decision -- I think we need, we are obligated to bring new information into this. Just getting a different group of experts together and saying, "I'm going to look at the same information," and conveniently come up with a different number because it solves my problem, that is not a good process. We need to find other information.

MEMBER RICCARDELLA: But, understand, for PTS I think it was a "No, never mind," right? And for this problem, it's controlling.

MR. KIRK: Well --

MEMBER RICCARDELLA: So, it is something you ought to look at.

MR. KIRK: Well, for PTS, it turned out to be a "No, never mind," but there was significant wailing and gnashing of teeth --

MEMBER RICCARDELLA: Yes.

MR. KIRK: -- at the beginning from our colleagues in the industry who said, "Oh, geez, you are putting in surface-breaking flaws. You're going to kill us."

It turned out -- I keep wanting to go to some future slide -- but we now understand why they are not controlling in PTS and they are here. But you're right, they are important here and they deserve further scrutiny. All I am saying is, to further scrutinize it, we need to bring in new evidence to get a new answering. Just looking at the old evidence and coming up with a different answer is I think not a good process.

CHAIRMAN BALLINGER: Going forward, like Peter was saying, you are going to treat the K distribution around the flaws in a more rigorous way? No?

MR. KIRK: No. No.

MEMBER RICCARDELLA: They don't honorize that big flaw in this process. I am saying there really isn't the non-intuitive thing that they were talking about because, if you honorize that big flaw completely, you wouldn't come up with it being less harmful than a smaller flaw.

CHAIRMAN BALLINGER: Certainly, if the NRR, if we did a point-by-point K evaluation all around this, it would certainly increase the calculated probabilities, especially near the surface. I mean, if that conveniently made these numbers the same as these, fine. So, there is not a quarter t flow in the vessels. I think we all agree on that.

MEMBER RICCARDELLA: No, I am saying, if you did the deterministic analysis and you did the point-by-point --

CHAIRMAN BALLINGER: I understand.

MEMBER RICCARDELLA: -- you would come out with a worse result than what is commonly used as the deepest point analysis. But that is just a side point.

CHAIRMAN BALLINGER: Yes.

MEMBER RICCARDELLA: I mean, what is really killing us here is those numbers up there on E to the minus 3, E to the minus 4. I mean, you want to be below E to the minus 6 for a vessel. So, we have to look at the things that are driving those numbers. And I think what it is is the small flaws, right?

MR. KIRK: Yes. Yes. So, we will get to that.

So, given all that has been said, we commissioned Oak Ridge to do a detailed, I'll say reevaluation of the basis for the shallow-flow model and the basis for the cladding stress model. Really, those are the two things that are contributing.

They prepared this Oak Ridge Technical Memo. I think that was sent to the Committee for your review.

So, the next group of slides is going to be an attempt to distill all that down to points that might make you interested to read it in your spare time.

MEMBER RICCARDELLA: I don't think I got

this.

MR. KIRK: Yes.

MEMBER RICCARDELLA: I did?

MR. KIRK: Yes.

CONSULTANT SHACK: It doesn't say Oak Ridge. We have sort of got a preliminary version of it, I think.

MEMBER RICCARDELLA: Chris, will you resend that to me, please? Thank you.

MR. KIRK: Okay, and we will make sure you have the right version.

So, in the report is the discussion of the basis for having these flaws, which we have, I think, mostly covered. The stress is generated by the cladding, and the probability results, and I am just going to go through those here as well.

Okay. We have talked about this. So, I think we have covered that. In the Oak Ridge TM they reviewed the information in CR-6817 and operating experience of IGSCC in two BWRs.

This is my summary, and I will stand by it. There really hasn't been much evolution of the state of knowledge of the existence or non-existence or density of these types of flaws since the NUREG/CR was completed, at least not that we are aware of.

CONSULTANT SHACK: But, coming back to Dennis and John, who believe in model uncertainty and that, you would get different results if you weighted perhaps the plottable results in 6817 heavier than some of the other results.

MR. KIRK: Yes. Yes.

CONSULTANT SHACK: So, there is a question of how you evaluate even the data that you had then.

MR. KIRK: Yes.

CONSULTANT SHACK: And you took a conservative approach at that time because --

MR. KIRK: Right.

CONSULTANT SHACK: -- because, as you said, nobody is ever going to shoot you for the conservative approach if you can live with the answer.

MR. KIRK: Right. So, where we are now is, based on the NUREG and the Oak Ridge TM, right now the staff finds the model acceptable. Note the staff doesn't find the model perfect. It doesn't find the model even maybe realistic. That word hasn't been used, either. It is just that we don't have anything better right now.

And certainly, as Dr. Shack points out, different weightings of information could lead to different results. But I think the way I would put this is, based on the evidence available right now, the staff is uncomfortable saying, absolutely, no, we can exclude these type of flaws from our probabilistic model. We don't think that is a defensible position.

As I mentioned, the industry's model supporting the risk-informed provisions do not consider shallow surface-breaking flaws in MRP-250, which, if you don't have a copy, we should get you one. They explain their rationale for that, which has to do with high-fabrication standards that were applied to nuclear vessels, inspections and other factors.

So, here is another group of experts, well-respected engineers in their field, who have looked at similar information and said, "No, we feel comfortable excluding it."

MEMBER RICCARDELLA: Does it require actual destructive examination to come up with this kind of data, I wonder. I mean, you looked at basically 50 square feet of cladding. And your assumption, the .0037 is one flaw per 270 square feet, say 250 square feet.

MR. KIRK: Right.

MEMBER RICCARDELLA: So, if we look at five more vessels -- but what about all the vessels that are out there? Haven't there been in-service inspections? Don't they do some P-T exams on those?

MR. KIRK: Part of the problem is that -- and I realize I am talking to somebody that knows a lot more than me, so I might be about to say something totally wrong -- but the ASME inspection volume isn't anywhere close to the whole idea of the vessel, you know. So, you are only getting the area in the well.

MEMBER RICCARDELLA: Yes, and that is the volumetric. But I think there are some P-T inspection requirements.

CONSULTANT SHACK: Well, that is part of the argument for the MRP-250, is that you do the P-T requirements when you are fabricating the vessel. Therefore, at that point you do the P-T on the whole vessel. You don't see any. And so, their argument is that you are not likely to be generating these cracks in-service and you have inspected it completely. So, again, there is an argument for why it is a very low number.

And I think everybody agrees that it is a low number.

MEMBER RICCARDELLA: You are talking about how low?

CONSULTANT SHACK: It is just how low is low here, it comes down to it. So, yes, the P-T that you have done as part of your quality control would suggest that there is none, but --

MEMBER RICCARDELLA: Right. I think there is also some in-service cladding exams that are done, you know. Maybe someone --

CONSULTANT SHACK: I wouldn't want to be the guy to do them.

(Laughter.)

MEMBER RICCARDELLA: Huh?

CONSULTANT SHACK: I will go back and look that up. I will go back and look. I think originally we wrote that into Section 11, you know, back in the 1970s. Now whether that survived or not, I don't remember. Originally, we did have patches of cladding that needed to be examined.

MEMBER RICCARDELLA: Okay. But, again, examining patches of cladding, when we are talking at the levels that we are at, are going to -- you have to look at a lot of patches.

CONSULTANT SHACK: Add them all up. All the vessels that have been inspected in 30 years, that could be a lot of square inches or square feet.

MR. STEVENS: This is Gary Stevens, Office of Research.

The Appendix 8 exams that are being done on vessels for Section 11, PDI exams, aren't capable of detecting a flaw of the size that is being postulated here. So, the serious exams you are talking about would provide limited information regarding flaws of this size.

MEMBER RICCARDELLA: The ultrasonic exams?

MR. STEVENS: Correct.

MEMBER RICCARDELLA: At one time we had requirements in there to do ID surface exams.

MR. STEVENS: I will check it out.

MR. KIRK: Okay. So, now we are going on to a description of the FAVOR cladding stress model. So, from a stress analysis perspective, it is just simple 1-D, axisymmetric finite element model, which I am going to kind of skip over the details because it is pretty vanilla.

The main aspect of this is that the cladding effects get taken up in this Tref value, also sometimes referred to as the stress-free temperature. In FAVOR we have determined Tref from measurements, which I will describe in the next slide.

So, what was done -- and this dates back to the late 1990s -- is a block of vessel steel was taken out of, Richard, PVRUF? PVRUF. And four fiducial marks were placed on the cladding. And then, the base metal was machined away, which, then, led to a relaxation of the tensile stresses in the cladding. So, the cladding contracts. And then, based on putting -- those fiducial marks were measured as the machining was taking place, which would then likely to provide an input to a finite element analysis that allowed us to determine 21.3 ksi tensile stress in the cladding and 70 degrees Fahrenheit, due to the differential and the thermal expansion between the cladding and the ferritic steel. Put that into an RPV model, and you come up with the value of the stress-free temperature. So, that is the temperature at which the cladding is in a zero-stress state.

As you point out, certainly, we are not the only -- by "we," I mean actually Oak Ridge -- are not the only ones to make these type of measurements of cladding residual stresses. And the value in the 20s of ksi is very consistent with other measurements and simulations that have been done worldwide.

So, again, there could be differences in detail. I don't think there are differences in large numbers.

MEMBER RICCARDELLA: Could this go in as a random variable?

MR. KIRK: It could go in as a random variable if you had a basis on which to sample. Right now, it goes in as a single variable.

MEMBER RICCARDELLA: I mean, have you done a sensitivity study?

MR. KIRK: Yes, we have. We tried dropping the stress-free temperature to the point that the problem went away, if you will. And I can't remember the exact number, but that gives us a stress-free temperature in the low 200 range. It is just too far away to be credible. So, yes, we have tried that, and that doesn't help us out.

But the thing I want to draw the Committee's attention to is what this says is that the temperature during a heatup or a cooldown where you are the most different from the stress-free temperature, which if you go back to the equation is where you are going to have the largest sigma theta theta, is at room temperature. So, this is saying you get the maximum stress in the cladding, and therefore, the maximum applied driving force on any flaws that you postulate in the cladding when the RPV is cold, when the RPV is sitting at ambient temperature.

MEMBER RICCARDELLA: Or shut down.

(Laughter.)

MR. KIRK: I didn't want to go through my simulation again. Sorry about that. So, we said.

So now, depending on the specific flaw or cooling rate in geometry, that means that the peak K for the transient can occur at the very end of the transient. Here we are focused on cooldown.

So, you put in a linear ramp along the cooldown from operating temperature to ambient end temperature, say prescribed at the limiting cooling rate of the curve, which is 100; churn that through the K1c equation in the code. You are allowed the maximum pressure versus time.

And then, use that to calculate the K's for the small flaws, and it falls into one of two categories. Either you get a peak K here at the end of your pressure hold phase, because the pressure contribution is, of course, constant here. The thermal stress is steadily rising. As soon as the pressure drops, then the total K drops. But the thermal contribution continues to rise, especially the contribution of the cladding. And in some cases, in fact, in a significant number of cases, you get situations where the peak K, and therefore, the time during the transient that is controlling the failure probabilities occurs at the very end.

That is what all of these are going to look at. The numbers will be different, but the curves will be the same. And, of course, if that peak K is above the minimum fracture toughness, which it frequently is because the K, just due to the cladding alone, is often right below the minimum fracture toughness on the lower shelf. You get significant failure probabilities that we have seen.

MEMBER RICCARDELLA: Excuse me. What caused the pressure to go up at the very end?

MR. KIRK: Oh, that is just because you stopped cooling -- really, I chop this illustration off here -- because you stopped cooling, you would be allowed to have more pressure.

MEMBER RICCARDELLA: Okay.

MR. KIRK: But it turns out that the K drops. So, I should have raised that. That is meaningless; the transient is over.

MEMBER RICCARDELLA: And the ambient you are assuming is?

MR. KIRK: Seventy.

MEMBER RICCARDELLA: Seventy?

MR. KIRK: We have done sensitivity studies on that, and that didn't help us, either.

MEMBER RICCARDELLA: It didn't help?

MR. KIRK: No. It changes things. Yes, it changes things, but you are changing your failure probabilities around. It is not dropping them to zero.

MEMBER RICCARDELLA: When we refuel, do you really come down to ambient temperature?

MEMBER SKILLMAN: Well, yes, if you offload, you come down to the temperature inside containment. And depending on when you are doing your shutdown and refuel, you can come on down to 85 degrees Fahrenheit, 80, 75, 70. It depends on what the containment temperature is.

MEMBER RICCARDELLA: During the refueling.

MEMBER SKILLMAN: During the refueling. You know, if you do an offload, once you cool down --

MEMBER RICCARDELLA: But this analysis, I mean, doing refueling is the problem. Right? I mean, am I right?

MEMBER BLEY: You're not wrong.

CHAIRMAN BALLINGER: You're not pressurized.

MEMBER RICCARDELLA: I know, and the pressure is zero.

MR. KIRK: The big point is this is not a pressure-driven problem. As you will see when we get to the leak test, I can set the pressure to zero and I still have an issue.

MEMBER BLEY: Of course, now you've got the head off. So, it is a different vessel.

(Laughter.)

But I'm surprised.

(Laughter.)

MEMBER RICCARDELLA: I mean, a whole lot of vessels sit around for a lot of time, and none of them are broken yet.

(Laughter.)

MR. KIRK: I should say we did do a sensitivity study on T ambient. We had data for 50 cooldowns. And so, we took a distribution off that that ranged from -- and this was a year ago, so my memory is probably bad -- I think at the low end it was 50; at the upper end it was 100.

And, yes, it had an effect. At the upper end it didn't make it go away, but certainly there were also data for end temperatures lower than the ones we were using.

MEMBER RICCARDELLA: Lower than 70?

MR. KIRK: Lower than 70.

MEMBER RICCARDELLA: Could be.

MR. KIRK: Yes.

MEMBER RICCARDELLA: Could be.

CONSULTANT SHACK: Chicago.

MEMBER RICCARDELLA: Kewaunee.

MR. KIRK: So now, I am going to take you through some of the things we have done to try to critique, and you are reminding me of things that we have done that maybe I should have shown you some slides on, critiqued different parts of this model.

So, first off, well, we have an LEFM model. We wanted to go back and, just as a check -- we have done it before, but to be thorough -- compare the LEFM K solution in FAVOR, which uses 10 nodes through the thickness, to an LEFM solution using ABAQUS, which I think just in my little picture there is more than 10 nodes.

And the ABAQUS LEFM and the FAVOR track reasonably well. I am showing you results here for an a/t of .05. It turns out .05 is an interpolated result in FAVOR. When we did the comparison for an a/t where it is not an interpolative result, you couldn't see one curve on top of each other. So, as we kind of knew going in, we benchmarked FAVOR to ABAQUS LEFM before, and we are getting the same result.

The next step was to look at EPFM to kind of touch on the effects of stress relaxation, because this is a secondary stress. And you can see here, up to the first peak, actually, the EPFM is a little bit higher than FAVOR is predicting. But, when you get to the second peak that is controlling everything, the EPFM calculated K, due to the yielding and the relaxation in the cladding, is about 13 percent below FAVOR. So, there is a little bit of benefit there.

But the thing I want to point out is in this analysis the second peak is still higher than the first peak, which means it is out here at the end of the transient that is controlling the CPI and CPF. So, yes, this would drop the failure probabilities if we implemented an EPFM solution. It wouldn't make them totally go away. So, maybe part of an answer, not the whole answer.

MEMBER RICCARDELLA: But the first peak versus the second peak, that is just whether you get warm pre-stress.

MR. KIRK: Right, and we adopt the warm pre-stress model.

MEMBER RICCARDELLA: But how high the second peak is is important.

MR. KIRK: Is important, yes, absolutely. Yes. Right. Absolutely.

But they are all above. I mean -- my

pointer is gone -- this horizontal line, I believe, yes, the horizontal line represents the absolute minimum of the K1c distribution in FAVOR. So, in this case the second peak, you are still getting failure.

MEMBER RICCARDELLA: You are getting some failures, but --

MR. KIRK: Yes.

MEMBER RICCARDELLA: But it is likely better than 10 to the minus 3rd or 10 to the minus 4.

MR. KIRK: The other thing we looked at was to see if we could get any benefit from accounting for constraint loss because, of course, these are very shallow flow. If you were to test a shallow flow in a fracture mechanics test in the laboratory, you would have lots of constraint loss and lots higher toughness. But this, of course, isn't a shallow flow in a bend bar. It is a shallow flow in a big, thick pressure vessel.

So, to assess that, we calculated the evolution of the T stress, which is the constant stress acting parallel to the clad tip throughout the loading. And generally speaking, if you have a positive T stress, you are in a situation of high constraint like you would be in a fractured mechanics specimen. And in that case, using typical fracture mechanics data is the right thing to do. So, in this case the T stress analysis told us that there is really no benefit to be gained by accounting for constraint loss in the calculations group. Our fracture toughness distributions are based on standard fracture mechanics specimens, are the right things to use.

Finally, we look at an analysis of one transient. We had a set of about 50 that were available. We have analyzed a few. This is just one to show you as an example.

What we wanted to do is, as I said, on the bottom here is the pressure temperature curve. Here is the curve we are normally following then. And the blue line represents the actual cooldown that was measured in the plant. And you can see here there is a little bit of a repressurization at the end, of course, staying below the limit curve. And you can see that repressurization right there.

So, we applied that actual pressure, temperature, time -- we put that into FAVOR and calculated the CPFs for the various wall depths. Really, it is only the shallow ones that are of interest here.

What we see is we have taken the CPFs for the limiting or allowable P-T values from 10 to the minus 5ish regime and dropped it down to 10 to the minus

9.

So, as we expected, as I would say we all hoped, following the actual cooldowns results in a considerable diminution of CPF, which is good. So, in large part, this is the basis for saying it is not a current safety issue. But, nevertheless, cooling down along the reliable curve does still give you these high values.

MEMBER BLEY: I am a little confused here, and I have been hanging up on the things you guys were talking about a minute ago. That time scale is fair. I thought we were doing cooldowns that were primarily -- the first cooldown like 100 degrees.

MR. KIRK: Right, right.

MEMBER BLEY: But we are out here at four hours --

MR. KIRK: Right.

MEMBER BLEY: -- 400 hours --

MR. KIRK: This is real deal.

MEMBER BLEY: Oh, this is a real deal?

MR. KIRK: Yes.

MEMBER BLEY: Okay. Okay.

MEMBER RICCARDELLA: Is that 400 or 4?

MR. KIRK: No, that is 400.

CHAIRMAN BALLINGER: That is 20 days.

MEMBER RICCARDELLA: That is real slow.

MR. KIRK: We have looked at others that are faster and we get similar results. Actually, this was the highest one.

MEMBER BLEY: So, when Pete was asking if you go all the way down to something under 100 degrees, and Dick was saying, well, if we get all the fuel out -- well, at that pace that is not going down. I mean, you are going down in temperature inside, but that is very quickly, 100 degrees an hour, for not this, but for the others.

MR. KIRK: Right.

MEMBER BLEY: And how long does it take for the temperature to equilibrate across the vessel if you are assuming you come down to the outside ambient temperature inside the vessel?

MR. KIRK: We are applying the ID temperature of the vessel to the first node of the model.

MEMBER BLEY: Uh-hum, but, then, the rest of it is heat conduction.

MR. KIRK: I don't have the time in my head, but --

MEMBER RICCARDELLA: But you are talking about a vessel that is not cooling down --

MR. KIRK: That happens after a couple of days. It has got to be equilibrated.

MEMBER RICCARDELLA: But you would still have a problem --

MR. KIRK: Yes.

MEMBER RICCARDELLA: -- even then.

MR. KIRK: Yes. Yes. The thing to appreciate is, I mean, the cooling rate, whether you are coming down at 500 degrees Fahrenheit every hour or what -- I think this one worked out to, we figured out an average cooling rate of like 1.3 degrees Fahrenheit per hour. It was just painfully slow.

