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UNITED STATES OF AMERICA

NUCLEAR REGULATORY COMMISSION

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ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

(ACRS)

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METALLURGY & REACTOR FUELS SUBCOMMITTEE

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MONDAY

NOVEMBER 15, 2021

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The Subcommittee met via Video Teleconference, at 2:00 P.m. EST, Ron Ballinger, Chairman, presiding.

COMMITTEE MEMBERS:

RONALD G. BALLINGER, Chair

CHARLES H. BROWN, JR. Member

VESNA B. DIMITRIJEVIC, Member

GREG HALNON, Member

JOSE MARCH-LEUBA, Member

DAVID PETTI, Member

JOY L. REMPE, Member

MATTHEW W. SUNSERI, Member

ACRS CONSULTANT:

STEVE SCHULTZ

DESIGNATED FEDERAL OFFICIAL:

CHRISTOPHER BROWN

ALSO PRESENT:

BOB CALDWELL, NRR

DAN DENIS, Structural Integrity Associates

ALLEN HISER, NRR

ELLIOT J. LONG, EPRI

SCOTT MOORE, Executive Director, ACRS

JEFFREY POEHLER, NRR

DAVID RUDLAND, NRR

R O B E R T T A Y L O R , N R R

T-A-B-L-E O-F C-O-N-T-E-N-T-S

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P R O C E E D I N G S

2:00 p.m.

CHAIR BALLINGER: Good afternoon, the meeting will now come to order. This is a meeting of the Advisory Committee on Reactor Safeguards Subcommittee on Metallurgy and Reactor Fuels.

I'm Ron Ballinger chairing this Subcommittee meeting. The ACRS Members present are Charles Brown, Dave Petti, Dennis Bley, Greg Halnon, Jose March-Leuba, Joy Rempe, Matt Sunseri, Vesna Dmitrijevic, and our consultant Steven Schultz.

The purpose of today's meeting is discuss reactor pressure vessel monitoring and prediction in long-term operations, it's actually an update. The Subcommittee will gather information, analyze relevant issues and facts, and formulate proposed positions and actions as appropriate.

This matter will be scheduled for a future full Committee meeting at which time the Committee may develop a letter report on this topic, something some time in the future.

By way of background, the Committee has been following this issue for several years and has had several briefings and has written at least two letters on the related topic.

In that letter, one of them, Reg Guide 1.99 letter that we wrote, we cautioned that the high fluids issue is important and suggested that the newer more accurate correlation, ASME 900-15, which had been underdeveloped for quite some time and contained an enormous amount of data compared to the original database, will be considered for use in an updated revision of Reg Guide 1.99.

The Staff disagreed with this suggestion and provided an explanatory document, Reg Guide 1.9 on Revision 2 evaluation status March 19, 2021. Also a document where the favor code was used to evaluate the effective high fluids was developed.

Additionally, a petition for rulemaking has been submitted by NuScale Power LLC docketed by the NRC in September 11, 2019 and has been signed Docket PRM50-120. To allow the use of the trend curve suggested in the ASME 900-15 as the basis for RPV embrittlement.

Based on more recent analysis by the Staff, a rulemaking effort may be one path forward to ensure embrittlement is adequately addressed and high fluence, especially the uncertainty.

ACRS was established by statute and is governed by the Federal Agents Advisory Committee,

FACA. The NRC implements FACA in accordance with its regulations found in Title 10 of the Code of Federal Regulations Part 7.

The Committee can only speak to its published letter reports. We hold meetings to gather information and perform preparatory work that will support our deliberations at a full Committee meeting.

The rules for participating in all ACRS meetings including today's were announced in the Federal Register on June 13, 2019.

The ACRS Section of the NRC public website provides our charter bylaws, agendas, letter reports, and full transcripts of all full and Subcommittee meetings including slides presented at these meetings.

The meeting notice and agenda for this meeting were posted there.

As stated in the Federal Register notice and in the public meeting notice posted to the website, members of the public who desire to provide written or oral input to the Subcommittee may do so and should contact the designated official five days of the meeting.

I should say that the designated federal official for this meeting is Mr. Christopher Brown. Today's meeting is open to public attendance and we

have received one request to make an oral statement.

I think that's correct. Time is provided in the agenda after presentations are completed for this oral statement and for spontaneous comments for members of the public attending or listening to our meetings.

Today's meeting is being held over Microsoft Teams, which includes a telephone bridge line allowing participation to the public over their computer using Teams or by phone.

A transcript for today's meeting is being kept, therefore, we request that meeting participants on Teams and on the Teams call-in line identify themselves when they speak and to speak with sufficient clarity and volume that they can be readily heard.

Likewise, we request that the meeting participants keep their computer and/or telephone lines on mute when not speaking to minimize disruptions. I also ask that the Teams attendees make sure that they are all muted so we may commence the meeting.

I should say that when it comes time to make comments, the way to do that is to use star 6, I think that's correct. We'll now proceed with the

meeting and I think it's Rob Taylor. Rob Taylor, are you there?

MR. TAYLOR: I am, can you hear me?

CHAIR BALLINGER: Yes, very well. If you'd like to make some comments, please do so.

MR. TAYLOR: I'd like to make just a few opening remarks and thank you very much for the opportunity. Good afternoon, for those who don't know me my name is Rob Taylor, I'm the Deputy Office Director for New Reactors at NRR.

I don't just do new reactors, my portfolio includes materials, issues, and subsequent license renewals for the operating fleet as well so the staff that are working on this topic work for me.

And this is an issue that I've been following very closely and working with them on here for the last year or so as we've been working up the issue in more and greater detail.

So, we appreciate the opportunity to discuss this topic which we are working on to assess its safety significance and the potential need for regulatory action.

Specifically, today you'll hear from NRC Staff about their effort associated with monitoring and prediction of reactor pressure vessel

embrittlement during long-term operation of nuclear power-plants.

As you indicated, this is part of a continuing discussion of issues that were first presented in a May 2020 public meeting. These issues related to the embrittlement trend curves in Reg Guide 1.99 Rev 2 and 10 CFR 50.61 and the surveillance testing in Appendix H.

During the meeting, the Staff will describe a holistic risk-informed analysis performed of these issues and its potential impact on reactor pressure vessel integrity.

I want to assure everyone that the NRC has high confidence that operating plants remain safe and currently the NRC regulations provide reasonable assurance of adequate protection against brittle fracture of the reactor pressure vessel.

The issue we are going to hear about today has the potential down the road to impact the Staff's confidence in the integrity of the reactor pressure vessel during long-term operation for some plants in the United States.

The NRC Staff has further work to do to determine which specific plants are impacted and to what extent. The NRC Staff is proactively considering

risk-informed operations to address the combined effects of both issues to ensure continued reasonable assurance protection agenda brittle fracture in the reactor pressure vessel during long-term operation.

The Staff is very interested in receiving feedback from ACRS regarding the NRC Staff's approach taken and its holistic risk-informed analysis being presented today.

Other potential adverse impacts to plant operations some of that should be considered and is now the appropriate time to pursue these issues?

We sincerely appreciate the interest in these topics and we're expecting a very interesting and productive meeting.

So, that concludes my opening remarks. Should I turn it over to Dave or do you want me to hand it back to you?

CHAIR BALLINGER: I think we'll turn it over to Dave but let's ask if any Members have any comments that they would like to make before we pick this up? We have a five-second rule for Members and donuts so I think we're okay.

Dave, over to you.

MR. RUDLAND: Thanks, I think everybody can see my slides, right? I'm going to talk a little

bit about this that Rob just gave us background on and the reactor pressure embrittlement monitoring prediction, especially long-term operations.

My name is Dave Rodman and I'm a senior technical advisor for materials in the Division of New and Renewed Licenses in NRR.

And just for bandwidth, I'm probably going to keep my camera off while I'm making presentations, and then I may turn it back on during questions and answers if needed.

So, the purpose today is to go over some of these issues. As Ron pointed out in his opening comments, we have talked to the ACRS Subcommittee several times about some of these issues so I'm not going to go into too much detail about the individual issues.

But I will touch on the embrittlement trend curve that's in Regulatory Guide 199 Rev 2 and the same trend curve that's in 10 CFR 5061 and the issues there, as well as some issues with Appendix H surveillance testing.

I want to spend a little bit more time talking about a holistic risk-informed analyses that the Staff did and its thoughts on the potential impact to reactor pressure vessel integrity.

And then I'll discuss some path forward options. Even though we've had a couple of briefings in the past I thought I'd go a little bit over background of what it is that we're looking at and how the uncertainties may come from these issues.

Building a trend curve is an estimate of the change in fracture of toughness as a function of fluents. If you look at this plot that's in the lower lefthand corner, on the Y axis is the embrittlement with a measurement of temperature on the Y axis.

The X axis is operating time and/or fluents. The solid red line represents a schematic of some embrittlement trend curve that has some initial value of this transition temperature from brittle fracture to ductal fracture that increases as the operating time influence increases.

In addition, there's requirements for surveillance capsule testing that provides monitoring to ensure that this embrittlement trend curve properly predicts plant-specific behavior.

In that same stage, the orange data-points represent a fictitious schematic of that particular data. Typically, the way that the current regulations work is that embrittlement trend curve, there is a margin added to that.

That gives us our adjusted reference temperature, or ART in this particular illustration and then at different times those ART values are used with the formulations that are in 10 CFR 50 Appendix G to calculate pressure temperature limits for heat-up and cool-down, which are represented by the blue, green, and red lines on the slide on the right.

Those lines are the limits for operation that will move or shift to the right as material becomes more embrittled, so to warmer and warmer temperatures.

So, ideally, we want an embrittlement trend curve that provides conservative predictions of embrittlement and surveillance data that covers all of the operating periods for any one particular reactor.

If, for instance, the embrittlement trend curve under-predicts the data we could have a level of uncertainty which is illustrated in this left figure. Again, in this particular figure which is the same from the previous slide, you have a couple of data-points.

And we have future data-points that have not been pulled yet and if the particular trend curve that we have underpredicts that, we can give an uncertainty in what the actual embrittlement is from

that relationship.

Also, if the surveillance data is limited or if periodic embrittlement measurements are not made, that of course increases the uncertainties since we don't know if the plant-specific behavior is matching the embrittlement trend curve.

I can state this in a slightly different way and maybe a little bit more clear way.