The through-thickness thermal gradient is nil. You are getting nothing from that. All of this was in effect for the specialty temperature.

MEMBER RICCARDELLA: It is residual stress, you know, low temperature, and the flaw assumption --

MR. KIRK: Yes.

MEMBER RICCARDELLA: -- means that when you are sitting there during refueling, you have got --

MR. KIRK: It has nothing to do with thermal stress.

MEMBER RICCARDELLA: -- 10 to the minus 4 probability of failure.

MEMBER BLEY: You can take away the thermal stress and it remains.

MEMBER RICCARDELLA: The thermal stress is gone, and it is just --

CONSULTANT SHACK: It is waiting for the rest of the riddle.

(Laughter.)

MR. KIRK: It has been a while since I looked at the details of this analysis, but I am very uncomfortable in saying that most of the residual failure probability that you are seeing here is simple the result of the vessel being at room temperature and the assumed single stress pre-temperature being at 488. That's it. It is a consequence of the model.

MEMBER RICCARDELLA: And the distribution of the fracture toughness.

MR. KIRK: Right. Right.

MEMBER RICCARDELLA: It follow the fracture toughness curve.

MR. KIRK: Right. If we were more conservative in our assumptions on fracture -- and the fracture toughness model was pretty good in my opinion -- if we were more conservative, it would look worse. We are not. We have accounted for R.t and D.t.

So, we have beat that to death.

The risk-informed has a little bit higher CPF, but, you know, who would argue over an order of magnitude?

So, summary -- summary? -- so, considerable differences between P-T limit, between cooling down along the allowed limits, and cooling down along the actual transients, as we hoped and expected.

But what we find out is, when you look at these, here is the limit. There is generally lots of space between the actual curves and the limit curves. So, there are lots of things, plant-specific factors, that are, in fact, more limiting than embrittlement, with the exception being at the low-temperature, low-pressure end, where the curves approach the limit curve.

Let's see. Yes, from these analyses, okay, actual cooldowns have lower CPF. Even for the actual cooldowns, the second peak in applied K still generates CPF, and you saw the numbers.

What more do I have? Oh, okay, so here is the story on why did these not affect PTS. And so, we went back into our PTS rapid-cooldown databank and we picked a number of transients and categorized them in terms of their average cooling rate per hour, all the way from 75 Fahrenheit per hour to something like these normal cooldowns, all the way up to -- here's your main steamline break clocking in at 2,000 degrees Fahrenheit per hour.

The graph you see is the ratio of the CPI for the embedded flaws versus the CPI for the shallow surface-breaking flaws. And what we see is the faster the cooldown, the more the embedded flaws dominate. That is what was driving PTS.

But, for the slower cooldowns, it is the shallow surface-breaking flaws that are dominating. And the reason is illustrated in the cartoon. In both cases at the end you are cooling down to ambient temperature, whether it is 50, 75, 100; let's not argue. So, they are all going to come to the same K applied at the end for the shallow surface-breaking flaw due to the difference in the stress pre-temperature.

The difference is, with the very rapid cooling in PTS cooldowns, you get a huge K spike in the beginning which you are using a warm pre-stress model, as we do. This means this is where all the action is. So, the shallow surface-breaking flaws were effectively numbered benign by the early K peak due to the rapid cooldowns.

MEMBER BLEY: Rather than benign, the chance of failure was high enough for this that it washed out the other one. No?

MR. KIRK: No, because here you are taking a high K when you have got -- well, maybe I shouldn't have used the word "benign". I'll just go with "much less".

MEMBER BLEY: Yes, I like that.

MR. KIRK: Because, yes, you have got a high K applied, but you have got very high fracture toughness.

MEMBER RICCARDELLA: You stress it while it is warm, let's call that autofrettage.

MEMBER BLEY: No. In that period of time if it didn't break, eventually we would get to the same thing. Assuming you were shut down, eventually you have got residuals there.

MR. KIRK: But having gone through this, even though at the end of the transient you may still be above the minimum K1c, the criteria for failure that is adopted by FAVOR -- and FAVOR is certainly not unique in this regard; it is used in many areas -- it is that KFY needs to be above the minimum K1c and KFY need to be increasing with time, and it needs to be above the previous peak.

So, down there, even though --

MEMBER BLEY: It is not above.

MR. KIRK: Yes.

So, to summarize, the flaw model was established in NUREG/CR-6817. I think, as we have discussed, it is the best we could do at the time based on the available information. It was well-reviewed. The shallow surface-breaking flows were, I think, generally thought to be a good idea, but also they weren't significant. So, it hasn't gotten a lot of scrutiny in terms of the implications until now. And certainly more could be done with it. I would be first in line to say that.

The stresses in the cladding, a simplified model, but based on experiments, and, moreover, I would point out pretty much an industry standard. Lots of people use a stress pre-temperature model.

We have benchmarked successfully to ABAQUS, but the natural outcome of the model is applied stresses are maximum at room temperature. And that is vexing us, vexing us in the context that we calculate probabilities that are rather high for these flaws.

So, that, absent questions, is the end of this part.

MEMBER BLEY: But were they high enough that in the breadth of industry, not just power plants, we would have seen them somewhere under these really same conditions?

MR. KIRK: Without wanting to do algebra in my head, I am going to say probably -- were they high enough? I mean, I am getting my question I am answering.

MEMBER BLEY: We don't necessarily have nuclear reactors, but we have lots of high-temperature chemical reactors that cool down and have residual stress.

MR. KIRK: The actual CPIs and CPFs are going to be more like these values I have calculated here, 10 to the minus 9, because I think we all agree we are not -- even though it is the limit that is set in the code, people aren't following that limit. That is agreed to. So, the actual failure probabilities are more like 10 to the minus 9, 10 to the minus 12. You would have to do the math. I don't think it is --

MEMBER BLEY: Be unlikely.

MR. KIRK: It would be unlikely to have seen it.

MEMBER SCHULTZ: But you also had conditional statements in your previous slide where you talked about reasons why that should not be a significant concern.

MR. KIRK: I'm sorry, what? Refresh my

memory.

MEMBER SCHULTZ: You talked about the pathway which you followed to get to those points versus what an actual path --

MR. KIRK: Oh, yes. Yes.

MEMBER SCHULTZ: And so, I am not sure how we capture those conditions, that conditional piece of the description. So that, when one looks at the plot, one doesn't get excited.

MR. KIRK: That has been our problem.

MEMBER SCHULTZ: Yes. That is a problem, but we nee to talk about it or write it down.

MEMBER RICCARDELLA: Mark, on that previous slide --

MR. KIRK: This one?

MEMBER RICCARDELLA: I'm sorry. Yes. You know, I misinterpreted that at first. I thought that was conditional probability versus time. Would it be possible to make a plot of the conditional probability of failure versus time during the change?

MR. KIRK: Yes.

MEMBER RICCARDELLA: When it occurs during the change?

MR. KIRK: And that is coming up in the leak test.

MEMBER RICCARDELLA: Okay.

MR. KIRK: We haven't done. We don't have those plots for the cooldown.

MEMBER RICCARDELLA: I would just like to confirm that it is really happening at the end of the transient.

MR. KIRK: I will confirm that.

MEMBER RICCARDELLA: Okay.

MR. KIRK: yes.

MEMBER SKILLMAN: Mark, let me ask this: is there any international OE that would suggest that there have been flaws that grew to failures --

MR. KIRK: No.

MEMBER SKILLMAN: -- and at the time couldn't be explained? But now maybe they can be?

MR. KIRK: I think we would all know about that.

MEMBER SKILLMAN: Okay.

CHAIRMAN BALLINGER: Okay, this is a convenient break point. We are way ahead of schedule, by the way by this.

MR. KIRK: Well, we are right on schedule with the previously-published one.

CHAIRMAN BALLINGER: That's right. Well done. Well done.

(Laughter.)

In any case, can we take a break until 25 after?

(Whereupon, the foregoing matter went off the record at 3:09 p.m. and went back on the record at 3:25 p.m.)

MR. KIRK: Okay, so this part of the concerns the operating pressure leak test in boiling water reactors. Just as an example of some of the challenges that are proposed by surface-breaking flaws in our calculations, this is a briefing on the research report that we sent you in draft form several weeks ago.

So, it may be self-evident, but leak tests include, of course, both a heatup and a cooldown phase and a constant pressure and temperature hold in the middle. In BWRs leak tests occur at the start of every operating cycle, so between one a year and half a year. So, for all practical purposes -- and I should also say they also follow these curves -- so, for all practical purposes, for leak tests, CPF is approximately through-wall cracking frequency. And this I think the Committee is aware the agency adopted a 10-to-the-minus-6-per-year limit on through-wall cracking frequency in a PTS reevaluation.

In this example problem, we are focused on three different loading possibilities. One is loading following the ASME Appendix G risk-informed approach. So, the graph gives you the temperature ramp up and down. We followed a ramp of 40 degrees Fahrenheit per hour, the calculated maximum pressure. The same thing for ASME, Appendix G, current approach.

And then, we also give one loading following plant procedures. So, you see the same 40-F-per-hour thermal ramp, but the pressure, instead of being these rather higher values that are allowed by the equations at the beginning and the end, we started at zero gauge pressure and, then, step up following the plant procedures. So, per-plant procedure would be a much more realistic loading than following the permitted limits.

Just to show you where these come from equation-wise, leave it to help your sleep to work on the equations. So, all these are, these are the ASME Section 11, Appendix G, equations. K1c is less than 2 times K1m plus K1t. Solve for both the leak test temperature and the maximum pressure with all of the variables retained, so that you can see the effects of things like geometry and R's and square roots of t's and the various risk-informed factors like alpha and beta.

So, these equations give us the loading conditions for following the P-T limits. Also, the little table gives you the various factors.

For current practice, the structural factor on pressure is 1.5. There is no beta factor, which is essentially a transition temperature shift. And the trend curve and the margin term come out of Reg Guide 1.99, per a foot note in ASME Section 11, Appendix G.

The risk-informed approach, the structural factor on pressure is set to one. There is a beta factor, again, essentially a transition temperature shift of 60 degrees. It uses a different ETC, but for these purposes that is not a difference that matters, and zero margin. The plant procedure is as shown here, and the embrittlement is calculated by Reg Guide 1.99. So, those are our loading curves.

In terms of flaws or flaw populations, we did three different runs, one using the embedded flaw population we have been talking about a lot, another using the embedded flaw population that we barely talked about at all, the population of shallow surface-breaking flaws that we have talked about a lot.

And then, just for comparison purposes -- I am not saying that this flaw exists in a vessel -- is the single quarter t 6-to-1 surface-breaking flaw that established the P-T limits, just for purposes of comparison.

The results in the table I am not going to focus on. They are what they are. What is, I think, of more interest is to look at an answer to Pete Riccardella's question of earlier, is: where do these CPIs and CPFs occur for these different flaw populations?

Now we will look at the shallow surface-breaking flaws, and the graphs I will show are the cumulative percentage of CPI accumulated as a function of time in the transient. And on all the graphs, the light shaded area, that is the time during, I will call it during the operating pressure leak test. You are at the leak test temperature. You are at the full system pressure. And then, the dashed line is simply the time at which the plant returns to ambient temperature. And, of course, it is the ambient temperature time equals zero.

MEMBER RICCARDELLA: And pressure? The dashed line is also returning to essentially zero --

MR. KIRK: Well, what we are returning to in the ASME case is the allowed pressure, which was shown here. In the case of current practice, the allows pressure for this transient was about 500, 600, in the Appendix G, and this is just simply the difference between the 1.5 and the 1 factor. It is up to about 800.

MEMBER RICCARDELLA: Yes, but the plant procedure is zero.

MR. KIRK: The plant procedure is zero, yes. The plant procedure, zero applied pressure, beginning and end.

So, again, ignoring a few details, all very common in that at time zero there is some percentage of CPI accumulated, anywhere from 20 to 40 percent. And then, the rest of it occurs at the end.

The most striking factor is that absolutely nothing is happening CPI-wise or CPF-wise -- it doesn't matter -- associated with the time and duration of the leak test. It is totally irrelevant. And you can see why that is when you look at the variation of K with time. So, in these graphs, the green curve is a variation of the applied K for the shallow surface-breaking flaw. There are the orange curves, the minimum fracture toughness.

So, since you are heating up, the ID of the vessel is being driven more and more into compression. So, as you heat up, the applied K actually drops for an ID flaw. However, since it is above the minimum K actually in all three cases -- it doesn't show graphically very well at the bottom -- but it is just a tiny bit above. So, in all three cases, like was shown before, you get a significant percentage of the CPI occurring at time equals zero. Since K then drops, no more CPI accumulation. In fact, in all three cases, during the time of the leak test, the applied K is always below the minimum fracture toughness.

So, no possibility of additional CPI or CPF accumulation until you have the cooldown coming out of the leak test. Now, since you are cooling down, the ID of the vessel is going progressively more and more into tension. And again, brushing aside the particulars, you start to tick up more CPI as you return to ambient temperature.

And actually, all of this can be easily compressed onto a single diagram. So, really, the only significant difference between these three loadings is the initial or final pressure. Try to blind yourself to the CPI or CPF numbers for right now.

The ASME risk-informed alternative has higher CPIs and CPFs, and they are essentially identical to then current practice. And that is understandable because there is a higher initial allowed pressure.

Following plant procedure, which is a much more realistic view of how a plant would go through leak tests, the CPIs and CPFs are lower and, in fact, there is a greater difference, but they are still all above 10 to the minus 6.

I should point out these analyses are done for a plate-limited BWR at 72 EFPY. So, fairly high embrittlement BWR. We have done low embrittlement BWRs. We have done different BWRs. The numbers change a bit, but this isn't a rare case is what I would like to say. This is a good example of what happens.

So, the initial final pressure drives the CPI/CPF differences between these different loadings, current plant procedure being the lowest, but still above 10 to the minus 6. It probably drops a little with embrittlement.

But the significant thing is actually something that I didn't say in the middle. It is that there is nothing that an operator can do to change this result. It is all a part of the model. There is nothing going on here during the leak test portion. You can't increase the temperature of the leak test. Nothing is going to happen. It is all at the beginning and the end. So, it is all a consequence of the model.

That is not to say the model is right. It is just to say you can't change it by changing your operating practice.

I am just going to go quickly through embedded flaws because, frankly, they are not controlling. I will just point out that now the time of the CPI accumulation depends on the loading method. For the risk-informed, for ASME current and plant procedure, the time to CPI accumulation now corresponds to the duration of the retest itself. Whereas, with the risk-informed alternative, it ticks up predominantly you ever get to the leak test, and there is only a slight adder as you get to the leak test.

Again, I am not going to dwell on it because this isn't the significant part of the briefing. But you can understand better where the CPI is accumulating and not accumulating when you look at the KFYs. It is one, of course, follows from the other.

When we look at the end, if we look at loading along the risk-informed P-T limits, certainly it increases CPI and CPF to the current P-T limits and it changes the time that is important in the transient from during the leak test to before the leak test.

All those things said, the CPI and CPF values, even for the risk-informed alternative, remain well below 10 to the minus 6, presuming they are only embedded flaws in the vessel. And this is the same conclusion even for highly-embrittled BWR. And this is the same conclusion that the industry reached in MRP-250.

So, to summarize, for surface-breaking flaws, CPI and CPF are increased by the risk-informed alternative. It is always greater than 10 to the minus 6, even for a more realistic loading case. And the whole game is in the assumptions of the model.

We initially went into this thinking, well, maybe if we required a higher retest temperature, that would fix things. The action is enduring a leak test for surface-breaking flaws. So, the remedy, we need to look someplace else. For embedded flaws, all the values are low, even for a more embrittled BWR.

MEMBER SCHULTZ: Are low and very low in comparison?

MR. KIRK: Yes. Yes. Looking at what we are doing moving forward, obviously, we are here to summarize our findings to you and solicit your comments. We are working on completing our documentation of this work, sort of plugging through this a bit at a time. Within the next year, I think a year, we hope to complete 10 Technical Letter Reports and summarize them all in a single NUREG.

We are also motivated by the things that we talked to you about today, performing a comprehensive review of the conservatisms in the FAVOR model. That goes off a similar examination done during the PTS project and documented in NUREG-1808, but we are taking this opportunity to do it again, of course, motivated by some of the things we told you today.

As we work through that, we are performing more detailed investigations of factors we have identified as significant, which means offering a possibility, at least in our view, of significantly changing the results.

Currently, we are in the process of trying to develop more detailed model of cladding stresses and stress re-temperatures in FAVOR. We recognize that what we have got is a fairly rudimentary model. And so, we want to see if we can gain some improvement there.

Other topics that we have talked about but haven't initiated investigations on, some of which were alluded to today, some of which have been brought up today -- so I need to go through the transcript -- include elastic plastic effects, load history effects, the effects of actual loading, the effects of corrosion on crack driving force, including both blunting effects and corrective wedging effects, looking at making more measurements of cladding residual stresses. And, of course, we will be seeking peer review in this and other forums on the various insights.

Also something I should notice or I should say is we have brought these results to the attention of the ASME Boiling Pressure Vessel and the people that attend, and particularly our colleagues in the industry. And they are doing some work in this regard. In particular, we are following the industry's developing full-tolerance approach where they are working on a way to manage CPI and CPF accumulation by controlling heatup and cooldown breaks. And that was something that was just literally yesterday discussed. So, there are some ideas there.

And I just note that these and other research plans are consistent with NRR needs and are reflected in their current user need request to us, NRR-2014-007.

So, I think, with that, we are up to questions and comments.

CHAIRMAN BALLINGER: Can we get the bridge line open?

CONSULTANT SHACK: You gave the example of the elastic plastic fracture mechanics lowering the K, and it didn't seem to do very much. But did you actually run through a probabilistic calculation?

MR. KIRK: No. No, we have not done that. Like I said, that is one of the things on our list.

CONSULTANT SHACK: Small things seem to make such a difference here.

MR. KIRK: Well, they do, because in all these simulations the applied K is just getting into the K1c or K1a distribution. So, yes, small things can make a difference.

MEMBER RICCARDELLA: Yes, you know, on the surface-breaking flaw, could you go back to slide 31, please?

MR. KIRK: Yes, I can. Sorry. There we go.

MEMBER RICCARDELLA: You know, the EPF calculation for that shallow surface-breaking flaw is not just the standard EPF calculation because most of that cracked surface is in that blue ductile material.

MR. KIRK: Uh-hum.

MEMBER RICCARDELLA: And all you have got is that little tip of the crack --

MR. KIRK: Yes.

MEMBER RICCARDELLA: -- going out into the brittle material. And you are saying, if that little tip exceeds K1c, you get initiation and in some cases all the way through wall fracture. And you have tear that blue part, which is really hard to do. You know, it is a very ductile material. I think a detail of the elastic plastic analysis, pressure mechanics analysis of that might make a lot of these surface-breaking flaw go away.

MR. KIRK: Richard Bass from Oak Ridge National Lab, he did the EP analysis. So, maybe he can comment.

MR. BASS: What I wanted to say to address Pete's comments here, back in the eighties we at ORNL we ran some thermal shock experiments in large cylinders that were both clad and unclad with surface flaws through the clad. And we had no problem initiating those flaws, and they would run the full length of the cylinder beneath the cladding and well into the vessel.

And we have data that attests to the behavior of these flaws under thermal -- this is strictly thermal shock loading. It is not pressure loading. But we demonstrate a full capability of these shallow flaws to initially brittlely and run beneath the clad and into the vessel wall, in some cases two-thirds of the way through the wall.

MEMBER RICCARDELLA: But not through the wall?

MR. BASS: Well, driving a crack then strictly by thermal loading through the wall, that is problematic.

MEMBER RICCARDELLA: But is that what we are talking about though?

MR. BASS: Yes, but in our particular case here you could also have a foundation of partial loading, too.