If you look at this top behavior on this slide where we have periodic regular data that's pulled from particular plants, embrittlement trend curve, which is represented again by the red line, that matches that behavior relatively well.

Then we have known embrittlement behavior with a known uncertainty. And from that then are regulations and margins that we put on that would be perfect to keep the predictions conservative.

However, if we have gaps in the data or not future data plus an embrittlement trend that is underpredicting the experimental data from the plant surveillance, then we end up with very large uncertainties.

And so what we have in the regulations may not properly account for that amount of uncertainty and we don't know exactly what

embrittlement we have at a high fluence long-term state.

And that uncertainty and what those impacts are we felt needed to be studies holistically to really understand what the impacts of those uncertainties are on the behavior of the vessel.

I'm going to start a little bit with our conclusions and then I'll talk with her about the details afterwards.

And so from this the Staff still has very high confidence that the current operating plants remain safe and that our licensing actions that we've made to date remain valid.

However, there is insufficient embrittlement monitoring under prediction that occurs of this reactor embrittlement and that will eventually impact the Staff confidence in the integrity of the vessel.

MEMBER BLEY: Can I interrupt you at this point?

MR. RUDLAND: Sure.

MEMBER BLEY: This is Dennis Bley. Two questions for Ron and then something for the Staff. Ron, are we expecting to write a letter on this next month or soon?

CHAIR BALLINGER: To answer your question, I would like to write a letter on this topic but not right now. We need to decide on where there's a convenient milestone point, if you will, for this to happen.

The Staff is in the process of doing a lot of analysis and evaluating and should a rule be the path that they want to take, then we go from there.

I suspect that would be the best time, unless the Subcommittee wants something different, to write a letter because then we'll have a complete idea of what the path forward is.

MEMBER BLEY: Thanks, that helps me a lot to put perspective on this. I just wanted to make a comment for the Member first but then I'd be happy to hear what the Staff has to say.

When I think about uncertainty of the kind I think we're going to hear more about soon, good treatment of uncertainty gives us and is a reasonable approach, in fact, it's the only approach I think that allows us to have confidence in our decision-making.

On the other hand, using an uncertainty based on limited data when there's new data available just seems like we're dodging the issue of keeping current with the science and that sort of thing I find

uncomfortable and not part of best practice.

So, I'm done, if anybody wants to say on that, that's great, if not that's okay too.

CHAIR BALLINGER: This is Ron again. I would expect that the trend curve that was based on the latest data would certainly factor into and has been used in this analysis to determine the uncertainty.

Am I right, Dave?

MR. RUDLAND: That's correct.

CHAIR BALLINGER: So, also, there's a bit of a subtlety that may have been missed on Slide 2 and that is that we have been in the past time, much to my dismay, dealing with PTSand embrittlement in different ways, in effect.

And the analysis that the Staff is doing I think would seek eventually to rationalize and come up with a single trend curve for both PTS and embrittlement. Am I right again, Dave?

MR. RUDLAND: I'll be touching on that in the presentation.

CHAIR BALLINGER: That's kind of an important thing.

MR. RUDLAND: To be clear, right now the embrittlement trend curve that's in 199 Rev 2 and 5061

is the same trend curve, just to be clear. So, as we move forward and as I talk about this, I want you to keep that in mind.

CHAIR BALLINGER: But 61A allows a probabilistic approach, right?

MR. RUDLAND: Yes, 61A uses a different trend curve.

CHAIR BALLINGER: That's what I was referring to.

MEMBER HALNON: This is Greg. Could you just briefly tell us why you have high confidence that we're safe now, just that first bullet on that slide you were just on?

MR. RUDLAND: Again, I'll get to that as I'm discussing it but I think the reason why is because at the current state of where the plants are in terms of the fluence levels, the trend curve does a pretty good job of predicting the embrittlement.

And so we're not as concerned with the behavior now because, again, the trend curves are predicting things. It's out in the future that they begin to underpredict the behavior.

And it's out in the future where we also don't have surveillance data to make sure that the trend curves are being accurate.

MEMBER HALNON: I think at some point you're going to talk about the year 2025. If I haven't figured it out by then I'll get back into your questioning.

MR. RUDLAND: Is there anything else? Can I go on?

MEMBER HALNON: Sure.

MR. RUDLAND: So, as I was talking about, it will eventually impact our confidence.

Right now we're kind of estimating that it would be about 10 years before we would start to have an issue and I'll get into the details here in a second for the PTS.

And it's about 23 years for PT limits, and why those are different and stuff like that I'll get into in a second.

But the Staff needs to do continued work, especially to determine which plants are impacted by this potential issue because it becomes very plant-specific issue as you'll see in a second.

I'm going to start with the trend curve issues before I move on to the surveillance issues. In May of 1988 the NRC published Reg Guide 199 which contained an improved, and this is Rev 2, embrittlement trend curve that was fit to 177

data-points.

And in 1991, the NRC updated 5061 to include that same EPC from Reg Guide 199. Since then, we haven't really touched it all that much but we did a reevaluation for the continued adequacy in 2014 and in more detail in 2019, which kicked off basically this effort that I'm talking about today.

It was both those documents that are in Adams and publicly available. So, the issue is shown here.

This plot gives you on the Y axis is the difference between the predicted embrittlement and the measured embrittlement, and the measure from surveillance data predicted in this case by the trend curve in Reg Guide 199 where a zero value would be a perfect prediction against the fluence, which is on the X axis.

As you can see, the data is relatively scant. The red data here represents the U.S. surveillance data and the grey data-points represent international surveillance data.

What we see is that when we get to about 3e to the 19 neutrons per centimeters squared, the trend curve begins to deviate from that zero or perfect prediction.

By the time you get to 6e to the 19 it becomes statistically significant, which means the trends themselves are below the 2 sigma scatter within the data. The dashed heavy lines represent plus and minus 2 sigma on the data.

Those values are in Reg Guide 199. By the time we get to 1e to the 20th about 180 degree Fahrenheit under prediction in embrittlement. This particular plot is for base metals and again, we'll talk about what these values mean in terms of our current operating fleet in a little bit.

For weld materials we see similar trends but not as apparent, same plot but the data now represents surveillance data from welds and what you see is not as much data in high fluence.

Data seems to be more scattered but doesn't seem to have that large drop-off and that may just be due to the limited data of high fluence.

MEMBER REMPE: This is Joy. On the prior plot, I just looked at this, what was the reason that the non-U.S. seems to have more variance?

MR. RUDLAND: In terms of this data down in the --

MEMBER REMPE: Yes.

MR. RUDLAND: I think what's happening is

that we just don't have enough data at high fluence. So, we have some data here which represents these red data-points that are in this region.

I don't know if you can see my cursor or not.

MEMBER REMPE: I can.

MR. RUDLAND: This data in here is U.S. data. For international, we just don't have any data right now that's in this range.

MEMBER REMPE: That helps, thanks.

MR. RUDLAND: I think the thought at least from the Staff is that the data that we do have seems to be following the same trend. And so as more and more data is gathered, we suspect it will follow in this trend but we don't have that evidence.

And actually, Elliot Long will be talking about some programs that are currently underway to try to develop some of that data in a more efficient manner and he'll give some timeframes in when he expects to have that data.

MEMBER REMPE: Thank you.

MR. RUDLAND: You're welcome.

So, within Reg Guide 199, the prediction of the change in embrittlement due to radiation is represented by this functional form that's shown here

that's a function of something called a chemistry factor, which is a function of nickel and copper, and a function that is just a function of fluence itself.

So, if we were to plot that particular fluence function against fluence itself, we can see the trend and what we see is that once we get above 3 to the 19, the slope of that particular fluence function begins to change and begins to decrease and actually reaches a maximum of about 2e to the 20 and begins to drop off.

This is the same point at which we saw that the material in two slides above began to deviate from accurate predictions.

So, that seems to suggest that the fluence function itself is probably part of the issue of why we're seeing this under-prediction in embrittlement trend because the fluence function that's the base of those calculations begins to decrease at that point.

Whether the actual trend follows this light blue line or doesn't or is slightly higher is unknown at this point but the behavior seems to be related to the actual fluence function that is part of the embrittlement trend curve in Reg Guide 199.

I'm going to move on to a little background on surveillance capsules. Appendix H to

Part 50 requires periodic monitoring of the changes in fracture toughness caused by neutron embrittlement.

And typically, these programs are three to five surveillance capsules that are placed inside the vessel closer to the core than the vessel wall itself and they're pulled periodically.

The surveillance capsules contain sharpie specimens and pencil specimens and other specimens, and they're tested to make a prediction of what the embrittlement in the vessel would be.

Like I said, there's usually about three to five in there and Appendix H incorporates by reference ASTM Standard E185-82.

In that particular standard which was developed for a 40-year life originally, it allows the final capsule to be pulled at a fluence of about 2 times the design fluence, which over its life would be about 40 years.

However, plants have been changing that design fluence to the current license length of 60 or 80 years depending on if their license had been extended.

That allows the last capsule to be held without testing and the reason being that for a typical program with a 40-year life, the second to

last capsule typically had sufficient fluence to be able to represent the vessel wall at 40 years.

However, as plants began to apply for and receive extended licenses, these last capsules had been delayed a bit to represent the fluences at 60 or for subsequent license renewal 80 years.

And in 1997, the NRC wrote an administrative letter that stated that staff review of these requests of surveillance capsule withdrawal scheduled changes has stayed limited to verification of performance with the NSTN standard and cannot be based on a technical or safety review.

And because of that, the capsule withdrawals and testings all repeatedly delayed in some cases to achieve higher fluence.

In license renewal the regulations were unchanged when it came to surveillance testing.

It was that way and the recommendations were put into guidance and it was done that way for flexibility, to allow the plants to be flexible in how they demonstrated adequate aging management of DRPV due to embrittlement and different specific circumstances.

I'm sorry, is there a question? And in that guidance, which was both in the GALL Report which

is NUREG 1801 for license renewal and in SOR GALL which is NUREG 21 and 91, there were several statements about it.

In 1801 Rev 1, there was a statement that at least one capsule needed to be tested with the projected fluence equal to exceeding 60 years of life and in GALL SOR a very similar statement was put in that said a neutron fluence capsule between one and two times the peak fluence of interest at the end of the subsequent period of operation should be tested.

And it also specified that it's not acceptable to redirect or postpone the withdrawal of testing to achieve a higher neutron fluence.

In practice, what's happening is that many licensee are changing those capsule withdrawal schedules prior to the application of license renewal and receiving a review that is basically a conformance verification review.

And then when they submit their license for renewal, they are consistent with the GALL program. It's still allowing the plants to possibly delay their final capsule, leaving large gaps of time between data that's being pulled for embrittlement.

Here's a particular example of that. This plot shows neutron fluence, again the Y axis and the

date on which the capsule is pulled and tested on the X axis. The last data-points represent four capsules that were pulled and tested.

The orange symbols represent the fifth capsule that will delay four times finally for their subsequent license renewal of capsule that would be tested where you see the red symbols.

That's a lot of years, that's 20 years between the last capsule and the next, and many licensees have done this. Here are some examples that are shown here in this plot of plants that have delayed their final capsules.

But not all have done it. Many have actually tested capsules very periodically and not have these large gaps.

CHAIR BALLINGER: This is Ron. These capsules are forward-looking so if you look at the slide that says the 80 years point, how long is that in calendar year? Do you see what I'm getting at?

How much of a forward --

(Simultaneous Speaking.)

MR. RUDLAND: This is when the plant will get to 80 years and that's the 80-year fluence. So, that's the difference between when the plan is actually 80 years and when it reaches 80-year fluence.

When that capsule reaches 80 fluence it will be in 2020 whatever that is, 2024 or 2025. Compared to when it actually reaches 80 years which will be in 2051 or something like that.

CHAIR BALLINGER: So, it's considerably forward-looking?

MR. RUDLAND: Yes, and that's typical because again, remember these capsules are closer to the core than the wall so they have a higher lead factor so they're getting fluence at a much higher rate than the wall.

CHAIR BALLINGER: Thanks.

MR. RUDLAND: I'll show the same kind of data but in another plot and I think this goes to answering one of the questions earlier.

This is the same plot that shows the difference between the predicted and measured values of embrittlement as the functional fluence.

The four data-points here in green represent four of the capsules pulled and you can see when those four capsules were pulled at that particular fluence. The embrittlement trend curve does a pretty good job of predicting that embrittlement.

It reaches 60 years here and 80 years here

and this is where the fifth capsule will be pulled. So, it may be that particular plant has values of 150 to 180 degrees under-predicted. It may be, I don't know for sure until they actually pull the capsule.

But you can see there's that large gap there which, again, adds to uncertainty. I don't really know what the embrittlement state is beyond that 2020 value until they've actually pulled and tested that capsule.

And again, the way the rules are now, that particular plant could get to that time and decide they want to delay that capsule even further and we would have to approve that with the same performance check as we've done in prior approvals.

I show this in a slightly different space but it also shows the behavior of the embrittlement trend curve to predict some of these. These are the same four data-point, embrittlement on the Y axis versus fluence on the X again.

If you use just the chemistry for that material to predict the trend curve I would get this orange line.

Reg Guide 199 allows the user to fix the data-points they have, fit the embrittlement data-points they have, basically adjust the chemistry

factor to give them a new trend curve that fits their data.

That would be the blue line here. So, you can see that drops their prediction of embrittlement by about 25 to 50 degrees Fahrenheit.

If this particular data follows the trends that were expected, I could expect to have about 150 degrees Fahrenheit underpredicted for this data if it follows the trends of the database data that was shown earlier.

And again, if I fix that data with the trend curve as it is, I would get this orange yellow line and what's happening is because of that fluence function that kind of levels off, it does not accuracy predict this behavior.

So, I would still have even when I would fit that particular data about a 75 decree underprediction in the data.

CHAIR BALLINGER: This is Ron again. I've been looking at this for so long, sometimes you don't see the forest from the trees. That fluence factor is nothing more than an empirical fifth.

There's no physics associated with that.

MR. RUDLAND: That's correct.

CHAIR BALLINGER: And so the fact that it

all of the sudden goes a little strange after a certain fluence, well, it's just an empirical fit.

MR. RUDLAND: That's right, and realize it was only an empirical fit to about 170 data-points at the time. Now we have 1000 data-points or something like that, so it was fit well to the data they had at the time.

And it was not expected to be used for this high fluence values because there was no data at that point to help calibrate the fifth.

CHAIR BALLINGER: It's a good lesson, don't extrapolate.

MR. RUDLAND: Exactly right. What are the impacts of those two things? Any one can be explained away with conservatisms or whatever but together they may actually have a much larger impact.

So, the Staff wanted to look at these combined effects and they wanted to use risk-informed thinking in order to do that, which includes not just looking at how these changes affect the actual calculation of risk but also how do they affect performance margins, safety monitoring, defense in-depth in order to help us make a decision.

To do that, we used a targeted sample of plants and we used the data that we had available to

us. I realize that not much plant-specific information is available. We only have limited data when we did this particular analysis.

The assumptions that we made were that we wanted to do some comparisons with AASME 915, I think Ron talked about this a little bit earlier. A report was written in 2020 where the Staff found that this particular embrittlement trend curve provided the most accurate characterization of the database.

So, the database is what I'm talking about here. This is data that was used by ASPM to basically fit this embrittlement trend curve to this data. So, you would expect then that these trends would show that trend curve could accuracy predict through the third range of fluence those data.

And that's what it shows. And so we wanted to use that as kind of our comparison tool since we knew it was the most accurate to the data in that database.

We did a targeted sample, a targeted study, we looked at 21 plants, we emphasized high fluence plants but we threw in a few that had low copper and BWRs to round out the study.

And we looked at changes in these adjusted reference temperatures I talked about earlier, from

switching embrittlement trend curves.

How much would the adjusted temperature change if I switched from Reg Guide 199 to E915? And we called that the embrittlement shift delta. And the embrittlement shift delta results were used to help us benchmark our risk analysis.

So, what we found out from the data that we were able to develop for these 21 plants was that there's a tendency for the material reference temperatures to increase when switching from Reg Guide 199 to ASME 900.

And you've got to realize that there's other parameters in E900 besides what I talked about for Reg Guide 199, which is just nickel, copper, and fluence.

There are other things that E900 also uses. The trends were to basically increase that reference temperature when moving to ASME 10 E900. We saw that trend more in base metals and in weld metals, I'm not too sure why that is, but that was the trend we saw.

And only really a small handful of plants had changes in this reference temperature greater than 50 degrees Fahrenheit and those tended to be plants that were at higher fluences greater than the 6e to

the 19.

We assumed that this range that we got of the shift deltas bounded the three and so we used those in our risk studies. Staff did a probabilistic fracture mechanics calculations.

We looked at a bunch of different transients, we looked at a bunch of different flaw sizes. We didn't have a lot of information on fluence maps and things like that so we kept those kinds of things constant, and we ran these analyses.

What I'm showing here in this particular plot is one particular place. I had conditional probability of initiation and conditional probability of failure on the Y axis and this embrittlement shift delta on the X axis.

And remember, this embrittlement shift delta basically represents the under-prediction in the transition temperature in the delta RT and DT.

If you look at the conditional probability of failure just as a comparison for this point, a 50-degree shift in this is a 50 degree underprediction basically from Reg Guide 199.

This would give us about three orders of magnitude increase in the conditional probability of failure. And a 150-degree shift would give us about

six orders of magnitude, a change in additional probability of failure.

But please realize these values are conditional on the frequency of the transients. For instance, this particular one is for a cool-down that follows the PT curve, which is a very unlikely event.

We don't know really what the frequency of some of these transients are. We did do some actual plant transients, which I'll talk about in a second, but a lot of the frequency of some of these more rare transients is unknown.

There's also a lot of plant variations that we did not account for in these analyses that add to the uncertainty.

We don't know if these analyses are bounding and we really don't know how much protection administrative and other limits provide against violating PT curves and I'll get into that when we talk about safety margins a little bit.

All of the analyses are summarized in this report that I have here that was a 2021 report that's publicly available on ADAMS. So, the risk seems to be low because of the frequency of the transient but the uncertainties are very large.

This was again for heat-ups and cool-

downs.

MEMBER PETTI: Can I ask a question? What are the yellow curves?

MR. RUDLAND: The yellow curve is the conditional probability of initiation. So, the way these probabilistic fracture mechanics work is they look at when a crack may initiate versus when it may actually go through a wall and fail the vessel.

Those are always going to be lower because in some cases the cracks are rushed depending on the embrittlement.

CHAIR BALLINGER: This is Ron. The report has a lot more information in it but whenever I see a curve that has conditional probability of initiation or failure, 10 to the -7 or -8, I immediately ask the question what's the uncertainty?

And I look for air bars to be plotted on these things and I never seem to see them.

MR. RUDLAND: The air bars are difficult to determine what they are because there's so much unknown right now.

So, I'll talk about this in a second but that's why we decided to look at some other things besides just these risk numbers because the uncertainties are so large.

I need to make a correction to what I said. The yellow lines down here are actually a different flaw size so the difference between the dark purple and the light purple is the difference between the initiation and failure probability.

The difference between the light and dark lines are different flaw sizes. The Appendix G calculations assume a quarter T flaw where the flaw is a quarter way through the wall thickness.

So, that's the higher curves. The lower curves are smaller flaw, that's only 3 percent through the wall.

MEMBER BLEY: I guess that last discussion left me a little lost. If we can't characterize that uncertainty well because it's so large, we don't have a clue if these things are means, medians, or 90th percentiles or 20th percentiles.

They're just numbers. It's back to that question, how are you getting confidence? And if you don't have any confidence in the uncertainty, you can't have any confidence in what these numbers really represent.

MR. RUDLAND: Right, I think we tried to pick as many bounding results as we could to not be caught by the uncertainties so much. So, the fluence

maps that we picked, the geometries that we picked, the flaw sizes that we picked were all meant to try to bound the results.

MEMBER BLEY: Same thing for upper bounds?

MR. RUDLAND: I think so, yes, and as I talk about it in this particular plot, where we get worried is we don't know exactly what the event frequencies are.

When we calculate conditional probabilities of failure that are less than 1e to the -6, we know that the frequency of the transients doesn't matter all that much because the impact to core damage frequencies will be very low.

Because the two wall clash frequencies will be way lower than 1e to the -6. Remember the two wall clash frequency is conditional probability of failure times the transient frequency.