MEMBER RICCARDELLA: I am just looking at those high probabilities of fractures, you know, 10 to the minus 4, 10 to the minus 5th, at zero pressure.

MR. KIRK: Yes, and I think maybe Richard can also help me with this one. In FAVOR a crack is said to have gone through a wall when it is predicted to propagate to 90 percent or more through a wall by either cleavage initiation arrest, reinitiation/rearrest, and/or leaving an instability.

I know we went through this in PTS. I don't remember the details, but I believe the reason for the 90 percent is just the computational difficulties of getting influence coefficients out to the --

MR. BASS: Well, that is also user input, too. You can specify what you want to be a failure.

MR. KIRK: Yes.

MR. BASS: And typically, we run 90 percent.

MEMBER RICCARDELLA: Well, it just seems to me that at zero pressure, by the time that crack gets to be 70 or 80 percent through a wall, and you driving force is predominantly that cladding stress, which has pretty much gone away, and your irradiation embrittlement attenuates as you go through a wall.

MR. KIRK: And all the things you have said are accounted for in --

MEMBER RICCARDELLA: I just can't understand how you could break that vessel at zero pressure. I'm sorry.

MR. BASS: Well, I can tell you from our experiments that we were able to drive the flaw strictly with thermal loading through the majority of the wall thickness in these large-scale experiments.

MEMBER SCHULTZ: What was the thermal loading?

MR. BASS: We basically took the vessel, heated vessel, and submerged this into liquid oxygen. And when you open the top of this thing, it is floating with liquid nitrogen and you have thermal shock. It initiates the flaw. It runs under cladding and through the wall.

MR. KIRK: And I know you said "break the vessel," but I think we need to be careful. We are predicting a vessel failure probability. That means in all the simulations that we run we are getting failure at zero pressure conditions in the end a little bit more than 1 in a million. That, to me, isn't the same as "break". "Break the vessel" sounds, I will use your word, "deterministic" to me for that trial. In the huge majority of the trials, it didn't break the vessel. So, I think your intuition is correct almost a million out of a million times.

MEMBER BLEY: When you say "a trial," does that mean a crack is initiated or a trial includes initiation?

MR. KIRK: A trial is an RPV, a RPV simulation.

MEMBER BLEY: Okay. So, to turn that around a little bit, every crack initiation, every trial that had crack initiation, what fraction actually go 90 percent?

MR. KIRK: If we look at the cases where there was significant pressure, for the risk-informed

Appendix G, the end pressure was -- I lost it here -- like 800, 800 pounds per square inch. Let's just say that. There CPI and CPF are identical. So, essentially, everything that initiated went through the wall at 800 pounds.

Down here, where there is no applied pressure, we have got about 9 times 10 to the minus 6 CPI, but only 3 times 10 to the minus 6 CPF. So, roughly, a third.

MEMBER BLEY: So, that's the number that he was talking about. One out of three seems pretty high.

MR. KIRK: It seems high.

Certainly, we can follow that through. In any probabilistic code, what you will find that is self-evident, especially to this group, these failure probabilities are going to be driven by the tail. So, you sort of already know the answer. It is going to be location of the simulated at high TOP or high fluence, whatever. But that is the result.

All I can say is all of the things that you indicated as mitigating factors, the temperature gradient, the fluence gradient, all those things are modeled in FAVOR the best we could at the time. And all the things you outlined are pretty good models.

MEMBER BLEY: Now I want to ask you about one other thing. And I haven't studied this, and I need to go back and do more reading.

In the experiments on which so much of this is based, where we see you have tried to initiate cracks and we have purposely created cracks, my question is really, where are we calibrated on the probability scale for, say, crack initiation? In the experiments, I would expect several conditions where it is pretty likely or one out of one or one out of ten experiments leads to an initiation. And yet, through our models, we are predicting cases of 10 to the minus 4.

It is that translation from places where it is quite likely and we have studied it carefully to these cases where it is quite unlikely and we are depending on our models.

MR. KIRK: Yes.

MEMBER BLEY: And I don't have a good feel for how well we are calibrated as we make that transition from what we do in experiments to these cases where we are seeing quite unlikely cases.

MR. KIRK: I think Richard can reflect on it -- I am not sure if this is the nature of your comment or not -- on the model test, both thermal shock and pressurized thermal shock that were done years and years ago at Oak Ridge.

I think, to me, the big-picture outcome of that when your elastic plastic mechanics to predict the failure of vessels.

MR. BASS: As a matter of fact, we made that presentation here about 10 years ago --

MR. KIRK: Yes.

MR. BASS: -- to the ACRS.

MR. KIRK: To a previous version of the ACRS.

MR. BASS: To a previous version of the ACRS.

MR. KIRK: Maybe it is time for a revision.

MR. BASS: On the basis of the very question that you --

MEMBER BLEY: But is it very easy to point me to the papers that describe that?

MR. BASS: We can do that after the fact.

MEMBER BLEY: I would appreciate it because I don't have a good feel for that.

MR. BASS: Yes, again, we did a whole series of large-scale pressured thermal shock experiments in the eighties, of which I was a part of. And in that particular case, we were very successful in predicting the initiation of surface flaws under pressurized thermal shock loading. And this has all been very well-documented in the literature, and I think we can certainly provide you with whatever we have got --

MEMBER BLEY: Yes. That would be helpful to me.

MR. KIRK: Actually, I think we will look, but I am pretty sure it is an appendix to NUREG-1807.

MEMBER BLEY: That would be great.

MR. BASS: Probably the best document to direct him to would be the document that we used for the review with the ACRS back 10 years ago, whatever it was. But that gave the best summary of providing the relevance of LEFM to the FAVOR methodology. But we will make that available.

MEMBER BLEY: That would be great. Appreciate it.

CHAIRMAN BALLINGER: Any other questions by the Committee members?

(No response.)

The bridge line is open. Is there anybody on the bridge line that would like to make a comment?

MR. LEWIS: Yes, thank you. Marvin Lewis, a member of the public.

CHAIRMAN BALLINGER: Yes, Marvin?

MR. LEWIS: I just was thinking. I have been listening to all this stuff, the probabilistic risk analysis predictions. I was thinking, you know, there is a lot about metals that turn out to be a surprise. I don't know if anybody noticed about the Liberty ships back in World War II, but they started cracking on the North Ocean, no, North Sea. And it didn't take us long to figure out why.

But what I am trying to say is there are surprises hidden in the numbers, and we should really look at them and find out what these numbers are trying to tell us.

All right. Thank you.

CHAIRMAN BALLINGER: Thank you.

Any other comments by people on the bridge line?

(No response.)

Hearing none, thank you.

Comments from people in the audience? Anybody have comments?

(No response.)

I'm speaking to the choir out there?

Okay. One last question. You mentioned several times you are interested in feedback. In what form would you like that?

MR. KIRK: I am going to defer to my boss, by boss' boss to tell you that answer.

MR. RUDLAND: My name is Dave Rudland. I am the Chief of the Component Integrity Branch in Research.

I don't think we need anything real formalized.

CHAIRMAN BALLINGER: Okay.

MR. RUDLAND: I think we are looking just more for the informal discussions. So, I don't think we need a letter or anything like that.

CHAIRMAN BALLINGER: Okay.

MR. RUDLAND: And I think the minutes will reflect the information that we need.

CHAIRMAN BALLINGER: Thank you.

MEMBER BLEY: Just for the record, the only way we can give advice is through a letter.

MEMBER SKILLMAN: Anything that has been said in this meeting has absolutely no bearing on ACRS opinions.

CHAIRMAN BALLINGER: Okay. Lucky thing the Chairman is sitting here.

(Laughter.)

MEMBER SKILLMAN: No, that is just a fact.

CONSULTANT SHACK: Well, unless you have

an official opinion to deliver.

MEMBER SKILLMAN: A subcommittee can't deliver an official opinion.

CONSULTANT SHACK: Right.

MEMBER SKILLMAN: Well, you can decide whether you have an official opinion to deliver or not.

CONSULTANT SHACK: And then, you can write a letter.

(Laughter.)

MR. RUDLAND: I have another thing to add. When we talked about this informally, we talked about leaving the decision up to you whether or not to go to full Committee. So, we will leave that decision up to you, if you think that is necessary.

CHAIRMAN BALLINGER: Thank you.

I guess we are done, unless there are any other --

MEMBER BLEY: I would ask one question. If we don't say anything, what are you going to do next? What you've told us or is it hinging on what we say in any way?

MR. KIRK: Well, I mean, like I said, I have tried to be writing. I am hoping my colleagues were taking notes because my job was to talk.

But I think you have reminded us of some things that we might have left aside. This is pretty much our short punchlist of things to look at.

And I will just say, personally, one thing that I have recognized in preparing for this and talking to you and hearing your comments is in many ways I think we have been looking for one thing that would fix everything. And, well, we haven't found that yet. I think we have fairly convinced ourselves of that, and I hope we have convinced you of that. Perhaps we need to be looking at a combination of factors.

MEMBER BLEY: I don't want to put you completely on the spot, but --

MR. KIRK: Sure you do.

MEMBER BLEY: -- is it fair for us to believe that, if we don't give you any specific advice in a letter, there are items that you have there that are actually going to get attention over the next couple of years?

MR. KIRK: Yes. Yes, that's a fair assumption.

MEMBER BLEY: Okay. All right.

MEMBER RICCARDELLA: I think that is the right list of things. The only thing I might add would be also a relook at surface-breaking flaw distribution and where we could possibly get some other data to support or change that.

MR. KIRK: Okay. Thank you.

MEMBER RICCARDELLA: But, other than that, I think you have got everything listed.

CONSULTANT SHACK: And I think adopting a PRODIGAL model would make the problem go away. I mean, it really is tied to that distribution. Okay? But I have no reason to think why we would do that.

(Laughter.)

It is a region of uncertainty. I mean, when you are dealing with core distributions that are kind of as sparse as this, it is hard to come up with good answers.

MEMBER RICCARDELLA: I mean, you are taking data from one vessel that you have examined and found none of these flaws. And somehow getting that two per vessel are going to be these two breaking flaws. I mean, that might be right, but it needs to be examined.

MR. KIRK: Yes, it is a model. It is an approximate model.

CHAIRMAN BALLINGER: Any more questions?

(No response.)

Then, thank you very much for a really great presentation.

MR. KIRK: Thank you.

CHAIRMAN BALLINGER: And I think we are adjourned.

(Whereupon, at 3:59 p.m., the meeting adjourned.)

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Protecting People and the Environment

Advisory Committee on Reactor Safeguards

Materials Subcommittee Meeting

Technical Brief on NRR Bifurcation of 10 CFR 50 Appendices G and H Rulemaking and RES Research Efforts on 10 CFR Part 50 Appendix G

Thursday, August 21, 2014
NRC Headquarters
Rockville, MD

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Bifurcation of 10 CFR 50 Appendices G and H Rulemaking

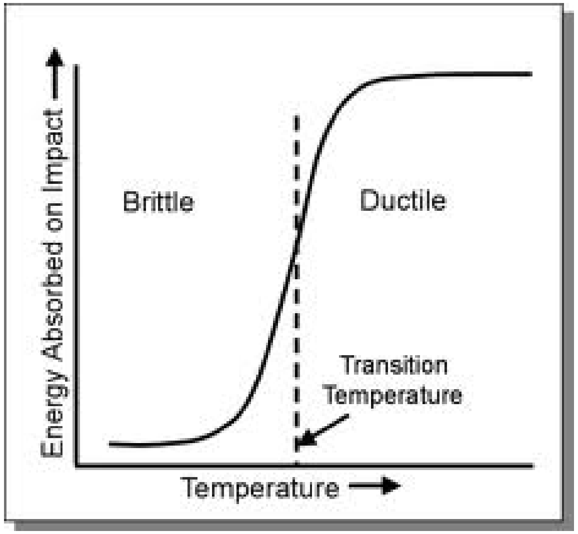
Robert O. Hardies

Senior Level Advisor – Materials Engineering

Office of Nuclear Reactor Regulation

Background

- Title 10 of the Code of Federal Regulations, Part 50, Appendix A, General Design Criteria
  - Fracture Prevention of Reactor Coolant Pressure Boundary



10 CFR 50 Appendices G & H

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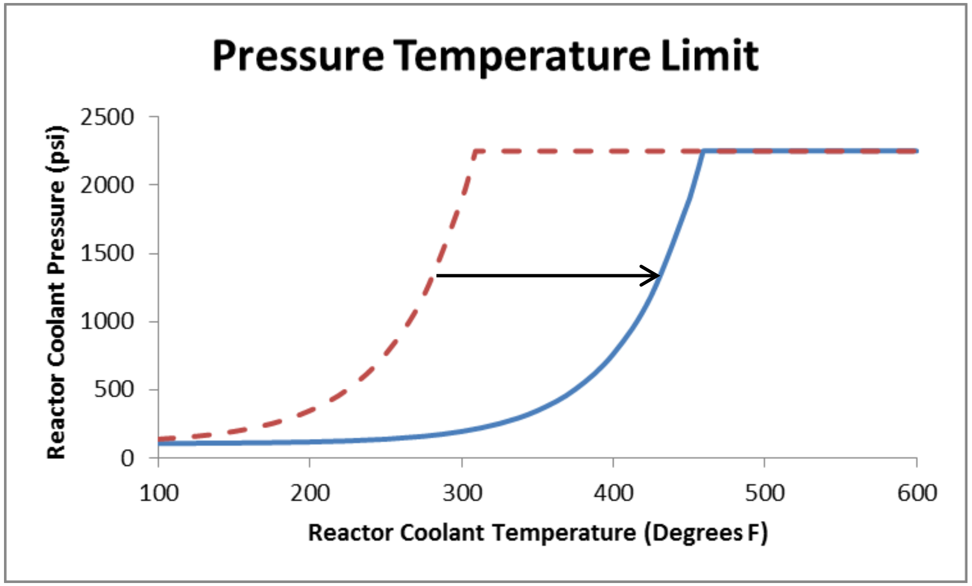
- Appendix G establishes heat up and cool down curves (P-T curves)
  - Shape and initial location
- Appendix H provides data to inform the curve shift due to irradiation



Surveillance Program

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- Design
  - Which materials go into the program
  - What kind of specimens
  - How many specimens
  - How many capsules and where to place them
- Implementation
  - When to test
  - Guidance for number and temperature of tests
  - Retention of specimens
  - Evaluation or revision of withdrawal schedule
  - Report description

Surveillance Capsule Locations

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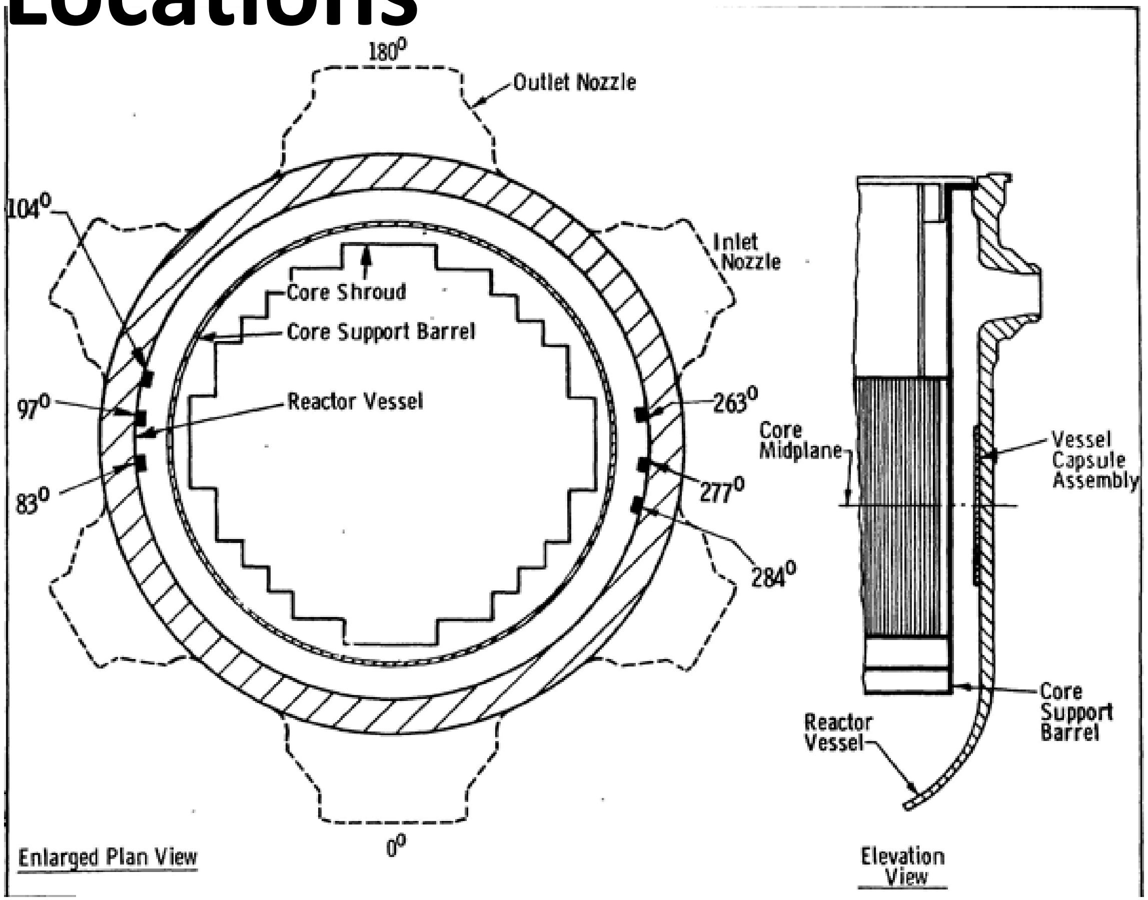

Surveillance program design is completed before the vessel is delivered

Proposed Appendix H Changes

- Change ASTM edition control from Appendix H to 10 CFR 50.55a
- Current rule requires ASTM E 185 (1982 version or earlier) for design and implementation of the reactor vessel surveillance program
  - Proposed change to permit later versions
    - ASTM split standard E 185 into two standards, E 185 for design and E 2215 for implementation
    - New E 185 requires fracture toughness specimens
    - New E 185 eliminates a low-fluence capsule
    - New E 2215 provides guidance for life extension withdrawal schedule changes
    - New E 185 and E 2215 eliminate HAZ specimens

Proposed Appendix H Changes (cont'd)

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- Current rule requires transmittal of capsule analysis reports within one year of capsule removal
  - Consider increasing to 18 months or two years
    - Integrated programs and shared capsules with multiple participants require more time for reporting
    - There is sufficient fleet-wide and plant-specific data in the database to allow time extension

Bifurcation of Appendices G and H Rulemaking

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- Appendix G is a high priority rulemaking
- Appendix H is a medium priority rulemaking
- Appendix G technical basis not yet complete
- As a result, NRR requested, and Commission granted (8/8/2014), bifurcation of these two activities
- NRR/RES will proceed with Appendix H rulemaking

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Questions or Comments?

NRR Regulatory Perspective on 10 CFR Part 50 Appendix G

Robert O. Hardies

Senior Level Advisor – Materials Engineering

Office of Nuclear Reactor Regulation

What are P-T Limits?