And in a risk analysis, we equate the two wall clash frequency to core damage frequency for conservatisms. So, any conditional probability of failures that are less than 1e to the -6 are not concerning to us.

The ones that are the most concerning are the ones where the conditional probability of failures are greater than 1e to the -6 but I don't really quite

know what the event frequencies are.

That's where I start to get concerned. I know they're probably low because following the PT limit is a very low frequency event, I just don't really know what it is and so I'm uncertain about that.

For the leak test, for instance, what drives the leak test are not the frequencies so much as the cool-down rates and I need additional information to determine if the high cool-down rates really are an issue.

That's the added uncertainty there. And because it was difficult for us in this study to answer these questions, that's why we looked at some of the other things like safety margins and performance monitoring before making the decision that we need to consider change.

CHAIR BALLINGER: The key here is I think that the embrittlement trend is slowly varying and as long as some other phenomenon doesn't rear its ugly head that we don't know about, which I suppose is possible, we're in a good way.

MR. RUDLAND: Right now we're in a good way and I think our concern comes in the future when we begin to have this underprediction.

Because what happens is that will continue to get worse, it will continue to underpredict at higher and higher fluences, which drives the uncertainty even higher.

In addition, we looked at 5061, which is the thermal shock rule and again, in that particular rule, a calculation of RPPS is done using the embrittlement trend curve. That might be impacted.

And what you need to remember is there's a screening criteria where if the RPPS exceeds 270 axel welds or 300 for circ welds, then something needs to be done for PTS.

However, for the sample plants that we did, we ran those through the analysis as part of 5061A and demonstrated that the wall crack frequency for PTS were all less than 1e to the -6 for all the cases investigated.

And so the impact on risk for a single shock was shown to be low.

CHAIR BALLINGER: But 61A uses a different correlation. How does that work?

MR. RUDLAND: We actually looked at the correlation using Reg Guide 199, the correlation which is in 5061A as well as E900-15. We looked at all three of those trend curves in doing these

calculations.

CHAIR BALLINGER: Thanks.

MR. RUDLAND: So, because of this whole discussion of uncertainty and our feelings that we were very unsure about the behavior, especially at high fluence, we wanted to look at other things.

We knew we needed to resolve these issues to maintain safety and be comfortable with the uncertainty so we decided to look at both the impacts on the safety margins as well as on performance monitoring.

I illustrate these safety margins with this particular schematic. The Y axis again is pressure and the X axis is temperature, and the shaded area is a typical operating window where a plant may cool down or heat up.

So, it starts up here at a high temperature and high pressure and decreases pressure and temperature to stay within this window.

There's a limit that sits out here, a structural limit, where if the plant was to be in this region up here for the high temperature and pressure and decrease temperature without decreasing pressure, they may cross this structural limit and increase the chances of a brittle fracture.

On the regulations with an accurate PT curve, we have a regulated PT curve that lays here that restricts them from getting close to that structural limit by an adequate amount of margin.

So, now that when they're cooling down they need to stay to the right of this orange curve and the amount of margin that is chosen here is directly proportional to that uncertainty in the problem.

This margin was chosen knowing the analysis methodologies that went into calculating that, the amount of conservatisms, the amount of unknowns, and that margin was chosen to be appropriate.

However, if your PT curve actually is here because we're using a trend curve that underpredicts, we can get a false sense for what the actual operating margins are and a reduced margin to brittle fracture.

What that's showing is that actually, even as the uncertainties are increasing, the margins to brittle fracture are actually decreasing. So, that's going opposite to the trends that we want to stay consistent with in our definition of margin.

So, with a reduced PT curve we're reducing that particular margin but the uncertainties are

increasing. That's something that we think we probably need to fix because the margins that we have need to be represented by the amount of uncertainty that we have.

Same with performance monitoring. The performance monitoring that we have ensures a couple of things. It ensures that analysis results remain valid with time and that there's nothing unexpected, there's no adverse safety issues or changes that we were not prepared for.

And delaying those capsules for a long period of time with the possibility of no future data because, again, remember ASTM E185-82 allows the last capsule not to be tested. That really represents a lack of performance monitoring.

Improved dictations were aware for particular plants we have no data at those high fluence levels. With our current state of knowledge, the general analyses that we did suggests that the overall risk of brittle fracture is low.

And again, we tried to be as bounding with those analyses as we could based on our knowledge and the data that we had, but the uncertainty is high because of that and it increases with time.

A lot of the plant-specific details that

are needed for individual analyses weren't considered because it wasn't available at the time for the Staff. Under certain conditions, safety margins may be impacted and are probably decreasing as that uncertainty increases.

And delaying capsules at high fluence really does represent the lack of sufficient performance monitoring. But most of these issues of the plants with the fluences are greater than 60 to the 19.

Who is impacted by this? If we look at the embrittlement underpredictions within the fleet for both 1680, we have about 34 percent of the PODRs will surpass that fluence level on the ID of their vessel by 80 years.

They will surpass 15 percent by 80 years. Realize that plant-specific details such as limiting material and other things may contribute to which plants are impacted.

So, the Staff needs to have more time to be able determine which individual plants may or may not be impacted. About a third of the PWR fleet could be impacted by 80 years.

Of course, any plant that renews its license and chooses to renew the last capsule would be

impacted by these issues.

So, because of the time-dependent behavior, the Staff feel the regulations right now are sufficient for a reasonable show-in for adequate protection against brittle fracture for the plants as they are right now.

But the Staff wants to ensure continued reasonable assurance in long-term operations and come up with fixes for these identified issues of those embrittlement and surveillance, and use a risk-informed performance-based solution to provide those remedies.

We also want to make sure that whatever solutions we come up with are focused and doesn't impact plants that are not adversely affected by the issues. So, for instance, there are plants that have surveillance data that cover the end of their license already.

And there are plants such as BWRs, where they project improvements at the end of the license is going to be less than 3 to 19 so they're not going to be impacted by this.

To do that the Staff has been considering and doing continued study to determine what their options should be to find the remedies for this,

whether it's a blanket specific action or a focused regulatory action, or possibly some other tools to properly fix this for the long term.

But again, in summary, like I stated at the beginning, the Staff really does have high confidence right now that the operating plants remain safe and that the recent licensing actions are valid but the issue is a long-term issue.

It could be 10 years for PTS or 23 years for PT limits but these issues will eventually impact the Staff's confidence in the integrity of the vessel. I focused mainly on performance margins and safety monitoring because those seemed to be most highly impacted by these issues.

And further work needs to be done. But we want to come up with and we want to be proactive in coming up with a solution that provides continued reasonable assurance and use risk-informed performance-based solutions to do that.

And like I say here, we decided on a really focused solution and don't want to overburden any plant that's not adversely impacted by this issue. I think that's my last slide.

CHAIR BALLINGER: We are way ahead of schedule.

MEMBER REMPE: To help you slow down, Ron, I've got a question.

CHAIR BALLINGER: That was my next comment was now we have plenty of time for questions.

MEMBER REMPE: I have to go back again to that plot and the non-U.S. data, if you look at even before 10 to the 19 fluences, you can look at Slide 15 or several slides that have it there.

We talked about there isn't much data as you get near 10 to the 20th but what about earlier? Is it statistically significant, some of the data-points that are non-U.S. that are a lot larger in the difference between predicted and measured?

MR. RUDLAND: Are you talking about in the region that is --

MEMBER REMPE: Starting where the green line is on the left and you see one greyed off, and then you see several between there and 10 to the 20th.

MR. RUDLAND: I don't think that's a lot of data so it's not really significant.

Sometimes there are outliers and actually, when it comes to determining if material is credible or not, there are statistical rules you can do to check whether or not they are statistically

significant or not.

But these kinds of data-points that are that far away from the mean, they're outside of the signal from the mean. So, they're probably not significant.

MEMBER REMPE: It's just interesting that U.S. data seems to be closer to what's considered the mean value or zero variance than the non-U.S. data and I just wondered if there was anything to be learned.

But you just think all of those data-points are not statistically significant?

MR. RUDLAND: I think what I learned from this, Joy, is that the data that we have now demonstrates that the standard deviation is actually probably greater than what came from the Reg Guide 199 analysis.

So, remember these dashed lines are the standard deviation that came out of Reg Guide 199 Rev 2 from the 170 odd data-points that they originally calibrated the curve to.

And again, it's clear, and we've done these deviations from the database, it's slightly larger than that which was predicted back when Reg Guide 199 was developed.

So, standard deviation is bigger so the

scatter in data is more so than what was originally thought.

(Simultaneous Speaking.)

MEMBER REMPE: I'm just wondering if there's something to be learned about why the U.S. data seems to be closer. There's only a few data-points, I just thought it was curious.

MR. RUDLAND: Again, I don't know about this data-point here at 1e to the 19 but it may be that certain conditions may not be fully as representative to our data as the data-points because they actually come from our plants.

I don't know about those particular data-points, we'd have to go back and take a look at them.

MEMBER REMPE: It will be interesting as you go forward if you see the same thing is still occurring.

For example, if it stays around -50, whereas the data-points on the far right down low are a bit lower, if there's something going on with the U.S. versus non-U.S. data.

Just a question.

MR. RUDLAND: Priors look at the embrittlement trend curve, we tried to focus only on

the U.S. data in terms of whether the fix to the trend curves are good or not.

And only use the international data to help us understand the overall trends because there are some differences, of course, between the way international plants operate their plants versus how we operate ours in terms of the design and stuff like that also.

So, in developing the trend curve we would try to only use the U.S. data as best we could.

MEMBER REMPE: Thanks.

MEMBER HALNON: This is Greg Halnon. One of the public comments was to go after the decommissioned reactors to try to get more data. Was that useful?

MR. RUDLAND: I think the problem with that is that a lot of the decommissioned reactors don't have high enough fluence to really be useful for this particular study.

MEMBER HALNON: Yes, I was wondering about that because a lot of them are shutting down early --

(Simultaneous Speaking.)

MR. RUDLAND: And while it would be good data to have, I'm not sure it would be that useful for this particular issue.

CHAIR BALLINGER: Other questions from Members?

MEMBER PETTI: I have one, this data is all from actual plants but in the early days there was a ton of work done just in the test reactors and the like. And I recall there being some bias with that data.