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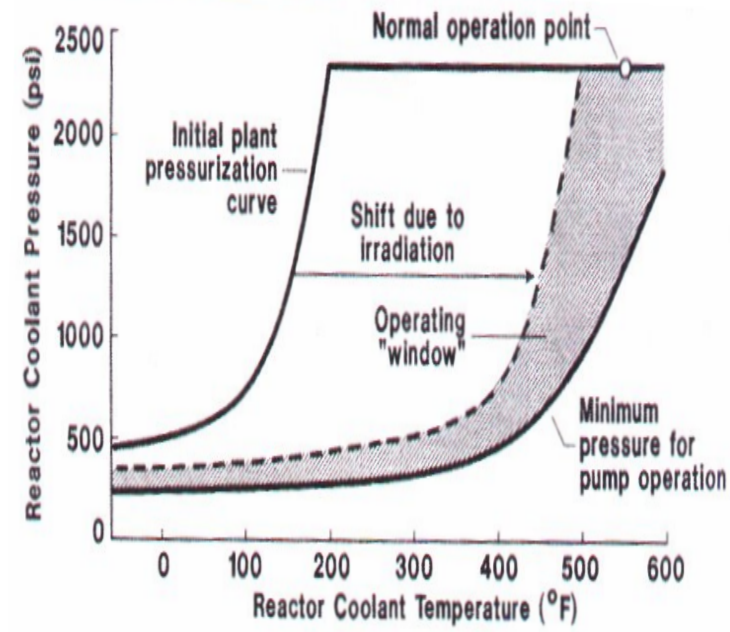
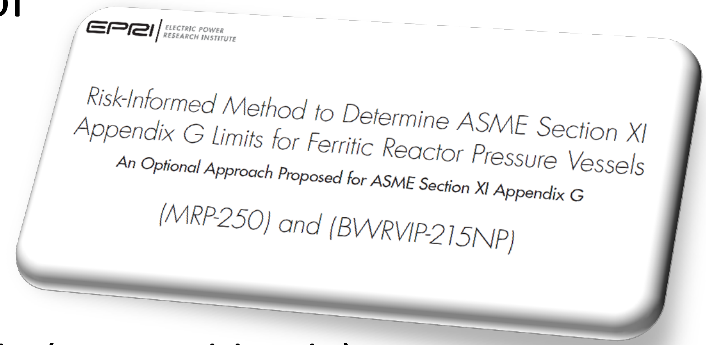
- Pressure-Temperature (P-T) Limits
  - Prevent non-ductile fracture of the reactor coolant pressure boundary
  - Impose limits on RCS operation
  - Based on LEFM analyses – establish minimum temperature necessary to ensure adequate margins against RPV failure as a function of pressure
    - Operate below/right of curve
    - Curve shifts as plant ages due to irradiation
  - Reside in plant Tech. Specs.



- P-T Limits Regulations and Guidance
  - 10 CFR 50, Appendix G: Fracture Toughness Requirements
    - Invokes ASME Code Section XI Nonmandatory Appendix G methodology for P-T curve development
  - RG 1.99, Rev. 2: Radiation Embrittlement of Reactor Vessel Materials

NRC Research Activities

- 2007: NRR developed User Need Request (UNR) 2007-001 that requested RES to re-evaluate the technical basis of 10 CFR 50 Appendix G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Risk-Informed Method to Determine ASME Section XI Appendix G Limits for Ferritic Reactor Pressure Vessels

An Optional Approach Proposed for ASME Section XI Appendix G

(MRP-250) and (BWRVIP-215NP)

- 2009: Industry publishes MRP-250, following on the investigation of NRC RES

- 2011:
  - MRP-250 recommendations adopted by ASME Code (2011 Addenda) as a "Risk-Informed (R-I) Alternative" in Section XI Nonmandatory Appendix G
    - NRC did not approve at ASME; disapproving in 10 CFR 50.55a Rulemaking
  - NRR requested that RES include an evaluation of the ASME Code R-I Alternative

- Now:
  - NRC staff evaluation of both the "Current ASME Code" and "R-I Alternative" approaches identifies two important issues:
    1. Shallow surface-breaking flaws (SBFs) – not considered in MRP-250 analysis
    2. Leak tests

Current NRR Position

- There are no immediate safety issues warranting any changes to Appendix G
- Working to understand research results
- Appendix G and RG 1.99 technical bases development on-going

Questions or Comments?

NRC Research Efforts on 10 CFR Part 50 Appendix G Reactor Pressure Vessel Fracture Toughness Requirements

U.S.NRC

Mark Kirk, Gary Stevens, Eric Focht, Mike Benson, and Josh Kusnick

Office of Nuclear Regulatory Research, Component Integrity Branch

OAK RIDGE National Laboratory

Terry Dickson, B. Richard Bass, and Paul Williams

Oak Ridge National Laboratory

Outline

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Protecting People and the Environment

- **Background and Objective**
  - Appendix G project
  - Probabilistic Fracture Mechanics Code “FAVOR”
- **Technical Issues #1 & #2**
  - Shallow inner-diameter surface breaking flaws & the FAVOR cladding model
- **Technical Issue #3**
  - Boiling water reactor leak tests

First, Some Definitions....

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Acronym	Description
CPI	**Conditional Probability of Initiation.** The probability that a pre-existing flaw initiates, conditioned on the occurrence of the loading being analyzed. Crack initiation occurs only by a brittle (cleavage) mechanism. The FAVOR code also checks for the possibility of ductile (upper shelf) initiation (but none has ever occurred for the conditions analyzed).
CPF	**Conditional Probability of Failure.** The probability that a pre-existing flaw initiates and propagates through the vessel wall, conditioned on the occurrence of the loading being analyzed. The possibility for cleavage, as well as ductile, crack growth, and vessel failure by ligament overload, is considered. A "through-wall" crack is assumed when the crack extends 90% through the vessel wall.
TWCF	**Through-wall cracking frequency.** TWCF is CPF weighted by the event frequency (yearly occurrence) of the analyzed loadings.
P-T Limits	**Pressure -temperature limits.** These are reactor operating limits established to prevent non-ductile failure of the reactor pressure vessel in accordance with the requirements of 10 CFR 50 Appendix G.
ASME (Current)	**Deterministically-based P-T limits and leak test temperatures** calculated according to the provisions of Articles G-2215 and G-2400, respectively, of ASME Code, Section XI, Nonmandatory Appendix G (adopted by ASME in the 1970s).
ASME (R-I)	**Risk-informed-based P-T limits and leak test temperatures** calculated according to the provisions of Articles G-2216 and G-2500, respectively, of ASME Code, Section XI, Nonmandatory Appendix G (adopted by ASME in 2011).

Background and Objective

THE APPENDIX G PROJECT

Request for Evaluation of 10 CFR 50 Appendix G

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- NRR User Need Request 2007-001
  - Requests evaluation of 10 CFR 50 Appendix G **(CFR-G)**, including possibility of risk-informed revision
- 10 CFR 50 Appendix G incorporates Nonmandatory Appendix G to Section XI of the ASME Code **(ASME-G)** by reference unless excluded by 50.55a
  - Effectively makes ASME-G part of Federal law unless excluded by 10 CFR 50.55a
- Joint provisions of CFR-G & ASME-G address
  - **P-T limits for normal operations (heatup, cooldown, leak test)**
  - Minimum temperature requirements for flange
  - Modifications to P-T limits caused by stress concentrations (nozzles)
  - Limits on CVN upper shelf energy

The "Risk-Informed" Alternative

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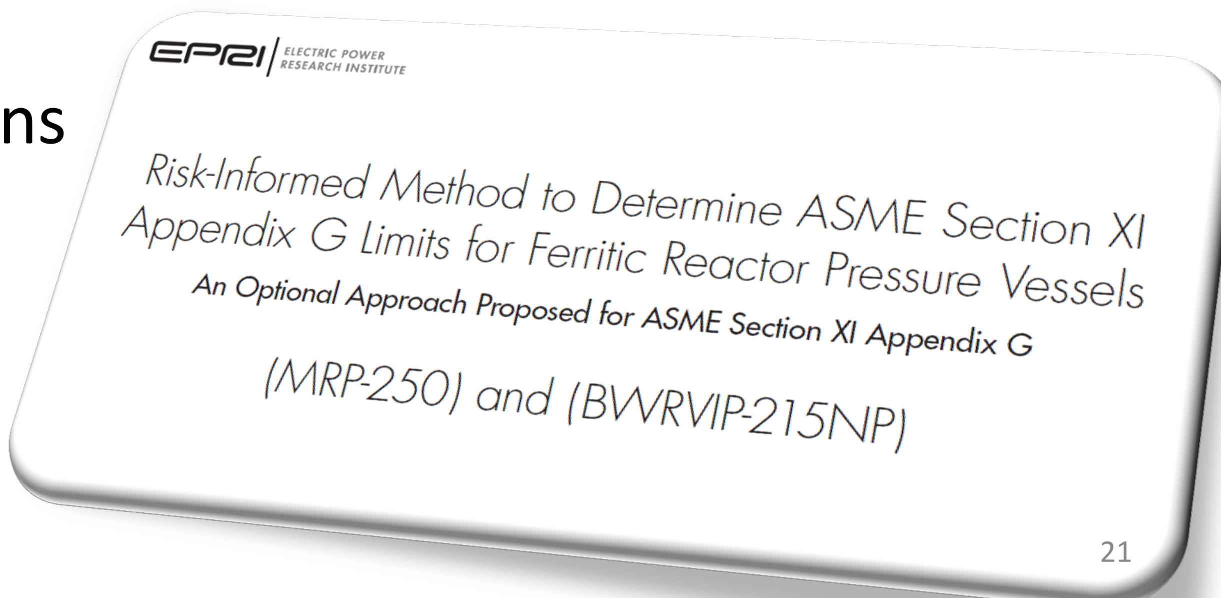
- **<u>2009</u>**: EPRI report providing technical basis for risk-informed alternative cooldown, heatup, and leak test limits
- **<u>2011</u>**: These recommendations adopted by ASME Code (2011 Addenda)
- **<u>Now</u>**: Included evaluation of the R-I alternative as part of NRR-UNR-2007-001 work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Risk-Informed Method to Determine ASME Section XI Appendix G Limits for Ferritic Reactor Pressure Vessels

An Optional Approach Proposed for ASME Section XI Appendix G

(MRP-250) and (BWRVIP-215NP)

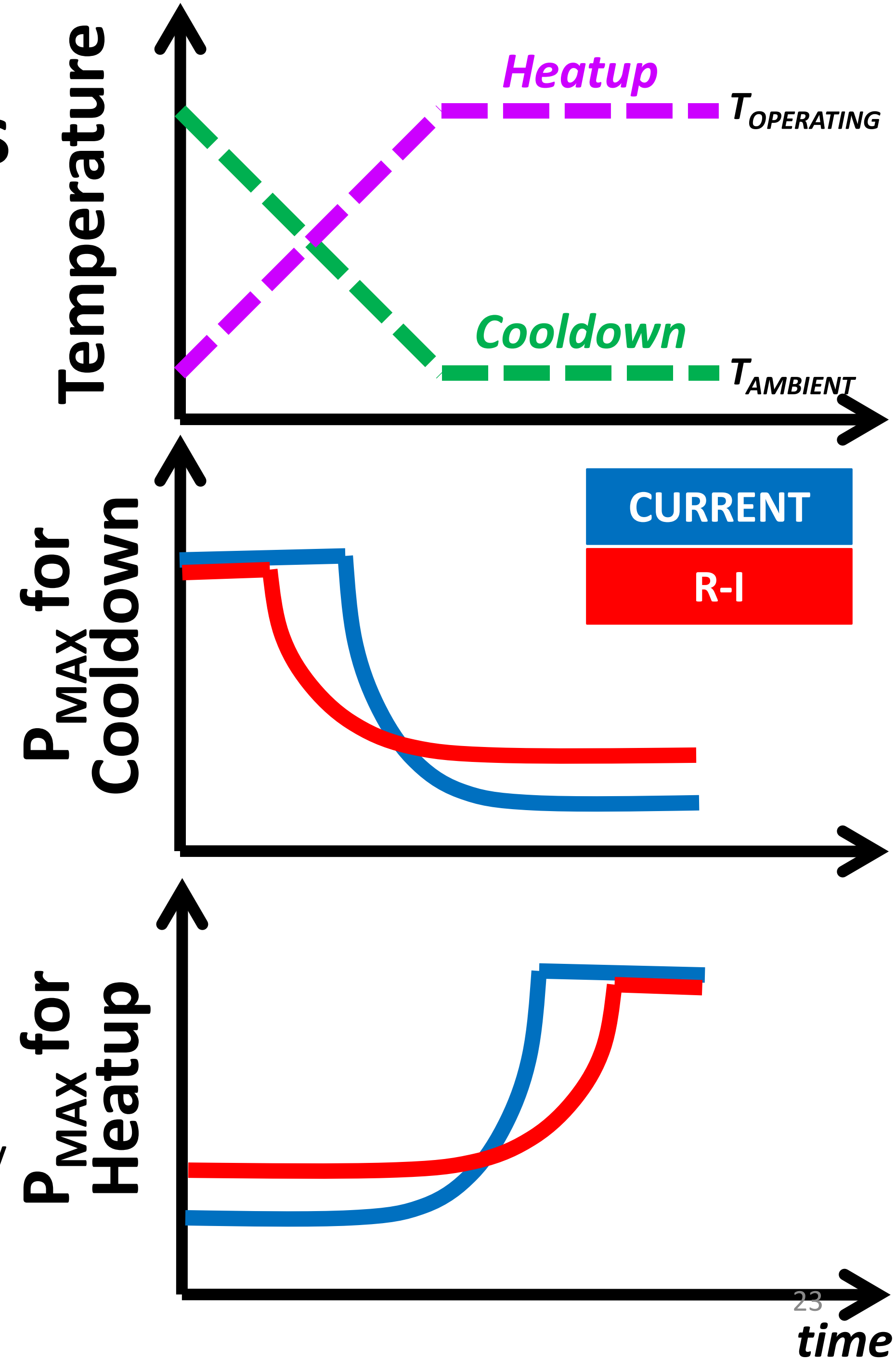
Today's Focus

- One aspect of the FAVOR PFM model (shallow through-cladding flaws) that influences significantly the results

- Operating pressure leak tests, as an example of:
  - The impact of shallow through-cladding flaws
  - A comparison of "current ASME" to "R-I ASME"

Staff's Approach to Evaluation of P-T Limits

- **Model of the RPV: FAVOR**
  - Same as used, reviewed, & approved, in PTS re-evaluation
  - Includes sub-models for flaw populations, embrittlement, toughness, attenuation, etc.
- **Loading**
  - Follows the P-T limits established by CFR-G & ASME-G
    - Recognized to be conservative
    - Based on PTS, failure probabilities believed to be low
    - Same approach used by industry
  - Also modeled actual & plant procedure loadings



Background and Objective

THE PFM CODE "FAVOR"

FRACTURE ANALYSIS OF VESSELS, OAK RIDGE

History of FAVOR

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Timeline

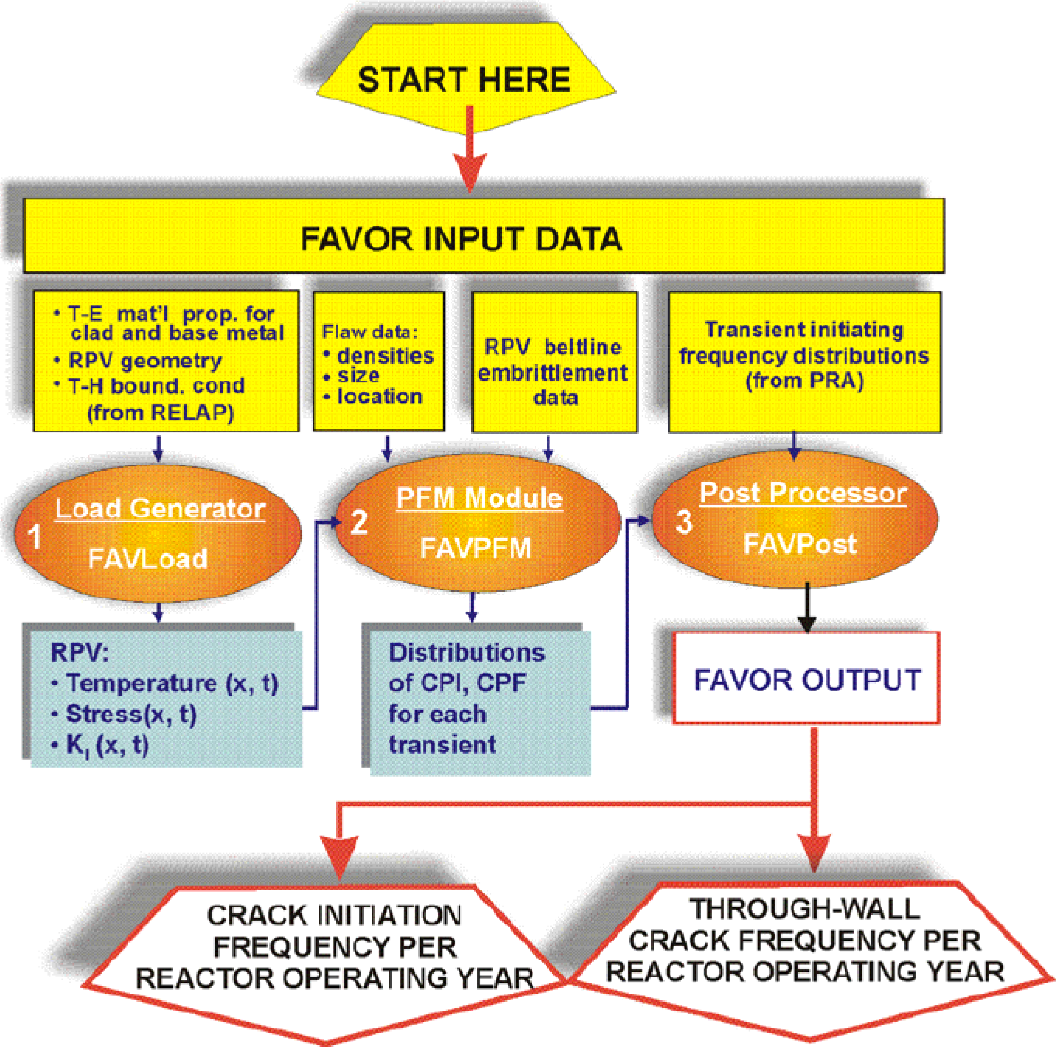
- Finds origin in PFM codes used for IPTS (80s) & Yankee Rowe (90s)
- 1995: 1st release of FAVOR
- 1999-2005: Significant development to support PTS project
  - Thorough evaluation of all models
  - Aleatory / epistemic distinction
  - Warm pre-stress
- 2009: Expanded to address
  - BWR geometries
  - Heatup (& leak test)
  - Flaws on or near the OD
- 2012: Most recent full release

Review, V&V, etc.

- 1999-2007: PTS re-evaluation
  - Thorough internal reviews of code and all models
  - 2007: V&V report (NUREG-1795)
  - 2007: External expert panel review (NUREG-1806, App. B)
- 2011: CNWRA/SWRI review
- Papers provide benchmarking of K solutions to ABAQUS (1995, 2000, 2004, 2010)

Structure of FAVOR

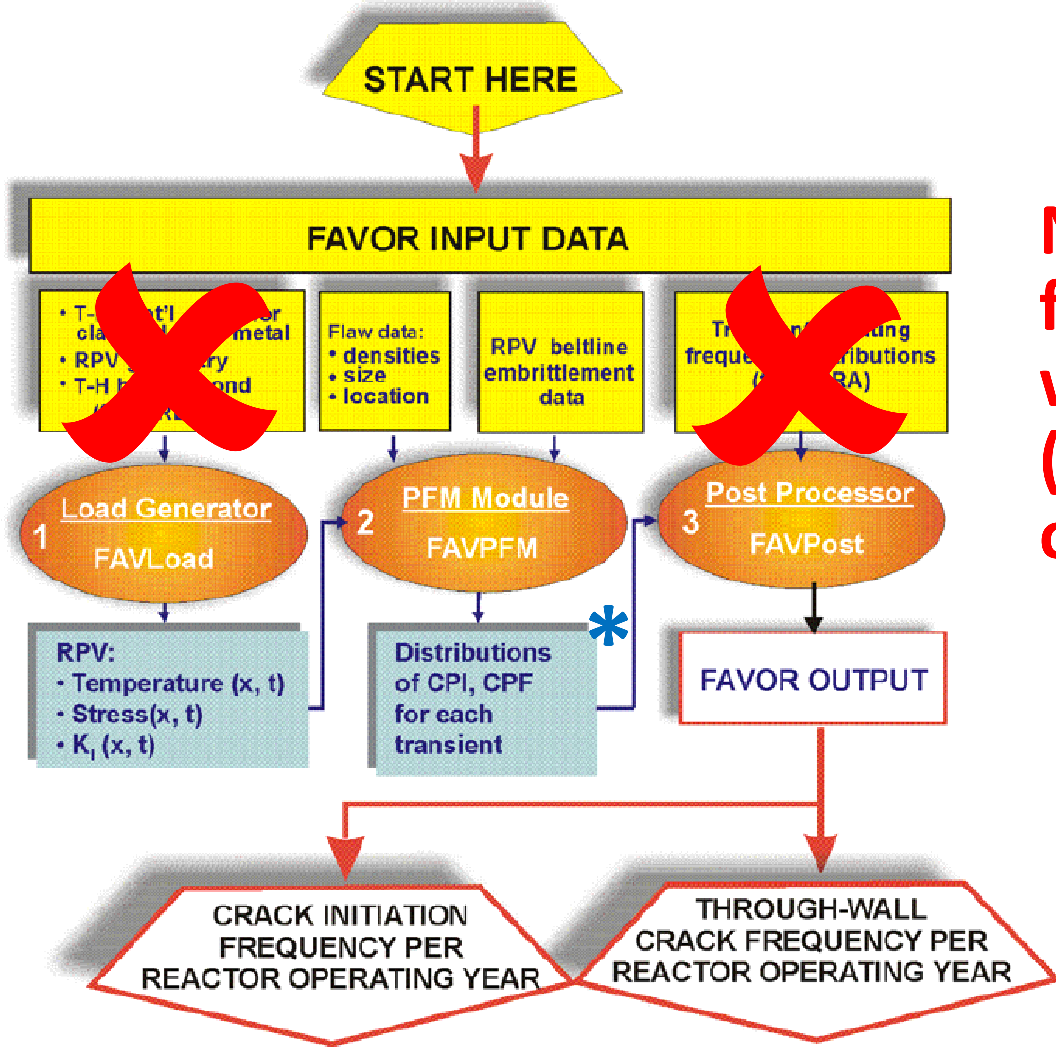
As used for PTS



Structure of FAVOR

As used in this study

Loading follows allowed P-T limits

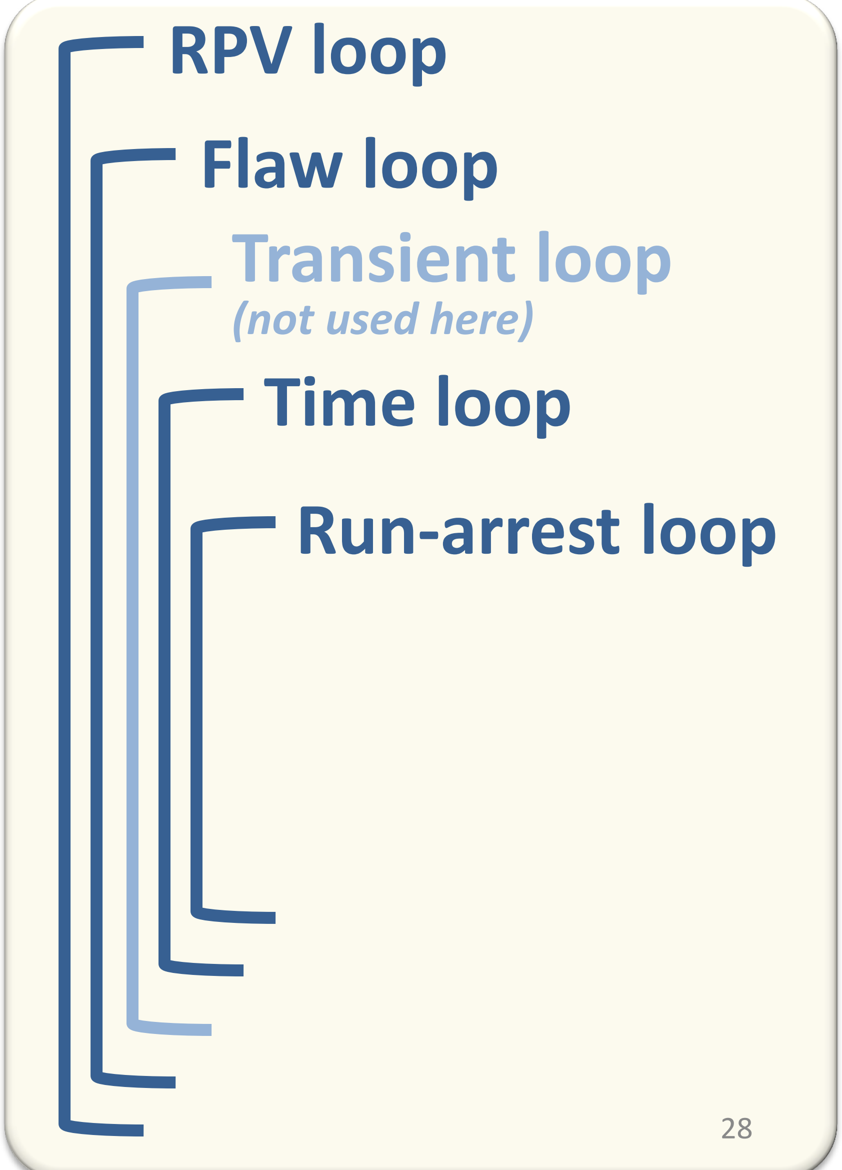


No event frequency weighting (at project outset)

* CPI = Conditional probability of crack initiation
CPF = Conditional probability of vessel failure

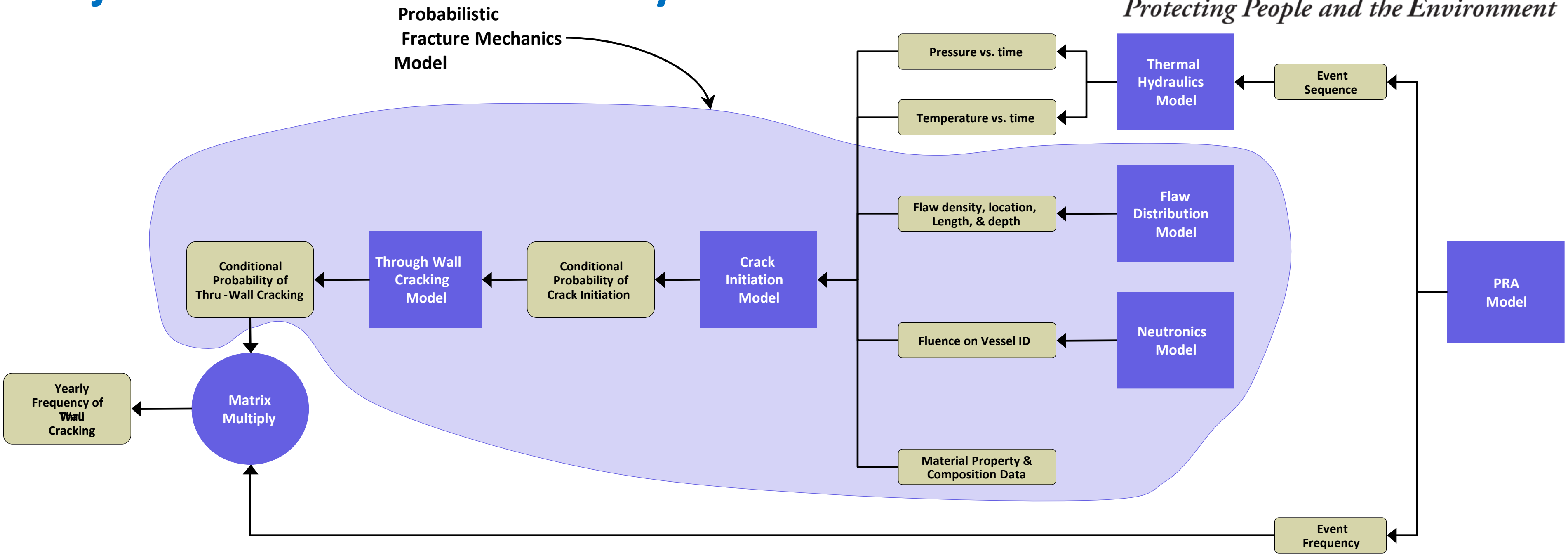
FAV-PFM Module

- Nested loop structure
- Monte Carlo simulation



FAVOR

Major Modules & Uncertainty Treatment

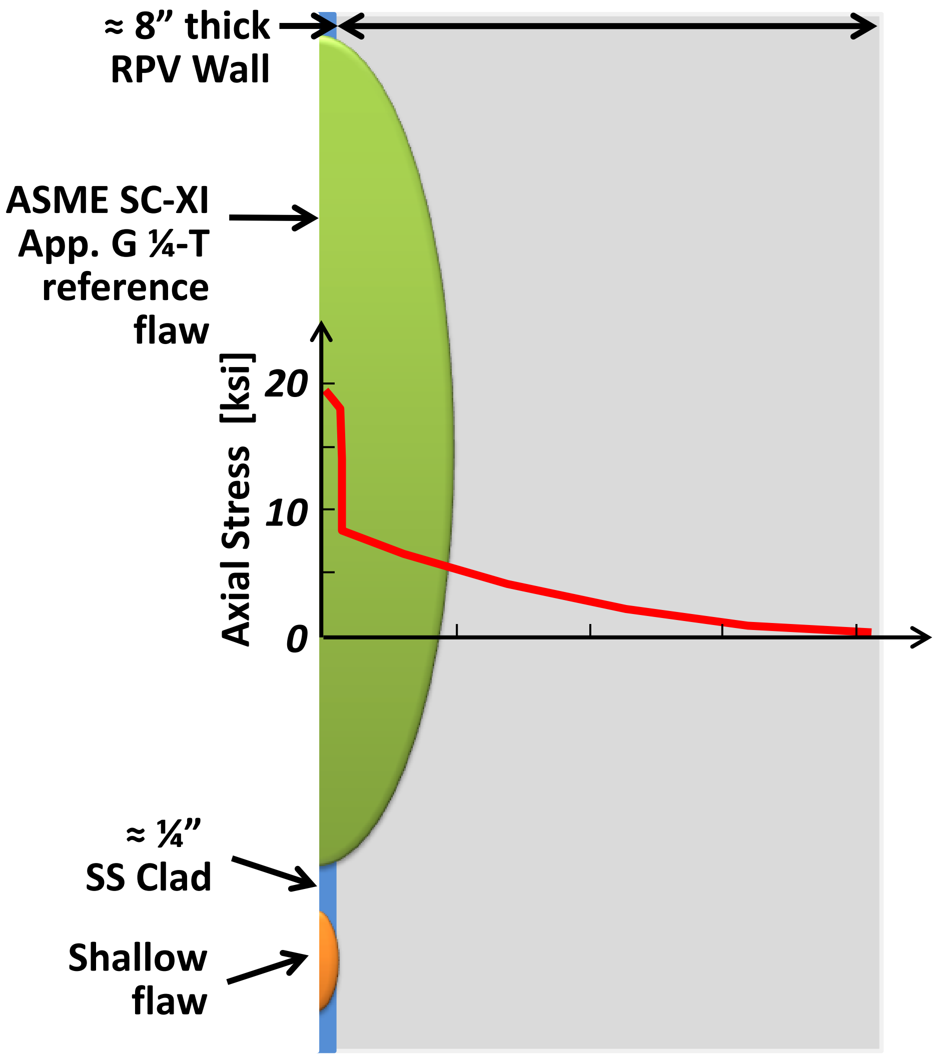


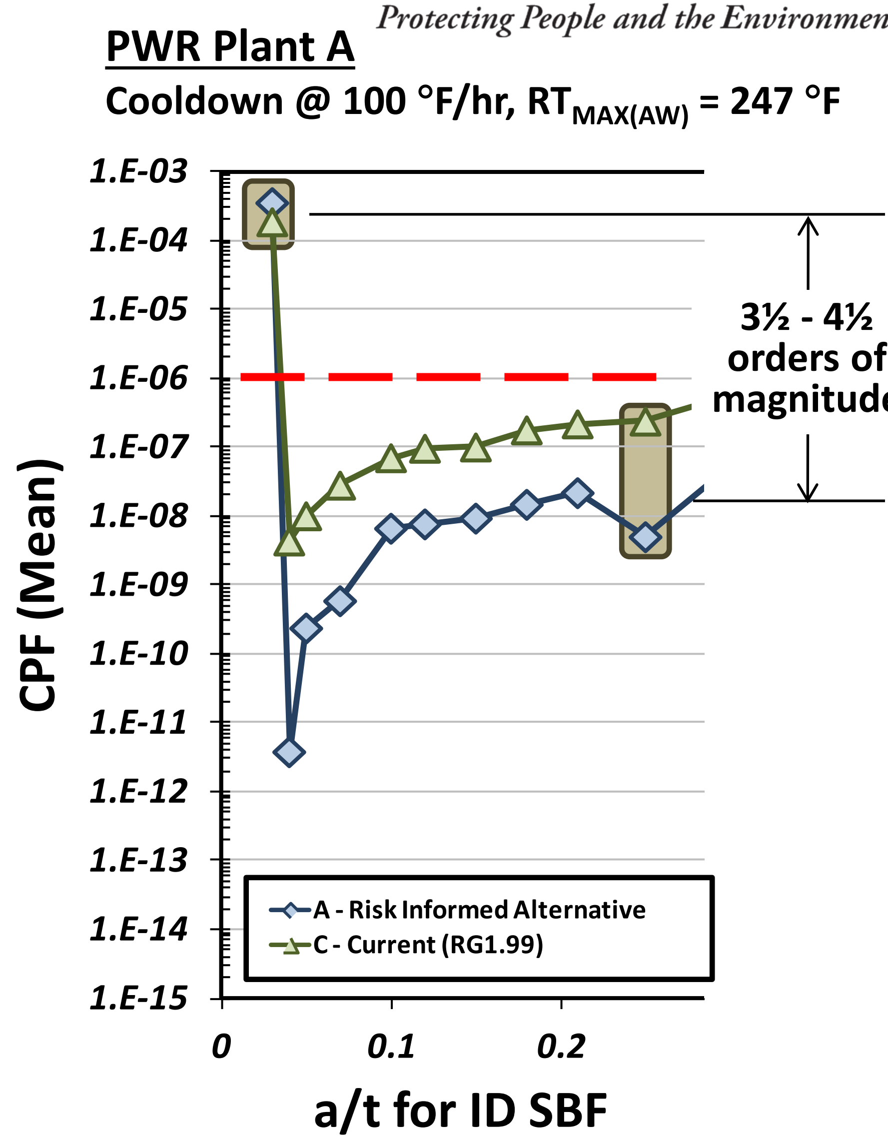
- **Treatment of uncertainties**
  - Assessed in all cases
  - Modeled if important/significant, aleatory or epistemic as appropriate
  - If less significant: represented as a constant
  - If not enough data: treated conservatively

Technical Issues #1 and #2

SHALLOW ID SURFACE BREAKING FLAWS (SBF) AND THE FAVOR CLADDING MODEL

Reason for Detailed Evaluation of Clad Model (& SBFs)





Clad Model & SBFs

Outline

- ORNL/TM-2012/489 provides full details
- Topics discussed here
  - **Flaws**: Basis for including SBFs in FAVOR's population of flaws sampled
  - **Stresses**: Additional stress generated by the cladding
    - Analytical representation
    - Experimental basis
  - **Probability**: Effect on FAVOR calculated initiation and failure probabilities
    - Normal cooldown following P-T limits
    - Normal cooldown following plant P-T records
    - Rapid (PTS) cooldowns

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ORNL/TM-2012/489

The Effect of Shallow Internal Surface-Breaking Flaws on the Probability of Brittle Fracture of Reactor Vessels Subjected to Normal Cool-Down Transients

Prepared by

Terry L. Dickson, B. Richard Bass, and Paul T. Williams
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Maryville, TN 37804

Prepared for
U.S. Nuclear Regulatory Commission

Prepared by
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Managed by
UT-BATTELLE, LLC
For the
U.S. DEPARTMENT OF ENERGY
Under contract DE-AC05-00OR22725

SBFs in Cladding

Basis

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Nondestructive & destructive evaluation of PVRUF RPV

46 sq-ft of cladding

[1998-2000]

Welding simulations using the PRODIGAL code
[Chapman & Simonen, 1998]

Cladding exams at Bettis
[Li & Mabe, 1998]

NRC Expert Elicitation
[Jackson & Abramson 2000]

NUREG/CR-6817, Rev. 1, Simonen, et al., *"A Generalized Procedure for Generating Flaw Related Inputs for the FAVOR Code,"*

[2003]

FAVOR Clad SBF Model

- **All flaws oriented circumferentially**
- **All flaws of depth = cladding thickness (rounded up to nearest 1/100th of wall thickness)**
- **Distribution of aspect ratios from 2:1 to ∞**
- **0.0037 flaws/ft^2 of ID area (≈2-3 per vessel)**

ORNL/TM-2012-489 (Section 2.1)

- **Reviews CR6817 & operating experience**
  - **IGSCC in Quad Cities 2**
  - **IGSCC in Japan Power Doubling Reactor**
- **No significant new data/knowledge on this topic has become available since 2003**

SBFs in Cladding

Current Evaluation

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- Based on NUREG/CR 6817(R1) & ORNL/TM-2012-489, the staff finds the model of SBFs size and density in FAVOR acceptable

- The industry's model supporting the R-I additions to ASME SC-XI App. G [EPRI MRP-250] did not consider SBFs

- For SBFs, FAVOR calculates high CPI/CPF values for both the R-I and current ASME methods

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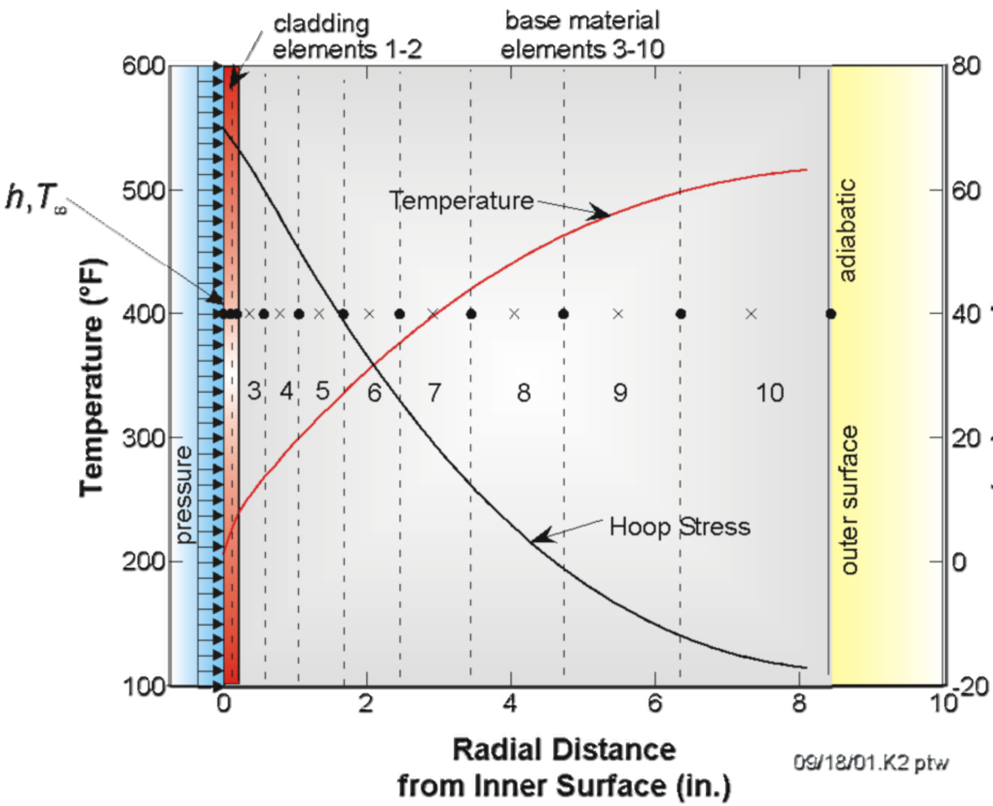
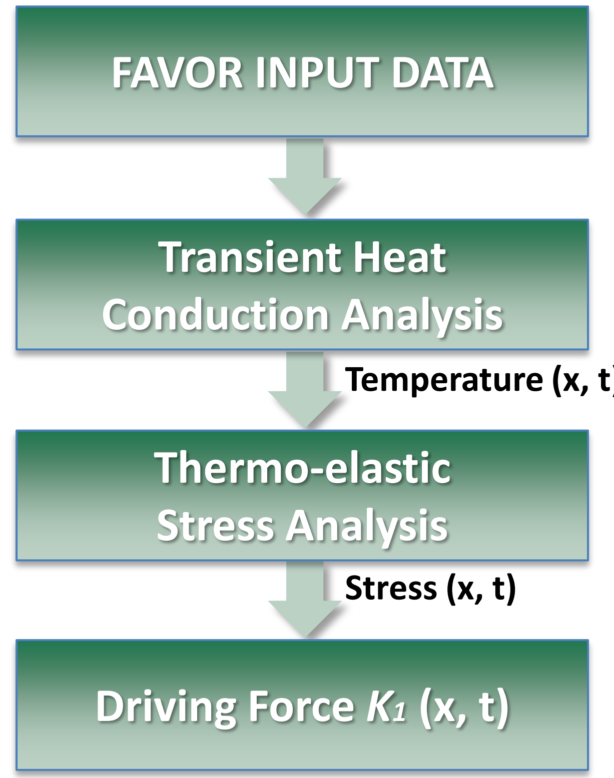
FAVOR Clad Stress Model

Transient heat conduction & thermo-elastic stress analyses performed using 1D axisymmetric finite element model of un-cracked RPV wall.