But in terms of trend, is there data out there from accelerated testing and material test reactors with these higher fluence? Does it confirm what you see in the green data-points?

MR. RUDLAND: Yes, there's data from test reactors and there appears to be a flux effects.

MEMBER PETTI: That's what I remembered, yes.

MR. RUDLAND: And actually, ASME Section 11 is putting together a code case and one of the things they're looking at is how to correct the test reactor data for the flux effect so that it could be used and prepared directly then to the data from operating reactors and power reactors.

MEMBER PETTI: But this decrease, this drifting away from the correlation seems to be in that data set too.

MR. RUDLAND: I'm not sure if it is or

not, to be honest. I don't know if one of my colleagues knows the answer to that. Allen, do you know the answer to that? I can't remember off the top of my head.

MR. HISER: I'm sorry, what was the question, Dave?

MR. RUDLAND: The question was whether or not this behavior of underprediction shows up in the test reactor data.

MR. HISER: I don't think that anybody has really looked at the test reactor data with the number of surveillance data-points from operating reactors. We've pretty much stuck with that.

MR. RUDLAND: I know there's a bias that occurs due to the flux but I don't recall there being the same trends. But I'd have to go back and look.

CHAIR BALLINGER: We need to remember this correlation is exactly that, it's not physics-based so you're outside of the range of its applicability out there.

MR. RUDLAND: That's absolutely right.

MR. HISER: For the record, this is Allen Hiser, the NRC Staff.

MR. RUDLAND: There was some chemistry correlation they used but Ron's right, it's not

mechanistic.

MEMBER HALNON: Just one more question. I saw somewhere, and I'm not sure where, that the PWRs will be effective until 2025 and it's just kind of a continuation of an earlier question.

I assume that's using the highest amount of uncertainty in margin and everything else that you add in there that's the earliest that you would be concerned, is that fair?

MR. RUDLAND: Yes, now where that number comes from is that's when the first plants' ID of their vessel reaches the 6e to the 19. That's where that number comes from.

MEMBER HALNON: So, it's an approximate number?

MR. RUDLAND: Yes, it's based on the plant's fluence predictions at this point.

MEMBER HALNON: I understand the fluence prediction. Does that also take into consideration potential past trainings and excessive cool-down rates or over-cooling transients that may have occurred?

Technically when that occurs an analysis is done and you pay your respects and you move on. Would you consider these operating events as well?

MR. RUDLAND: Those numbers come directly

from the plant's license renewal application so I'm assuming they probably do.

MEMBER HALNON: I was just curious how that was all factored in.

CHAIR BALLINGER: Is it my understanding that prior to startup after a refueling outage a new PT curve has to be established, right?

MR. RUDLAND: PT curves have a limited life depending on what they did, it could be for whatever EFP why they determined to calculate them for.

So, they're good to that particular time and then if they pull a surveillance capsule, they may need to make a change to the PT curve depending on what their data tells them.

CHAIR BALLINGER: But do they update it for history between the last outages and things like that? For example, if a cool-down occurs that's not part of the original number that people have used, they have to readjust?

MR. RUDLAND: I don't think they do typically.

CHAIR BALLINGER: I thought prior to each startup after a refueling outage, they update their PT curve.

MR. RUDLAND: I don't believe that's the case.

MR. HISER: Do you want me to take a crack at it?

MR. RUDLAND: If you know the answer, sure.

MR. HISER: A couple things because there was discussion of cool-down transients and things like that. Those do not impact the PT limits, they are evaluated against the PT limits to make sure the plant didn't violate the PT limits.

But then also, normally the PT limits themselves are calculated out ahead. Maybe if a plant is operating about 20 years, they may have curves that are good for 30 years so they don't have to continually change their curves.

They have some stability in operations.

MR. RUDLAND: Again, remember, they use the reg guide as a prediction of future embrittlement so they can set their PT curves at a higher fluence basically, at a higher EFPY.

And they will make a change, again, if they pull a surveillance capsule or something that tells them they need to change that particular prediction.

MR. HISER: Dave, if I can correct or maybe clarify one other thing? Where we believe there could be an issue is in about 10 years, in about 2032 as indicated on this slide.

The 2026 date on there is when the next capsule will be tested by this plant so there's nothing between now and between 2032 that we believe is critical for this issue.

I saw 2025 a couple of times and just wanted to clarify that part of things.

CHAIR BALLINGER: Other questions?

MR. RUDLAND: Somebody has their hand up.

CHAIR BALLINGER: I've got keep my eyes on this. Steve Schultz?

MR. SCHULTZ: This is Steve Schultz.

The calculations that you're talking about that the licensees do, Ron, you're probably referring to a licensee's evaluation of their vessel fluence and that's being tracked as a function of how the plant has operated year by year over its lifetime.

And it's also corrected based upon new information about technology associated with the calculation of fluence, which has changed over the years but the most up to date fluence calculation methodologies are periodically used to adjust the

plant's vessel fluence.

MR. SCHULTZ: I thought there was some ongoing adjustments that could be made. Okay, thanks.

CHAIR BALLINGER: I don't see anymore hands.

It's 3:10 p.m. and we're way ahead, we're not scheduled for a break until 4:00 p.m. so I would propose that if the EPRI folks are ready to go, we just push ahead and get the EPRI presentation going.

I'm not sure, I think that's the way we should probably go. So, let's see...

MR. BROWN: Elliot, are you okay with sharing a screen?

MR. RUDLAND: I can do it if you'd like, I just need to pull it up.

CHAIR BALLINGER: One thing, we have a public comment that's been requested. Chris, us being way ahead of schedule, does that impact this at all?

MR. BROWN: No, the person contacting me, they're not going to make the comment after all.

CHAIR BALLINGER: Thanks a lot.

MR. LONG: Can everyone hear me clearly? This is Elliot Long with the Electric Power Research Institute. I am giving again a set of slides that I gave to the NRC Staff at the October 18th public

meeting on RPD integrity.

And I will touch base on a few industry-wide actions that we have ongoing to generate additional high fluence data. Next slide, please, Dave.

There are two current ongoing industry initiatives to generate high fluence capsule data within the PWR fleet. The first is the Coronated Reactor Vessel Surveillance Program, documented in MRP 326, now Revision 1.

The second is the PWR Supplemental Surveillance Program, PSSP, and that's documented in MRP 412. We'll note, the red asterisk there, this is mainly PWR initiative. They have the higher fluence of the plant designs in the U.S.

The PWRs have their own NRC-approved integrated surveillance program through 60 years of operation and that is documented in BWR VIP 86 Provision 1-A.

There is a plan for subsequent license renewal, SLR, that has been accepted by the NRC and this plan that's documented in BWR VIP 3.1A shows the highest BWR unit will not exceed the threshold for fluence of 6 times 10 to the 19th neutrons per centimeter squared.

I will elaborate on that at the end of my presentation. Additionally, I want to reiterate and discuss the prior EPRI conclusions from the November 2019 ACRS meeting. My colleague, Tim Harden, made a presentation at that meeting and I wanted to revisit those.

I will also touch base briefly on the potential impact to PT limit curves, something that Dave began his presentation with as well. So, next slide. We'll first discuss the CRVSP.

So, the original intent of this program was to optimize the existing and remaining U.S. PWR surveillance capsule withdrawal schedules so that we can increase the amount of high fluence data.

This high fluence data can then be used to inform embrittlement trend curves for prediction of RPD operation beyond 60 years and higher fluences.

This project originally completed in 2011, where EPRI reviewed the reactor vessel surveillance programs for the entire U.S. PWR fleet, made some recommended changes to certain plants to delay capsules such that they would be withdrawn with higher fluence.

Our target date was by 2025 to ensure it was slightly timely but also that we got the high

fluence data we sought. 10 years have since elapsed since the Revision O version.

In 2021 we revised the report, basically reviewing how we did, what's changed, what's left to do, and what's going to happen over the next few years. These updates included all the capsules that have been withdrawn and evaluated since 2011.

Future pull schedules, updated capsule fluence values, and then we did look at how any plants that were closed or are going to be closed would impact the overall goal of the CRVSP.

The next slide summarizes some of the data and where we are. Next slide, please. Okay, so the cover page of the report is on the right. Currently, we have withdrawn and tested or plan to test 16 out of the 30 capsules in the program.

Of the remaining 14, 7 will not be tested or not plan to be tested, either due to a shutdown for instance or they'll be delayed beyond 2025. In summary, going back to Dave's plots, the red dots, 48 U.S. capsules have been tested at a fluence greater than 3 times 10 to the 19.

And then 4 of those are greater 8 times 10 to the 19. By 2025 we'll have 7 more, the final 7 capsules will be tested at fluences greater than 3e19

and two more of these will be a fluence greater than 8.

This report also reviewed and put a withdrawal schedule together for when the PSSP capsules will be withdrawn. The first in Unit 1 will be withdrawn in the spring of 2027 and then Sharon Harris's PSSP capsule will be available for testing in the fall of 2028.

Which leads me into the PSSP program itself. I'll go ahead to the next slide, Dave.

So, the PSSP program was again designed to generate high fluence surveillance data, much the same purpose as the CRVSP, to inform developed of ETCs, of embrittlement trend curve for higher and higher fluence and longer-term operation.

This specific project aimed to fill in gaps in the tested surveillance capsule database and to utilize RPD material that was irradiated and commercial reactors, not based on test reactor data.

The end game of this program was to irradiate two supplemental surveillance capsules for approximately ten years, which would have withdrawn, tested, evaluated and then published.

Within these two capsules, there are 288 sharpie specimens from 27 unique plates, forgings, and

welds. I should stress here that all of these materials in these two capsules were previously irradiated specimens, so they were taken from capsules that were already withdrawn, already tested for the plants in the program.

And then the materials were reinserted into these capsules for additional irradiation. Once everything has been withdrawn and tested, we will have 24 new transition temperature shift results and then 3 additional upper shelf energy-only results.

The fluence ranges for these specimens will be from about 4019 up to 1.2e20 or 12e19 for the various materials in these two capsule. Go to the next slide, please?

So, the history of when we manufactured and designed two capsules containing previously irradiated and reconstituted PWR materials. The MRP sponsored this fabrication and two U.S. utilities agreed to host the materials.

The first one was inserted in the Fall Unit 1 in October of 2016 and the second one was inserted into Sharon Harris in April of 2018. The fabrication report was then published in 2016, MRP 412.