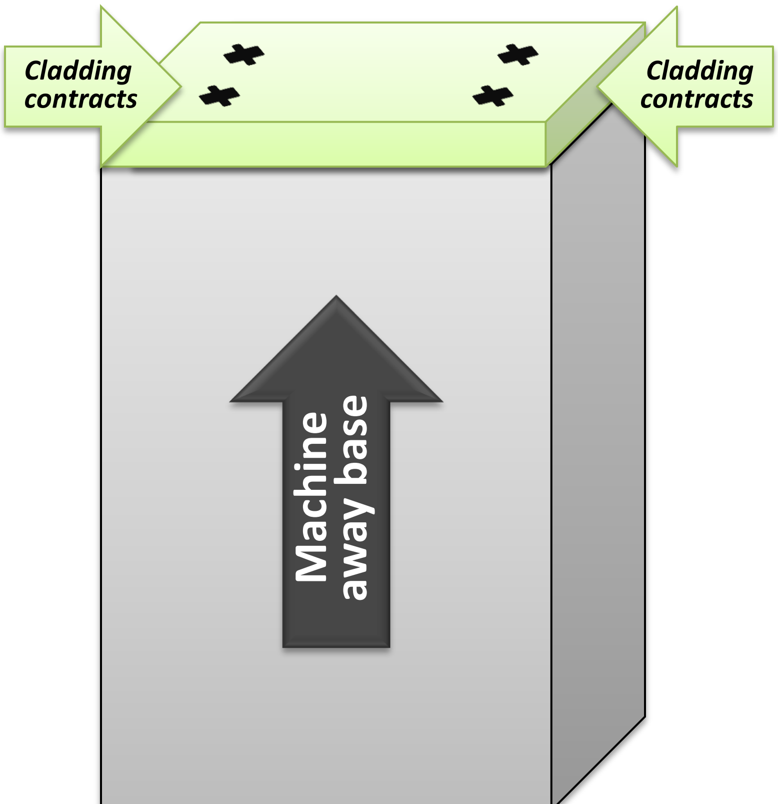




$$\sigma_{\theta\theta} = \frac{E}{(1+\nu)(1-2\nu)}\left[(1-\nu)\varepsilon_{\theta\theta} + \nu\varepsilon_{rr}\right] - \frac{\alpha E}{1-2\nu}(T - T_{ref})$$

Next: Determine T_{ref} from measurements

Determine T_{ref} from Measurements on PVRUF



Measured Displacements from Test Blocks at 70°F

↓

Displacements used as Inputs to Finite Element Analysis

↓

Produces 21.3 ksi Tensile Stress in Clad at 70 °F due to Differential Thermal Expansion

↓

Model RPV with Assumed Uniform Temperature at 70°F

↓

Stress Free Temperature of 488 °F Produces Tensile Stress of 21.3 ksi in Clad at 70 °F *

* Clad stresses, and therefore applied-K, are maximum when the RPV is cold.

Applied K During a Cooldown

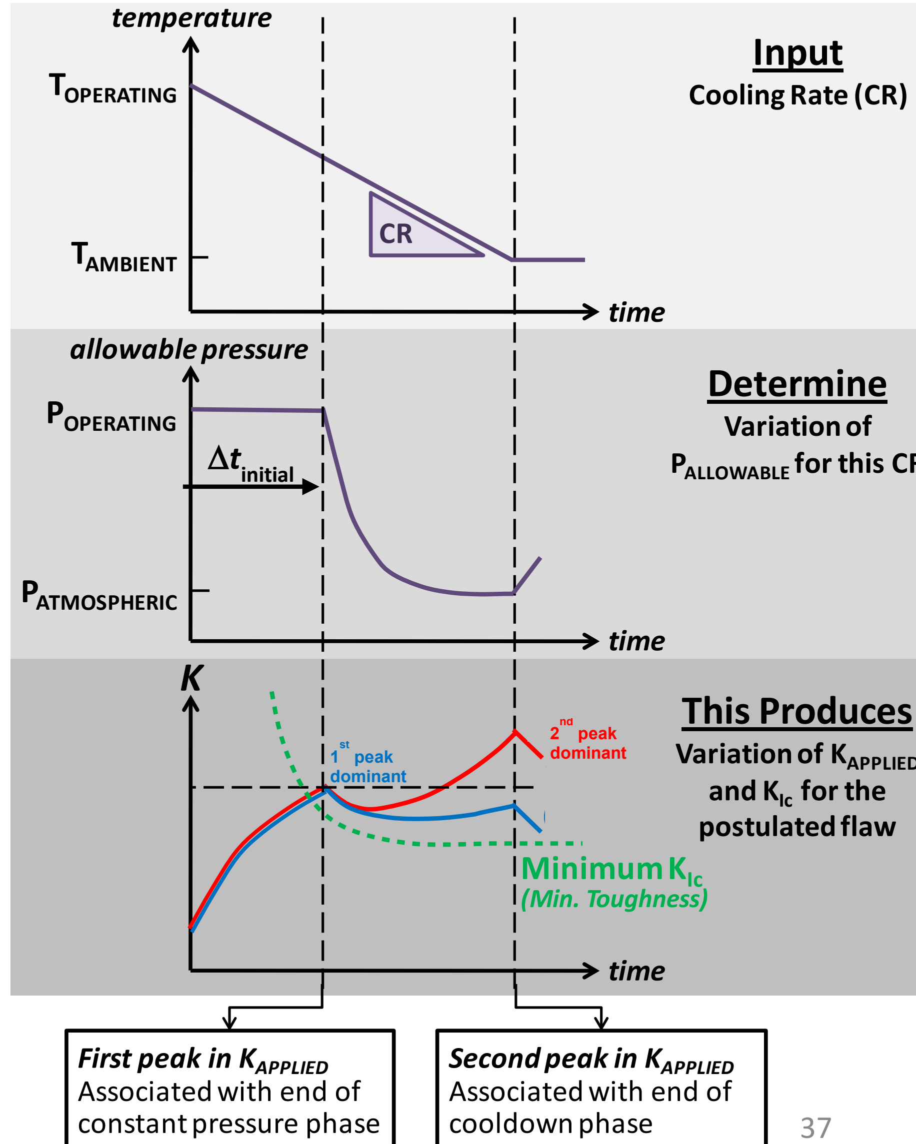
Schematic

- Greatest ΔT from stress free temperature of 488 °F occurs at room temperature

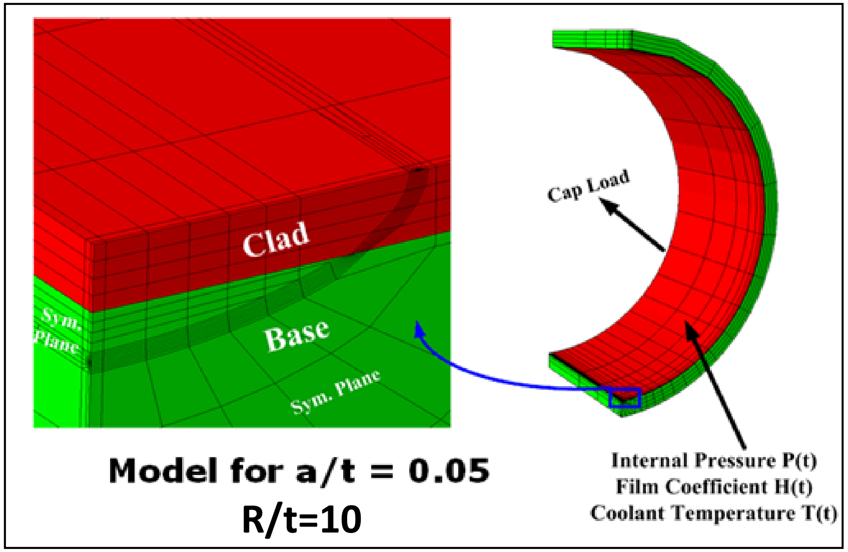
- Depending on specific
  - Flaw,
  - Cooling rate,
  - Geometry, etc.

  this can generate the peak K for the transient

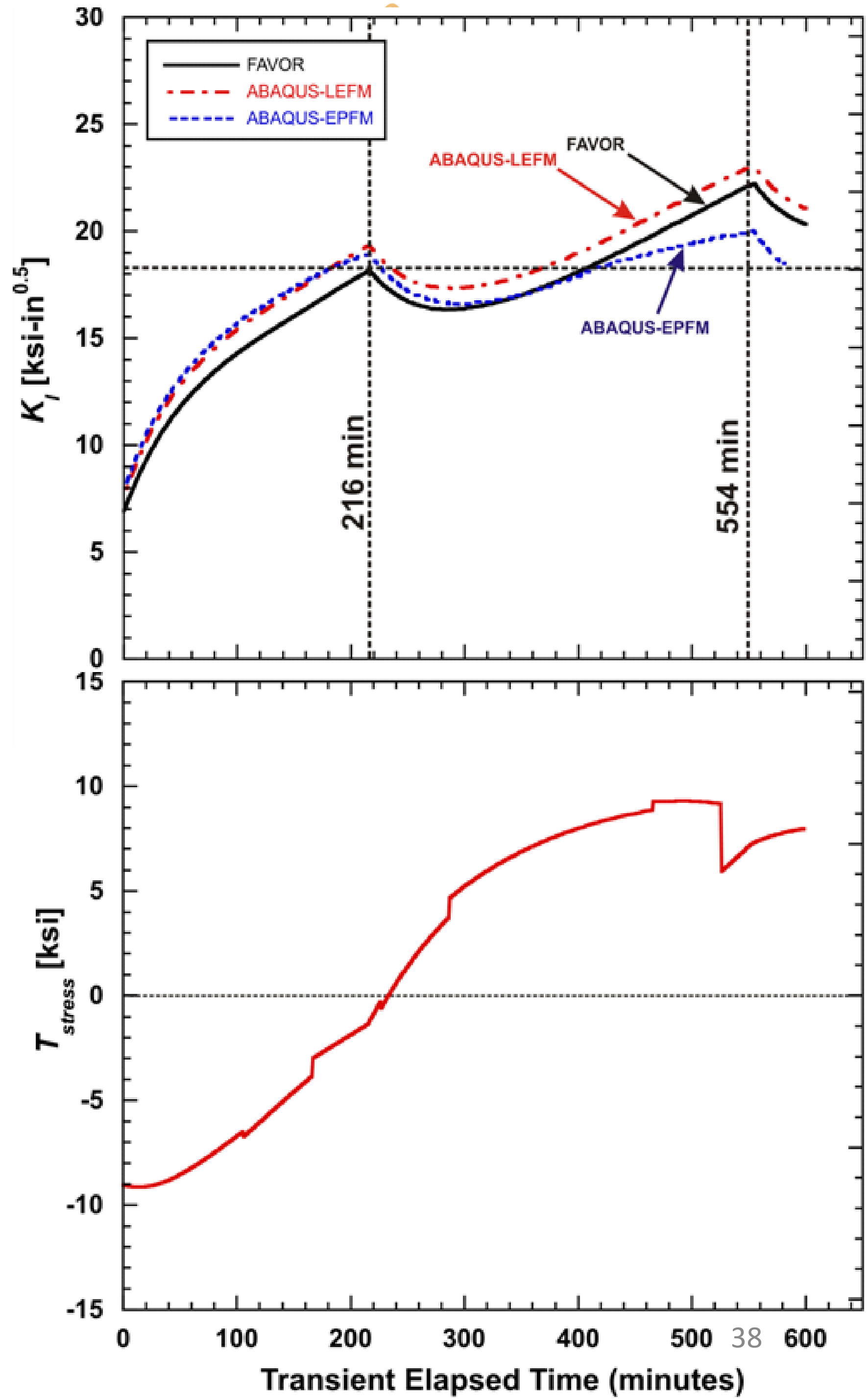
- If peak K exceeds minimum toughness, this controls failure probability



FAVOR K Solutions Compared to ABAQUS



- **LEFM**: FAVOR within 4% of ABAQUS (much less difference when crack depth not interpolated)
- **EPFM**
  - FAVOR within 13% of ABAQUS
  - Plasticity mitigates, but does not eliminate, the 2nd peak
- **Constraint loss?**: Even shallow flaws have high constraint at 2nd peak, so single parameter flaw assessment as done in FAVOR remains appropriate



Comparison of CPF for Actual *vs.* P-T Limit Cooldowns

Analysis of one transient (from ≈50 available)

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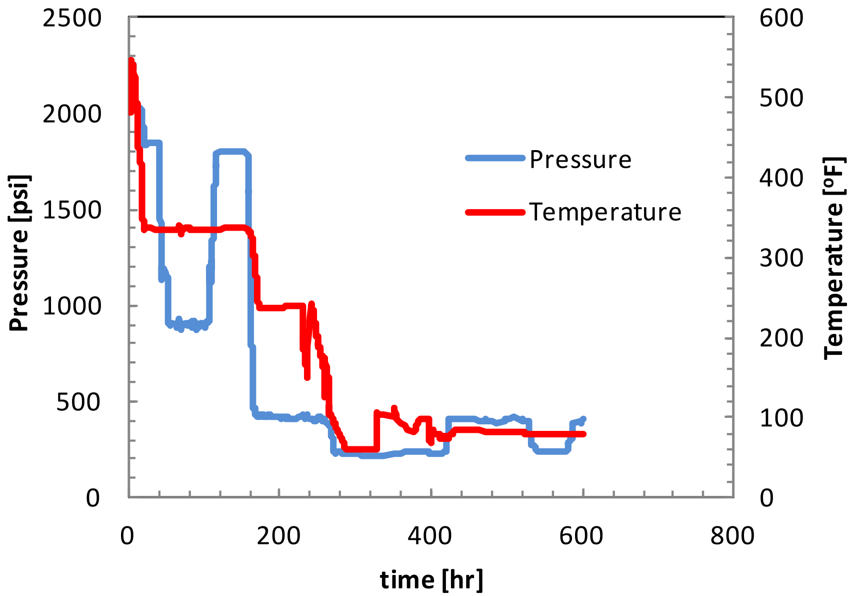
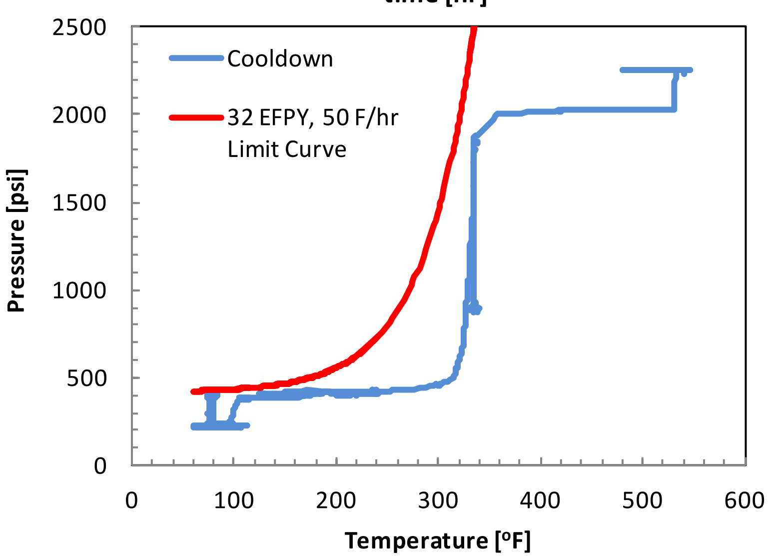
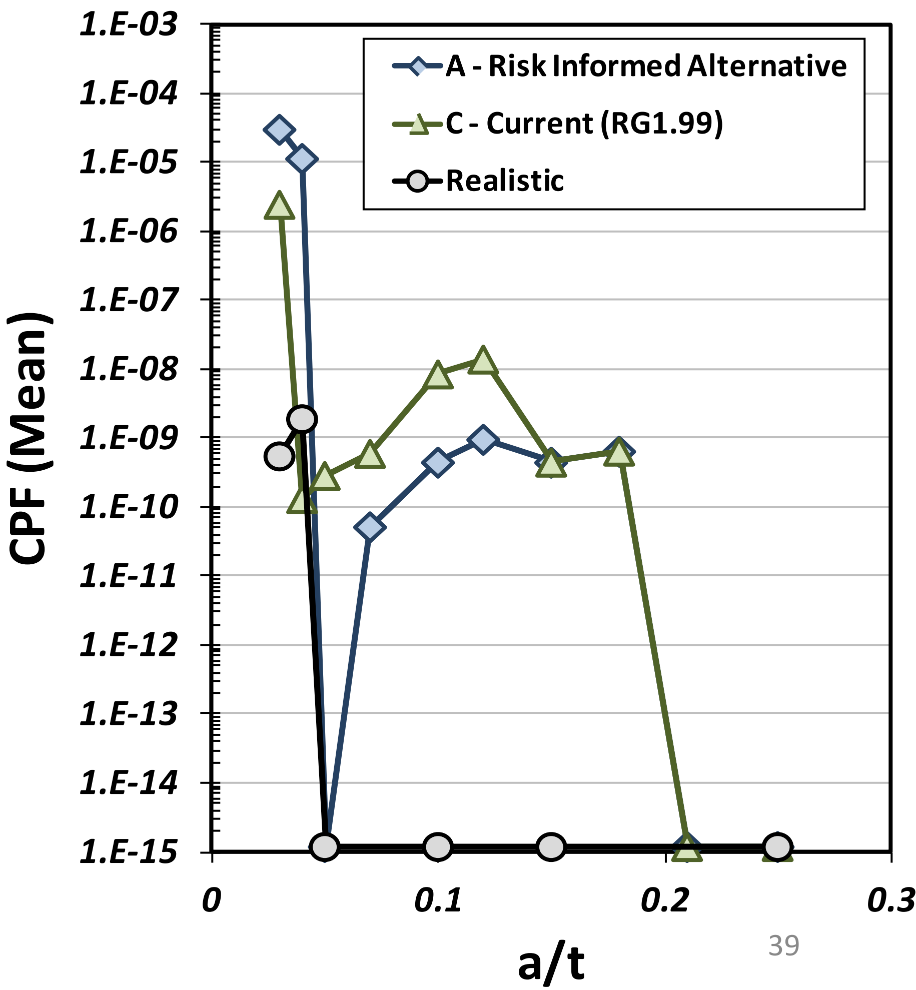