Next slide, please, Dave. As I noted from

the updated CVRSP report, Fall Unit 1 will be available to be withdrawn and tested in the spring of 2027, Sharon Harris in the fall of 2028.

Shown to the figure on the right, you can see how these specimens were made. The top image is that of a previously broken and irradiated sharpie specimen so that specimen was tested.

One half of the specimen was machine, to the second row the middle piece specimen insert is the top piece that was machined into the middle. The end tabs were then welded on to make a new sharpie specimen.

The middle image was then machine cleaned and cut the size and then that was inserted into the capsule, the bottom image there. So, that's how we refabricated and remade sharpie specimens out of previously broken, previously irradiated material.

After the withdrawal and testing of these capsules, they'll be evaluated in 2028 through 2030. The capsule reports will be delivered to the NRC Staff for review approximately 18 months after each capsule's withdrawal dates.

There will be two separate reports, one for each capsule, and thereafter we will analyze the data and its impact on future ETCs. That bottom right

image is just a picture of a PSSV capsule itself in a specimen holder in one of the two plants.

Before I continue forward, are there any questions in regard to either of these industry programs, again designed to generate high fluence capsule data for the U.S. fleet?

MEMBER HALNON: This is Greg. The welding and this machining and whatnot, what's the delta between that and a virgin, I guess, material?

MR. LONG: Great care was taken and a qualified process was developed to ensure that the welding process was done at a temperature such that the irradiation temperature was not exceeded on the specimens.

So, they were designed and qualified and then there was a benchmarking assessment in MRP412 that showed the sharpie curves between original material and material made in the fashion of the top right image were essentially the same.

MEMBER HALNON: So, you're pretty confident that any differences are not going to show up in the data so it's going to be just like an original specimen?

MR. LONG: That's correct, we are confident that it will be within the typical scatter

of a sharpie specimen curve. They look fairly identical.

MEMBER HALNON: Good, thanks.

MEMBER BROWN: This is Charlie Brown, I've got a question on this, I'm not sure it's an intelligible question.

It's a vague memory that sharpie venotch specimen sizes -- I'm springboarding out of Greg's comment -- there's some minimum sizes.

And once you chop one in half like this and try to reconstitute it, how do you know you haven't compromised it with results from the welding and the other testing that the other ends that have been involved in?

MR. LONG: There are standards within ASTM for reconstitution of sharpie specimens and those standards were adhered to in the development of these reconstituted specimens.

So, the sizing limits of the ASTM standards were achieved for the specimens included in the program.

MEMBER BROWN: So, there's no effect of the welding then? When you put them back together that's far enough away from the well zone?

MR. LONG: That's correct, they're far

enough away from the material itself and we again used a very specific welding process that did not exceed the temperature in which the original specimens were irradiated.

And then this was again benchmarked and qualified by the fabrication vendor and developers of the castles themselves.

MEMBER BROWN: Thank you very much.

MR. LONG: Dave, go onto the next slide, we'll change gears here a little bit and review some of the conclusions from the prior ACRS meeting on this topic. Go onto the next slide.

Back in the November 2019 timeframe, my former colleague and predecessor Tim Harden, who retired earlier this year, made a presentation to the ACRS in regard to potential changes to Reg Guide 199 Revision 2.

The conclusions from that meeting on the right are shown here and they have not changed. If in the future a revision to the reg guide is implemented, the ASTM model, E900-15 remains the preferred model.

It is understood and Dave spent a lot of time discussing those performance values. Below 6019 the reg guide at this point remains adequate for predicting RPV and embrittlement.

And noting that PT limit codes from 10 CFR 50 Appendix G utilized the quarter T fluence. I took some time to put together when certain plant designs will see a fluence of 6019 at the quarter T location.

So, go onto the next slide. So, this chart at the right, we're focusing on what surface fluence is needed to generate a quarter T and a three-quarter T fluence of 6 times 10 to the 19.

So, the top right chart was developed using the current fluence attenuation formula from the Reg Guide 199 Revision 2, and as you can see for the various plant designs, Westinghouse 2-loop, 3-loop, BMW, various 4 loops with different RPD manufacturers, some of the CE designs.

Everyone has a slightly different vessel thickness and the fluence needed at the surface to reach a quarter T value at 6019 is shown at the right.

So, for example, a Washington 2 Loop plan would need a surface fluence of 8.86 times 10 to the 19 to have a quarter T fluence of 6.

And similarly for the 2 loop plans, at three-quarter T you would need a surface fluence of 19.3 times 10 to the 19 to have a three-quarter T fluence of 6019.

So, that's obviously very high for the

three-quarter T location and as the vessels get thicker from the various designs you have a higher and higher surface fluence needed to generate a quarter T fluence of 6019.

Generally speaking, the 3-Loop Westinghouse design have the highest surface fluence at end of life. I then went in and summarized the various plants that have thus far applied for a subsequent license renewal, and that is the bottom right chart.

The bottom right chart shows the surface fluence at SLR for the six PWR plants that have thus far applied for a second license extension or SLR. Only 1 of the 6 will exceed the surface fluence necessary to have a quarter T fluence of 6019 before end of life.

That's Plant A and this is predicted to occur at about 65 BFPY for Plant A. The remainder of the plants have a surface fluence value that will never then subsequently lead to a quarter T fluence of 6 times 10 to the 19.

And then finally, I wanted to reiterate the BWR plans are not shown anywhere on this chart as they will never reach these fluence levels in any reasonable operational timeframe. 1 BWR SOR plant has

a surface fluence value of 5 times 10 to the 18.

So, very much orders of magnitude below the 6019 where the reg guide predictions begin to break down.

CHAIR BALLINGER: This is Ron again, probably a question for Dave regarding 61A analysis. Did that analysis consider the fluence gradient through the vessel each time?

MR. RUDLAND: No, because 61A only looks at the surface fluence.

CHAIR BALLINGER: This is a big factor because now one of the compensating things, I suppose, for a lot of the uncertainty is the fact that any crack would be growing into a tougher material by quite a bit.

MR. RUDLAND: That's correct. In the PFM stuff that we did, of course we took the attenuation into account.

CHAIR BALLINGER: You did? Okay.

MR. RUDLAND: For the PT curve stuff we did but for the PTS you only have to look at the surface because the screening criteria is based only on the surface fluence.

CHAIR BALLINGER: I got it, thanks.

MR. LONG: Yes, this chart was just

developed, these calculations here, just to show where the 6019 would be at the quarter T and is focused on pressure temperature limits in this case.

CHAIR BALLINGER: That's why in the presentation I said the staff would eventually be concerned.

I had different time periods between the PTS and the PT limits because of the difference between the fluence levels at the ID versus the quarter T.

MR. LONG: Right, and this is my last slide so if there's any other questions, please let me know.

Hearing none, I will turn this back over to you all. Thank you for the opportunity to present today.

CHAIR BALLINGER: Thank you for your presentation. Questions from the Members and consultant?

Hearing none, I think now the public line is available I suppose, are there any public -- oh, there's a hand raised. Where's the hand?

MR. DENIS: This is Den Denis from Structural Integrity Associates. I wanted to comment on previously if there are any questions regarding PT

limits curve generations, I noticed also Westinghouse is on the line.

But I know Westinghouse, GE, and Structural Integrity Associates, we provide the plan-specific PP limits curves as a vendor. If there are any questions on the generation or the processing of those analyses, we can take a conversation offline if desired.

I just wanted to offer that out.

CHAIR BALLINGER: Thank you.

MEMBER BROWN: I wasn't able to formulate my question, I'm trying to summarize it. After listening to all this, I'm trying to condense it down.

What I heard, and if I'm wrong please tell me, is that based on all the development data in the testing they've got coming, getting it for 2WRs, it looks like embrittlement is not going to be a limiting factor for 80-year SLRs?

Is that right or am I totally off base?

CHAIR BALLINGER: I think that's more or less correct. Dave can correct me. I think the issue is the uncertainty.

MEMBER BROWN: I understand that.

MR. RUDLAND: I think there's a couple of issues. I think one is the uncertainty, I think Allen

made the point that there isn't many plants that are going to reach the quarter T fluence of interest by 80 years.

But we still have to understand the behavior in PTS space to make sure we're bounding and what we've done to make sure there's not a concern there.

Plus, as Ron pointed out, there are a lot of uncertainties in the analyses at least that we did in terms of whether or not we've covered all the plant-specific issues.

I think in general what you said is not incorrect.

MEMBER BROWN: Are there plans to even be able to eventually agree, or you all agree, not we, propose going to an 80-year life that there are ways to at least withdraw a capsule to see if they have exceeded something during that last 20 years?

Is there some process in place for that?

MR. RUDLAND: Plants have capsules in there to be able to do it, they just need to pull them to test them.

MEMBER BROWN: But you could do that to make sure your uncertainties didn't kill you? That's what I'm trying to say.

MR. RUDLAND: That's correct. They've got that data and this data that Elliot talked about that's coming, which is separate from the actual plant-specific data.

And then again, between that and if we are able to fix the embrittlement trend curves, I think that would go a long way to really reducing the uncertainty.

MEMBER BROWN: Understood, thank you.

MR. HISER: Just to add a little bit, each of the PWRs that has an SLR at this point has good means to test a capsule to get a higher fluence. So, there are commitments to do the testing, as Dave said.

If they follow through on those commitments, we'll have the data, if they continue to delay the withdraw on testing, then we won't have the data.

MR. RUDLAND: Just to be clear on that point, Allen, the regulations allow them to delay or not test that capsule.

So, even though they said they'll do it as part of their renewed license, there's no commitment from them to do that and they can take the path that others have to delay or not test the last capsule.

MEMBER BROWN: How does this then allow

you as the NRC to say everything is okay if they choose to delay and not take that capsule out once they're into that SLR period?

MR. RUDLAND: I think that's why we believe a change is needed, to guarantee that they are.

MEMBER BROWN: That they will take them out?

MR. RUDLAND: Yes, that's something we're trying to determine the best path forward.

MEMBER BROWN: Does that require something from the Commission to go tell them that?

MR. RUDLAND: If they were to change the word, yes.

MEMBER BROWN: I'm just trying to understand that, I don't know as much about it.

(Simultaneous Speaking.)