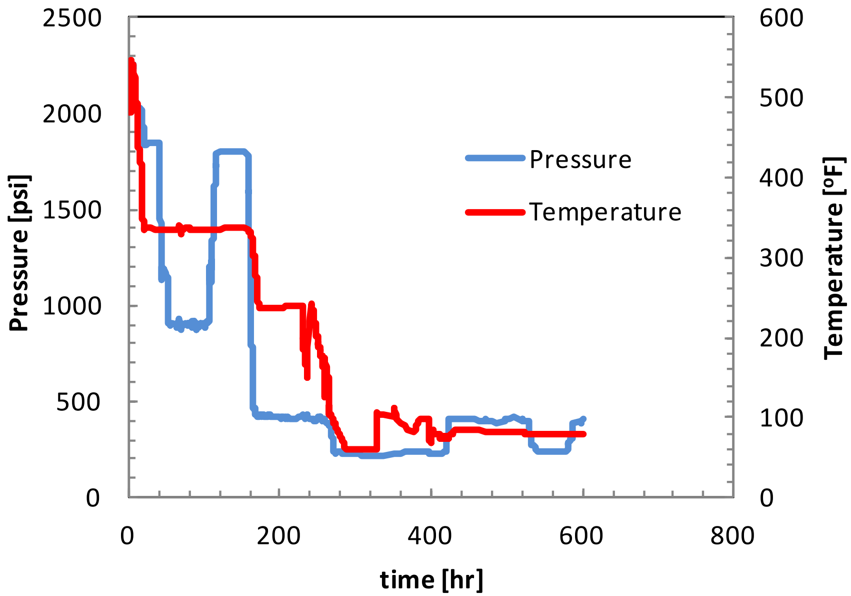
PWR Plant A

50 °F/hr, $RT_{MAX(AW)}$ = 222 °F



Comparison of CPF for Actual *vs.* P-T Limit Cooldowns

Analysis of one transient (from ≈50 available)



PWR Plant A

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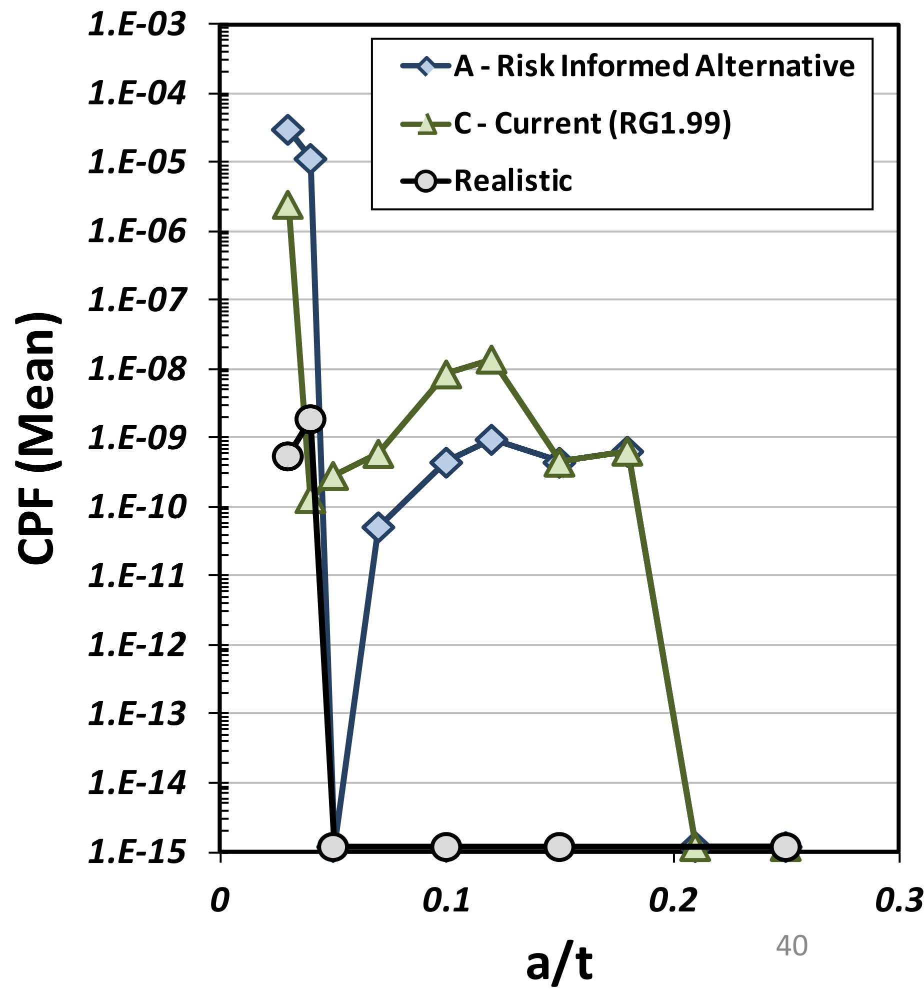

- Only shallow SBFs have non-zero CPF
- R-I transient has higher CPF than actual transient
- Current practice transient has CPF about the same as actual transient

Comparison of CPF for Actual *vs.* P-T Limit Cooldowns

Summary

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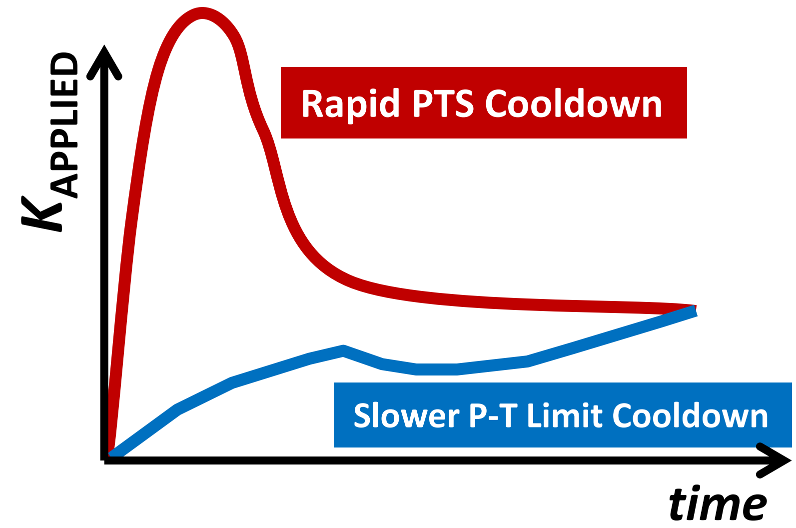
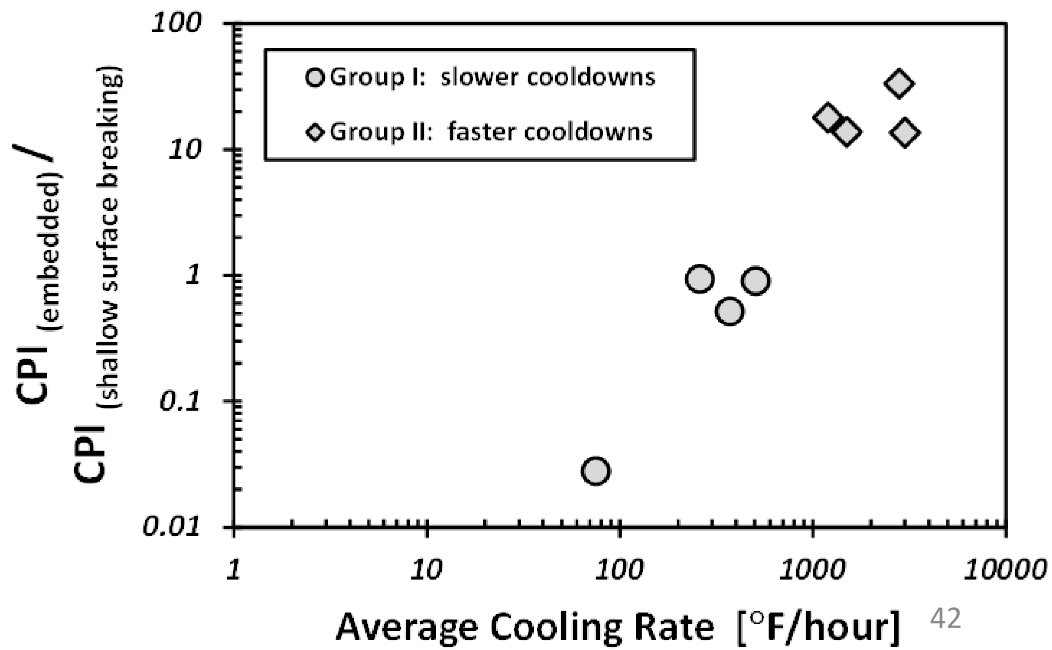
- **Considerable difference between P-T limits and actual cooldowns**
  - Other plant specific factors place constraints upon the actual cooldown curve in addition to those imposed by the CFR-G & ASME-G P-T limits
  - The CFR-G & ASME-G P-T limits are the current regulatory requirements
- **From these analyses**
  - Actual cooldowns have much lower CPF than cooldowns following P-T limits
  - 2^{nd} peak in applied K still generates CPF for shallow flaws
  - Maximum calculated CPF = 10^{-9}

Effect of Cooldown Rate on CPI & CPF of SBFs

- SBFs not significant for PTS cooldowns (generally rapid)
- Rapid cooldown associated with accident transients produces high applied-K early, suppressing dominance of late peak in applied-K produced by cladding
- Assessment of PTS cooldowns in ORNL/TM-2012/489
  - below ≈ 100 °F/hr shallow flaws in cladding dominate CPI & CPF relative to embedded flaws





Clad Model & SBFs

Summary

- **Flaws**
  - Model established in NUREG/CR 6817(R1)
  - Staff continues to find this model acceptable
- **Stresses**
  - Simplified model, based on experiments
  - Benchmarked successfully to ABAQUS
  - Clad stresses maximum at room temperature
- **Probability**
  - Higher for cooldowns along P-T limits
  - Lower for actual cooldowns
  - SBFs significant only at slow cooling rates

ORNL/TM-2012/489

The Effect of Shallow Internal Surface-Breaking Flaws on the Probability of Brittle Fracture of Reactor Vessels Subjected to Normal Cool-Down Transients

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Technical Issue #3

OPERATING PRESSURE LEAK TESTS IN BOILING WATER REACTORS

Examination of Leak Tests in BWRs

TLR-RES/DE/CIB-2014-009

United States Nuclear Regulatory Commission

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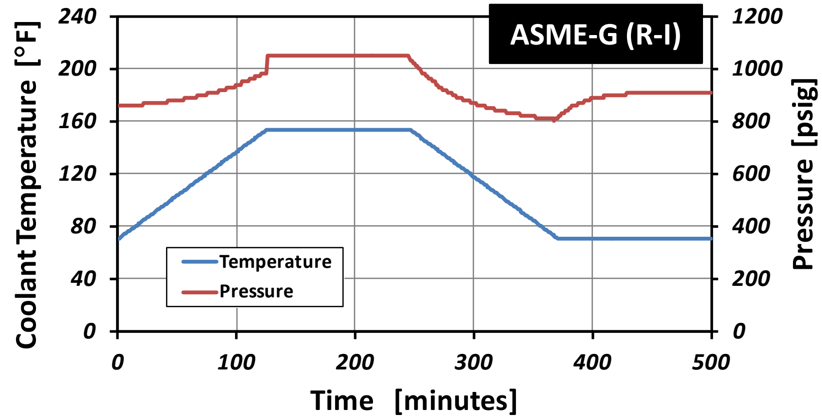
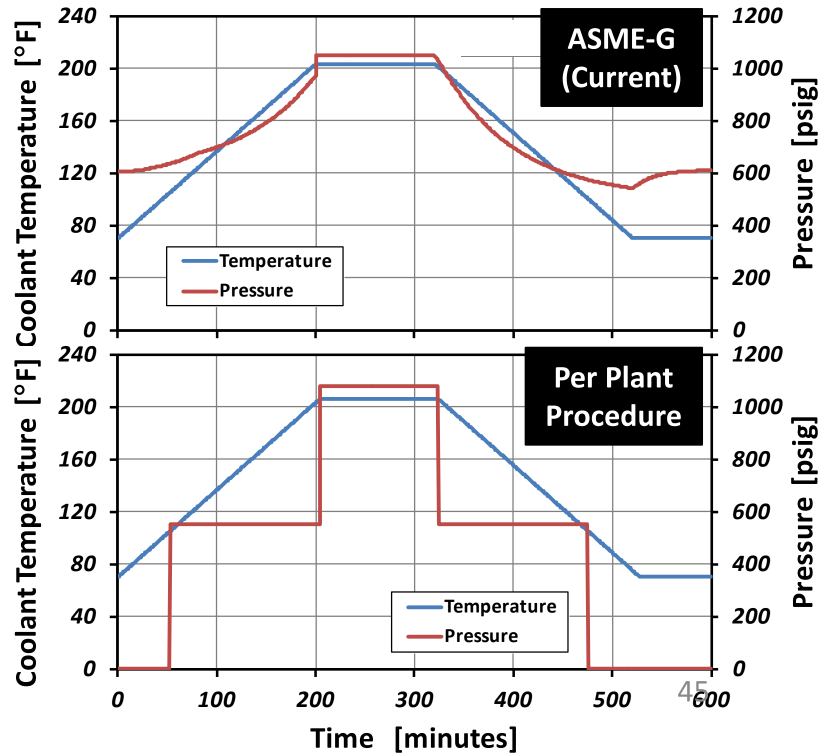
- Used ***as an example*** of the challenges presented by SBFs
- Leak tests include both heatup and cooldown
- In BWRs, leak tests occur at the start of every operating cycle
  - Between 1/year and 0.5/year
- So for leak tests, CPF ≈ through wall cracking frequency
  - 10^{-6}/year limit on TWCF used in PTS re-evaluation project





Loadings Examined

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Leak Test Temperature

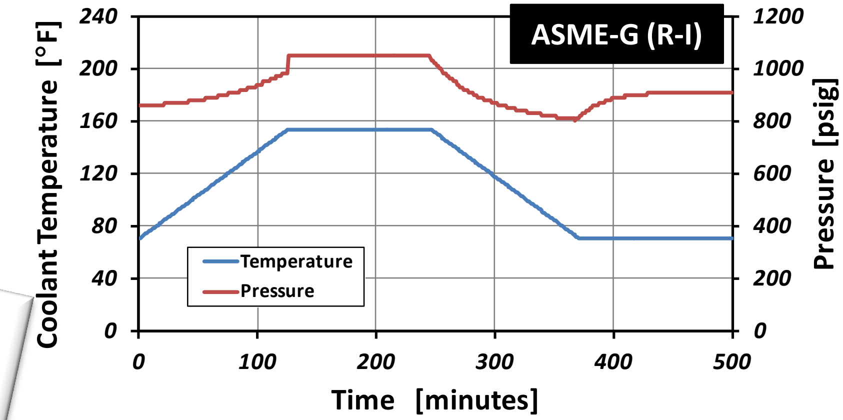
$$T_{LEAK} - RT_{NDT(I)} = Margin + \beta + \frac{1}{0.02} \times ln\left\{\frac{F_2 \times Rate \times t^{2.5} + \frac{\alpha \times F_1 \times P_{OPER} \times R_i}{\sqrt{t}} - 33.2}{20.734}\right\}$$

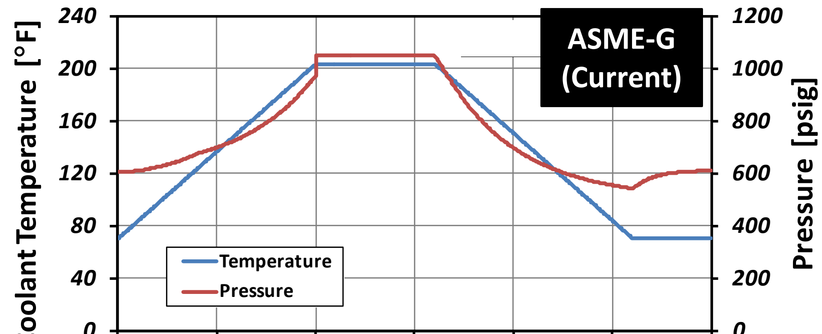
Max Pressure

$$P_{MAX} = [33.2 + 20.734exp[0.02(T - \{RT_{NDT} + \beta\})] - F_2 \times Rate \times t^{2.5}] \times \left[\frac{t}{R_i}\right] \times \left[\frac{1}{\alpha F_1 \sqrt{t}}\right]$$

		Current	R-I
Leak	α	1.5	1
	β	0	60
ETC		RG1.99	50.61a
Margin		RG1.99	zero

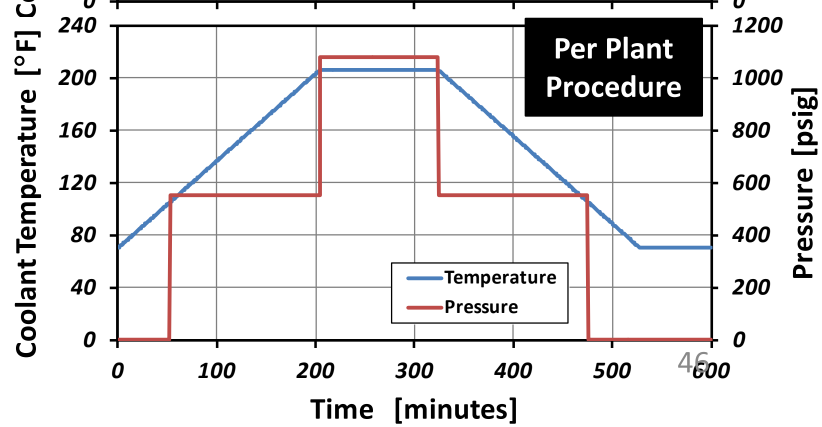
Following P-T Limits





	Plant Procedure
ETC	RG1.99
Margin	RG1.99

Following BWR Plant Procedure



Flaws, or Flaw Populations, Examined

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- Flaw populations that formed the basis of 10 CFR 50.61a
  - NUREG/CR-6817(R1) (i.e., FAVOR) embedded flaw population
  - NUREG/CR-6817(R1) (i.e., FAVOR) population of cladding SBFs on the vessel ID
- The single ¼-t 6:1 surface breaking flaw that establishes P-T limits
  - For comparison to failure probabilities for flaws that formed the basis of 10 CFR 50.61a
  - To assess the current ASME approach

CPI and CPF Results

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- Table summarizes results for the condition examined
- Results for other plants (other R/t) and lower embrittlement levels similar
- Following slides examine each flaw population individually

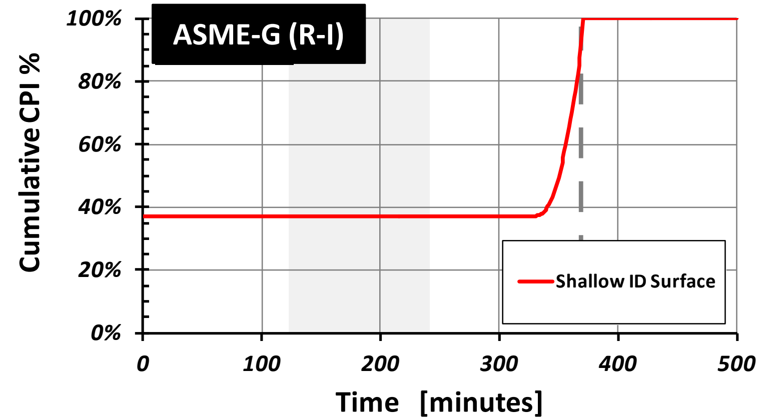
Loading Method	Surface breaking flaw population(1)		Embedded flaw population		Individual 6:1 ¼t surface breaking flaw	
	CPI(2)	CPF(3)	CPI	CPF	CPI	CPF
ASME-G (R-I)	1.8E-4	1.6E-4	5.7E-8	5.7E-8	7.2E-5	7.2E-5
ASME-G (Current)	6.7E-5	4.3E-5	1.0E-14	1.0E-14	1.7E-6	1.7E-6
Per Plant Procedure	8.6E-6	2.9E-6	2.5E-13	2.3E-13	1.7E-6	1.7E-6

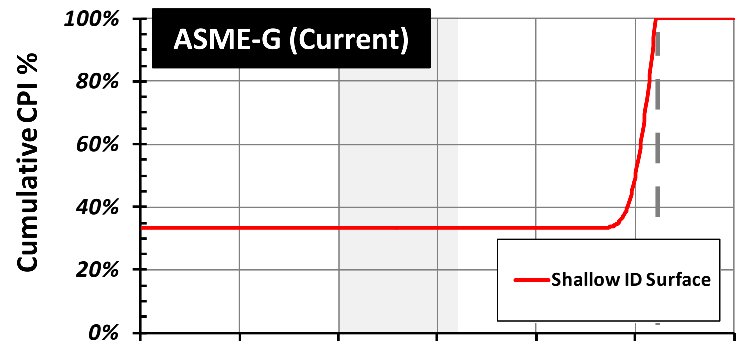
Notes:
(1) The surface flaw depth is 0.04t as this is the flaw depth that penetrates the cladding thickness (rounded up to the nearest 1/100th of the total vessel wall thickness). This depth conforms to the FAVOR flaw model used in the development of 10 CFR 50.61a [15].
(2) CPI: Conditional probability of crack initiation.
(3) CPF: Conditional probability of vessel failure (i.e., through-wall cracking).