MR. RUDLAND: That's why we wanted to specifically change Appendix H to say you need to test the last capsule. It was required in the rulemaking, we have to go to the Commission.

First, we have to go to the Commission to ask permission to change the rule and then we'd have to go through the rulemaking process.

CHAIR BALLINGER: That's a good segue, by

the way. Slide 30, options being considered, can you give us some kind of feeling for the timeline of when these decisions will be made, and then path forward?

Because there was a member and that's my question as well, sooner or later, we would probably get to a point where we would see something where we could get a letter.

This has been going on for quite a while.

MR. RUDLAND: Yes, it has and the Staff is actively trying to move quickly to a decision on what to do, I can say that.

We want to make sure that we do it but again, the issue is twofold, we want to make sure that we don't do something that is burdensome to those that won't have the issue for a very long time.

We want to make sure that the change is focused and if we do we need to talk to the Commission about it before and they have to decide whether or not it's appropriate to change the regulations or not.

So, that helps us take a little bit of time and it's difficult for me to give you a schedule on that right now.

CHAIR BALLINGER: So, the NuScale people will have to apply for an exemption?

MR. RUDLAND: I don't know, I can't

comment on the PRM right now. I don't know if somebody else can? The NuScale PRM is still under consideration, I do know that and so the decisions on that have not been finalized.

CHAIR BALLINGER: Because they want to directly use E900, right?

MR. RUDLAND: I believe that was what the request was. Bob Caldwell may have a comment.

MR. CALDWELL: This is Bob Caldwell, I'm the Director of the Division of Renewed Licenses. I just wanted to go back to a little bit about making the industry do stuff.

Right now they don't have to and to make them do stuff we have to go through and do the backfit analysis. That's not trivial so it's hard for us to promise one thing or another at the moment with regards to what our actions forward are.

The effort that Dave and the team went through was to help establish what the safety basis is, the safety case for what we want to do and go forward. And that will be a primary consideration as we move forward and make our decision on what needs to be done.

CHAIR BALLINGER: Thank you.

MEMBER HALNON: This is Greg, I've just

got one more question and then I'm not even sure if I know how I'm asking it makes any sense.

But getting a subsequent license renewal to 80 years, I see there's some prediction on the amount of fluence that will occur during that 20-year period such that you can assure there's a safety margin in the PT curves.

The first 20 years of operating these plants, the capacity factors are in the 60 to 75 percent. Now we're running these plants up to 95-plus percent capacity factor.

How does that factor in? Earlier, the first 20-year fluence is not going to equal the last 20-year fluence while operating it. But I guess also it would have low leakage cores and other things now too.

How does all that factor into the analysis? Are those all just inputs to it?

MR. POEHLER: This is Jeff Poehler from the Office of Research, I can maybe comment on that.

Plants specifically when they're doing the 60 to 80-year estimate will use a conservative estimate for capacity factor for fluence going forward.

Typically, 90 or 95 percent.

MEMBER HALNON: So, they take actuals and then they predict out at a very high capacity factor?

MR. POEHLER: Generally speaking, yes.

MEMBER HALNON: 40 years of fluence is not going to be equal to the second 40 years, it's going to be a lot less.

MR. HISER: Really, what they want to do is to make sure they're not non-conservative.

There are time-limited aging analyses on reactor vessel embrittlement so plants project those forward and I think in at least one case they were actually using the capacity factor that exceeded 100 percent just to make sure they would have a conservative prediction at 80 years.

MEMBER HALNON: It's front and center in all these analyses then.

MR. HISER: Absolutely, and what they do is they calculate cycle by cycle the accumulated fluence and then up to maybe the last cycle before their application submitted, and then they project forward from there.

MEMBER HALNON: Good, thanks.

CHAIR BALLINGER: Okay, I think I need to apologize. I think I've confused public comments from general questions. Are there any members of the

public that would now like to make a comment?

Okay, any last final comments from Members? Well, in that case I would like to thank you and I'm sure the rest of the Committee would thank you for doing this.

It's an important, at least in my mind, a very important topic and it behooves us to keep track of this. We appreciate the extensive effort, actually, that's been made by the Staff since the last time we wrote a letter.

So, that was another reason for asking for this update. So, if there are no other comments from the members then I think this meeting is adjourned.

(Whereupon, the above-entitled matter went off the record at 3:45 p.m.)

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Reactor Pressure Vessel Embrittlement Monitoring and Prediction in Long-Term Operation

ACRS
Metallurgy and Reactor Fuels Subcommittee
November 15, 2021

Meeting Purpose

- Discussion of Issues
  - Regulatory Guide 1.99 Rev 2 (RG 1.99) and 10 CFR 50.61 embrittlement trend curve
  - Appendix H surveillance testing
- Discussion of holistic risk-informed analysis of these issues and its potential impact on reactor pressure vessel (RPV) integrity
- Path forward options

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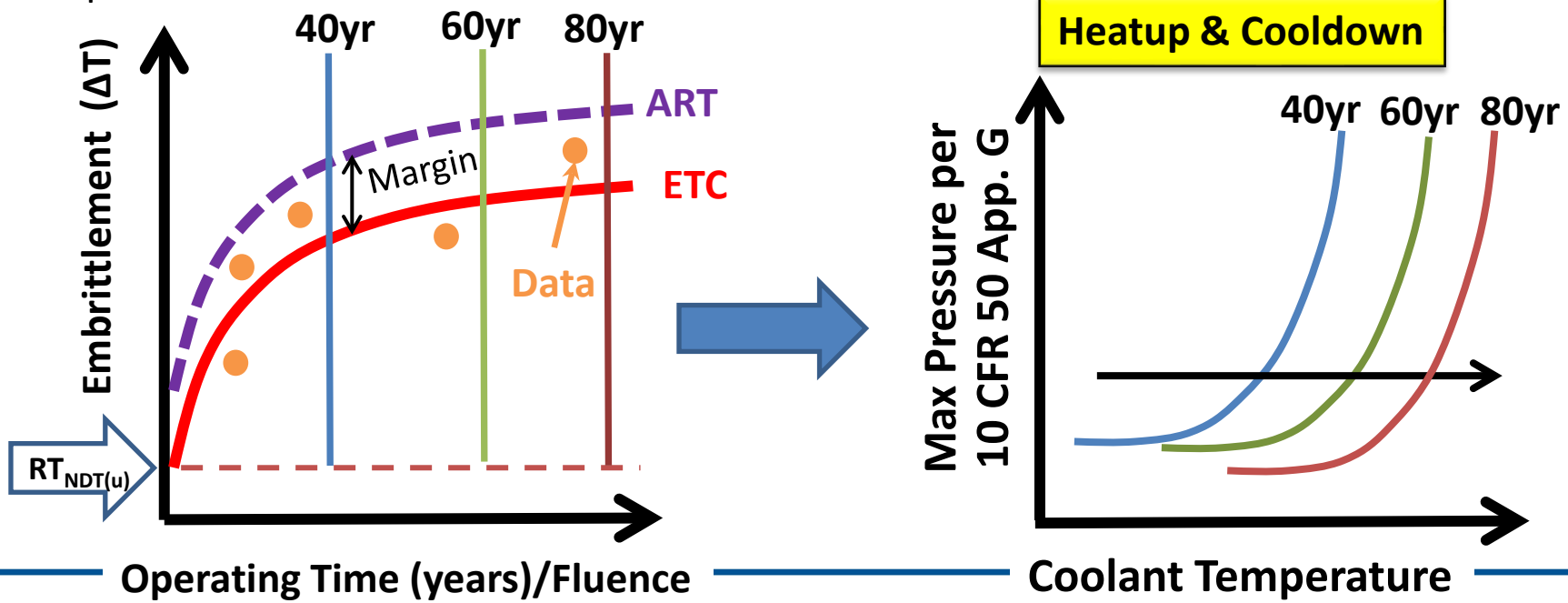
Background
Monitoring and Prediction of Embrittlement

- Embrittlement Trend Curve (ETC) provides estimates of change in fracture toughness (ΔT or ΔRT_{NDT}) as a function of fluence
- Surveillance capsule testing provides monitoring to ensure ETC predicts plant specific behavior properly
- Together they are used to determine pressure-temperature (PT) limits for normal operation



ART = Adjusted Reference Temperature

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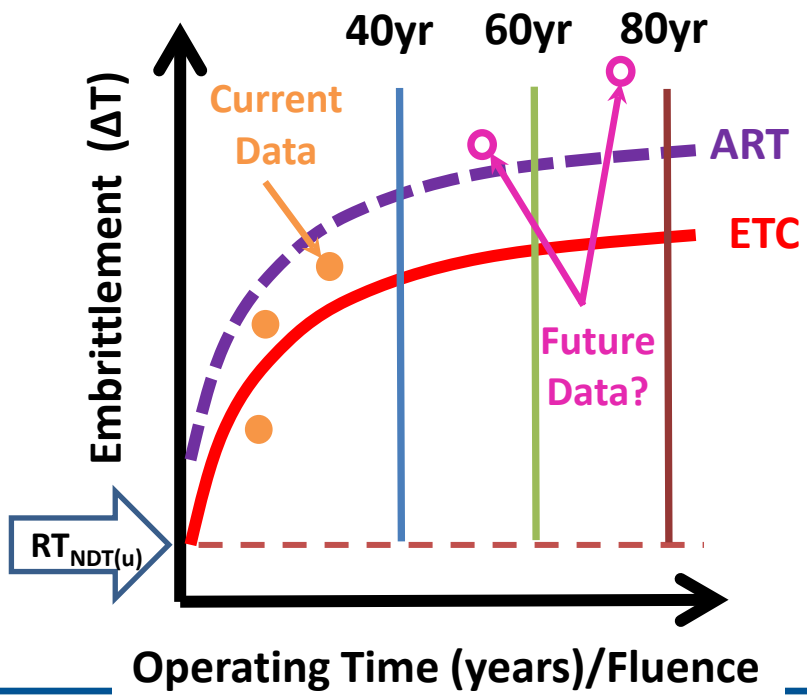
Ideal Scenario