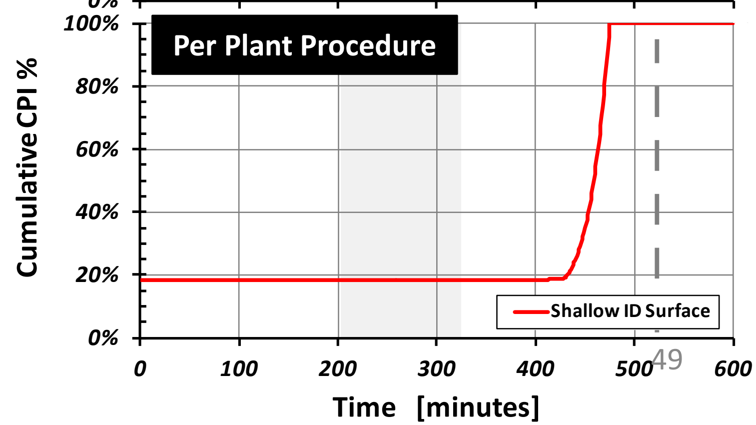
SBFs

Time of CPI/CPF Accumulation

- Irrespective of loading method, all CPI/CPF accumulates when the RPV is near room temperature





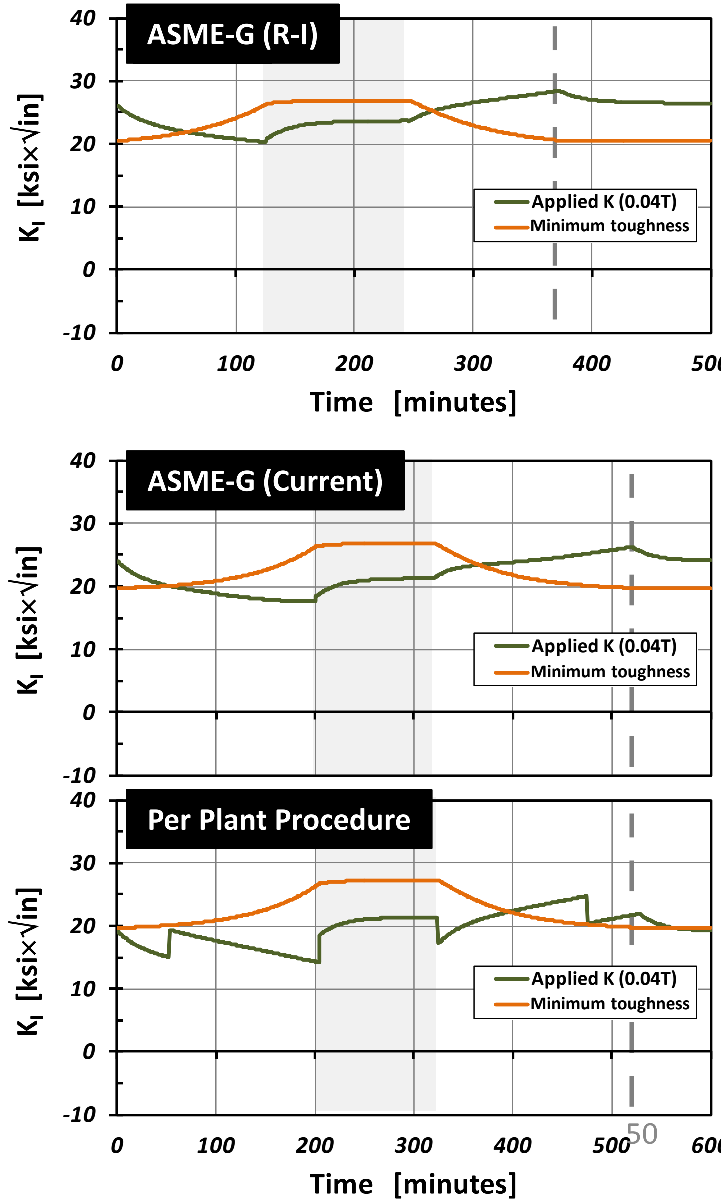


SBFs

Applied K *vs*. time

- Irrespective of loading method, all CPI/CPF accumulates when the RPV is near room temperature

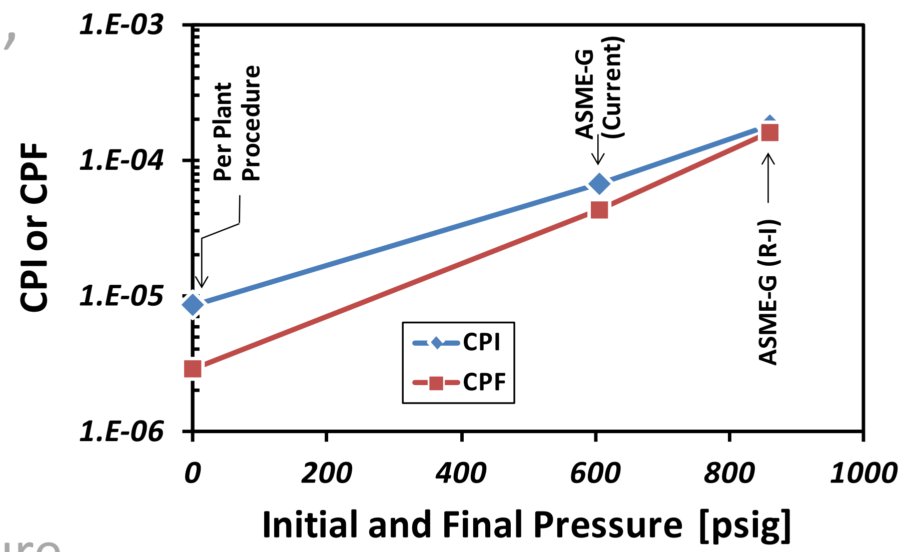
- Applied K exceeds toughness only at these times, not during the pressure hold that constitutes the leak test
  - Changing the leak test temperature and/or pressure will not change this result



SBFs

Effect of Initial/Final Pressure

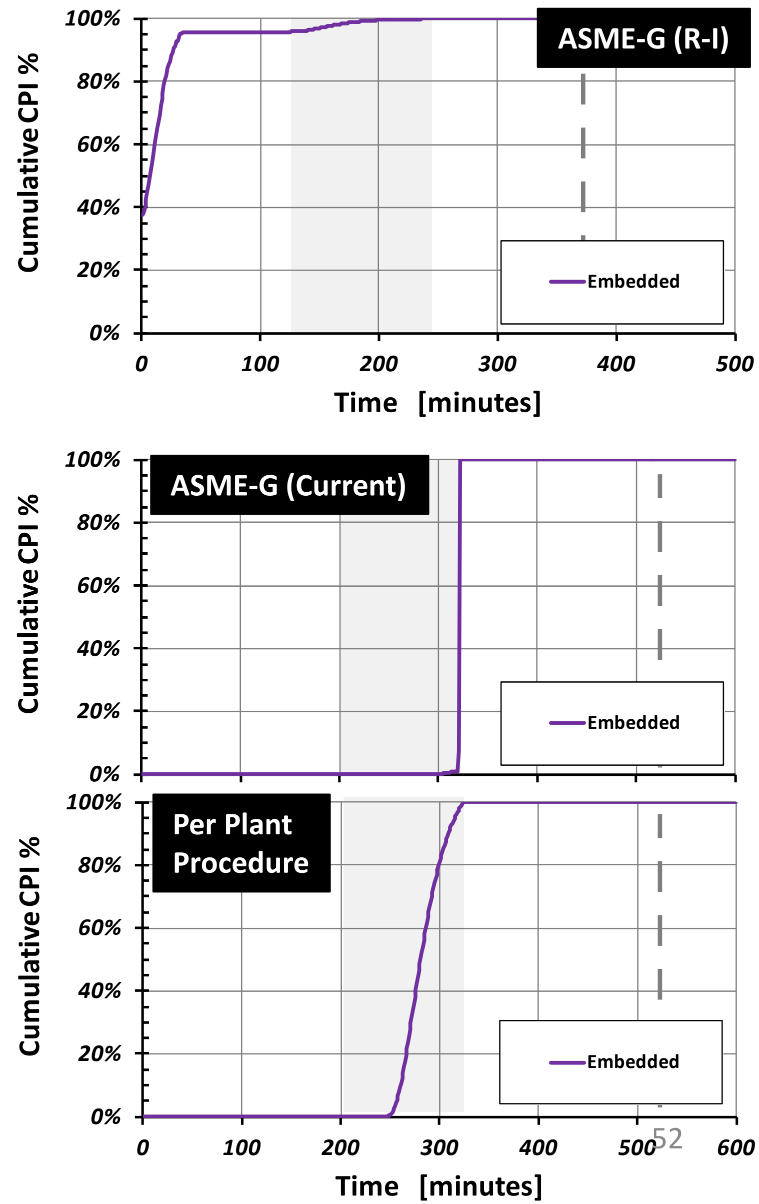
- Irrespective of loading method, all CPI/CPF accumulates when the RPV is near room temperature
- Applied K exceeds toughness only at these times, not during the pressure hold that constitutes the leak test
  - Changing the leak test temperature and/or pressure will not change this result
- Initial / final pressure
  - Increased pressure allowed by R-I increases CPI/CPF
  - Even at the lower pressures allowed by current practice (or zero pressure following plant procedure) CPI/CPF remain above 10^{-6}



Embedded Flaws

Time of CPI/CPF Accumulation

- Time of CPI accumulation depends on loading method



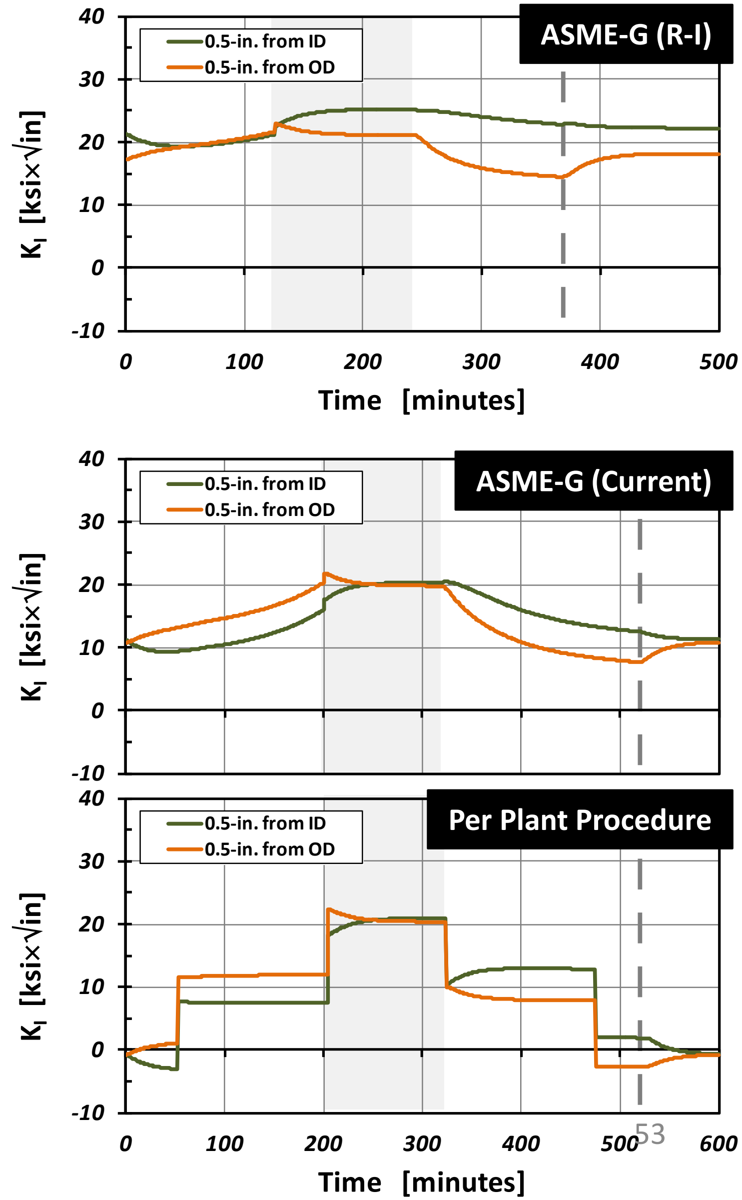
Embedded Flaws

Applied K *vs.* time

- Time of CPI accumulation depends on loading method

- K *vs*. time plots provide insights regarding which embedded flaws contribute
  - R-I: both flaws near ID & OD
  - Current: only near ID
  - Plant Procedure: Only near ID

- Plots also show that R-I loading shifts portion of transient responsible for CPI/CPF to the heatup portion, not the leak test



Embedded Flaws

CPI/CPF Values

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- Loading along R-I P-T limits
  - Increases CPI/CPF versus current P-T limits
  - Changes time during the transient that produces CPI/CPF to that leading up to the leak test, not the duration of the leak test itself

- CPI and CPF values remain well below 10^{-6} for embedded flaws

Loading Condition	Pressure at T=0 [psi]	Leak Test Temperature [°F]	CPI				
			Total	% before leak test	% during leak test	CPI at T=0	CPI at leak test
ASME-G (R-I)	860	154	5.7E-8	95.5%	4.5%	5.7E-8	3E-9
ASME-G (Current)	606	204	1E-14	0%	100%	0	1E-14
Per Plant Procedure	0	204	2.5E-13	0%	100%	0	2.5E-13

Leak Tests of BWRs

Summary

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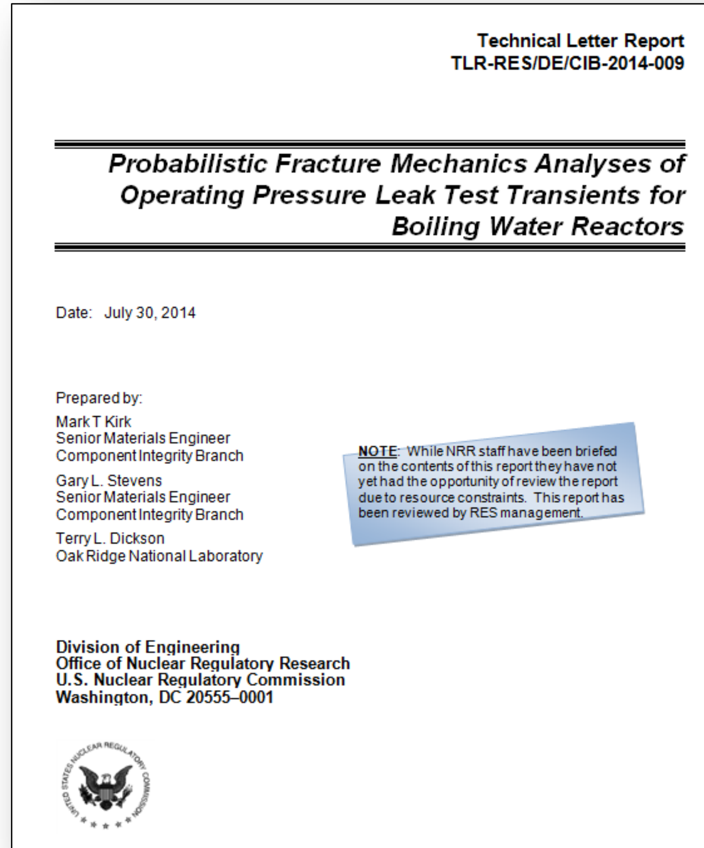
- **SBFs**
  - CPI / CPF increased by R-I alternative
  - CPI & CPF > 10^{-6} for all loading conditions evaluated, including plant procedure and current limits
  - Changing the leak test temperature or pressure will not alter these results
- **Embedded flaws**
  - CPI & CPF increased by R-I alternative
  - CPI & CPF < 10^{-6} for all loading conditions evaluated
  - R-I alternative changes the time of transient that produces CPI/CPF to that occurring before the leak test



Technical Letter Report
TLR-RES/DE/CIB-2014-009

Probabilistic Fracture Mechanics Analyses of Operating Pressure Leak Test Transients for Boiling Water Reactors

Date: July 30, 2014

Prepared by:

Mark T Kirk
Senior Materials Engineer
Component Integrity Branch

Gary L. Stevens
Senior Materials Engineer
Component Integrity Branch

Terry L. Dickson
Oak Ridge National Laboratory

NOTE: While NRR staff have been briefed on the contents of this report they have not yet had the opportunity of review the report due to resource constraints. This report has been reviewed by RES management.

Division of Engineering
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555–0001

Wrap Up

NEXT STEPS

Next Steps

U.S.NRC
United States Nuclear Regulatory Commission
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- **Receive ACRS feedback and comments**
- **Complete documentation of existing work**
  - 12 technical letter reports
  - 1 NUREG
- **Comprehensive review of conservatisms in the FAVOR model. Builds off a similar examination during PTS project [NUREG-1808, 2006].**
- **Detailed investigations of factors identified as significant**
  - Currently: FAVOR cladding stress model
  - Others topics will be investigated as identified, contingent on resources, for example
    - Elastic plastic effects
    - Load history effects
    - Actual loading instead of loading along P-T limits
    - Effects of corrosion on crack driving force
    - Measurement of cladding residual stresses
  - Peer review will be sought in various forums
- **These and other research plans are consistent with NRR needs, and the current User Need Request (NRR-2014-007)**

United States Nuclear Regulatory Commission
Protecting People and the Environment

Questions or Comments?