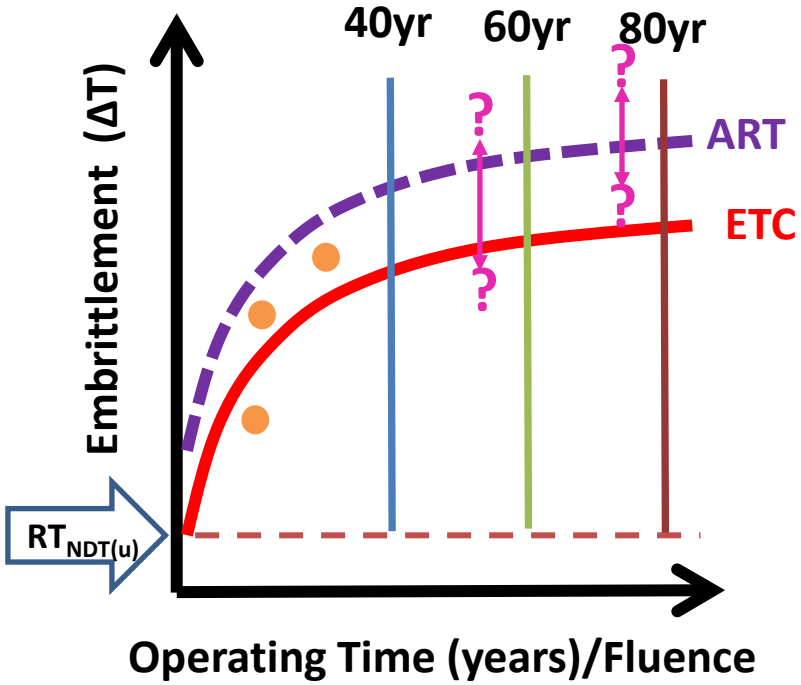
- ETC provides conservative predictions of embrittlement
- Surveillance data covers all operating periods

Potential Uncertainty Sources

IF **ETC under-predicts measurements**



IF **Limited Surveillance Data is Available**



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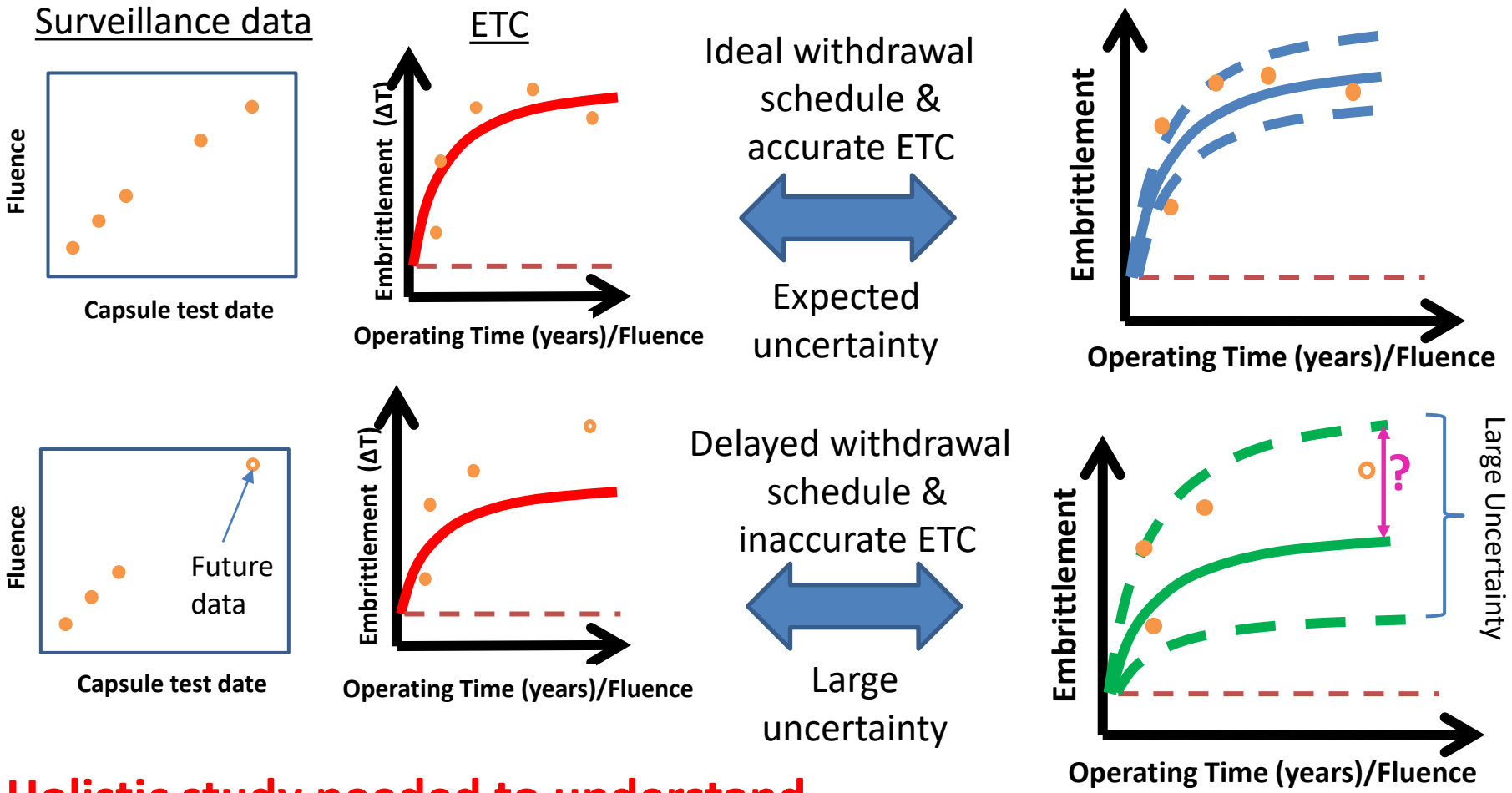
Embrittlement Uncertainty



Holistic study needed to understand impact of uncertainty

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Current Perspective of Potential Issue

- High confidence that currently operating plants remain safe
- Recent licensing actions remain valid
- Insufficient embrittlement monitoring and under predictions of reactor vessel embrittlement will eventually (after about 10 years for PTS; after about 23 years for P-T limits and upper shelf energy) impact the staff's confidence in the integrity of the reactor pressure vessel in long-term operation, i.e., both safety margins and performance monitoring may be impacted
- Further work is needed to determine which plants are impacted by this potential issue

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Embrittlement Trend Curve

- May 1988, NRC published RG 1.99, which contained an improved embrittlement trend curve (ETC)
  - Fit based on 177 datapoints
- June 1991, NRC updated 10 CFR 50.61 to include the ETC from RG 1.99
  - Addressed lower than measured predictions (up to 60°F) of embrittlement in some vessels
- This ETC was re-evaluated for continued adequacy in 2014 (ML13346A003) and in more detail in 2019 (ML19203A089)

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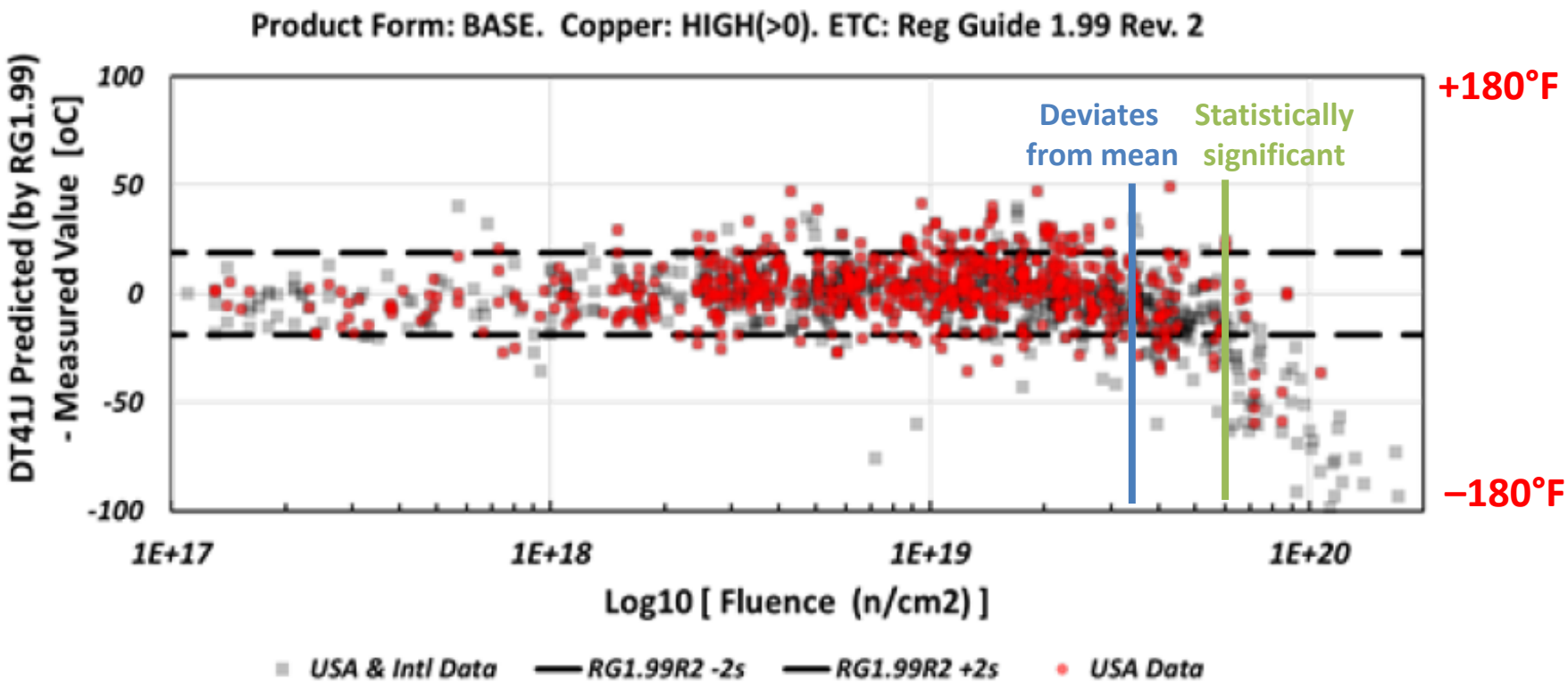
Issue – ETC



DT41J = ΔT_{41J} is a measurement of embrittlement representing the shift in transition temperature from brittle to ductile fracture at an impact toughness of 41J

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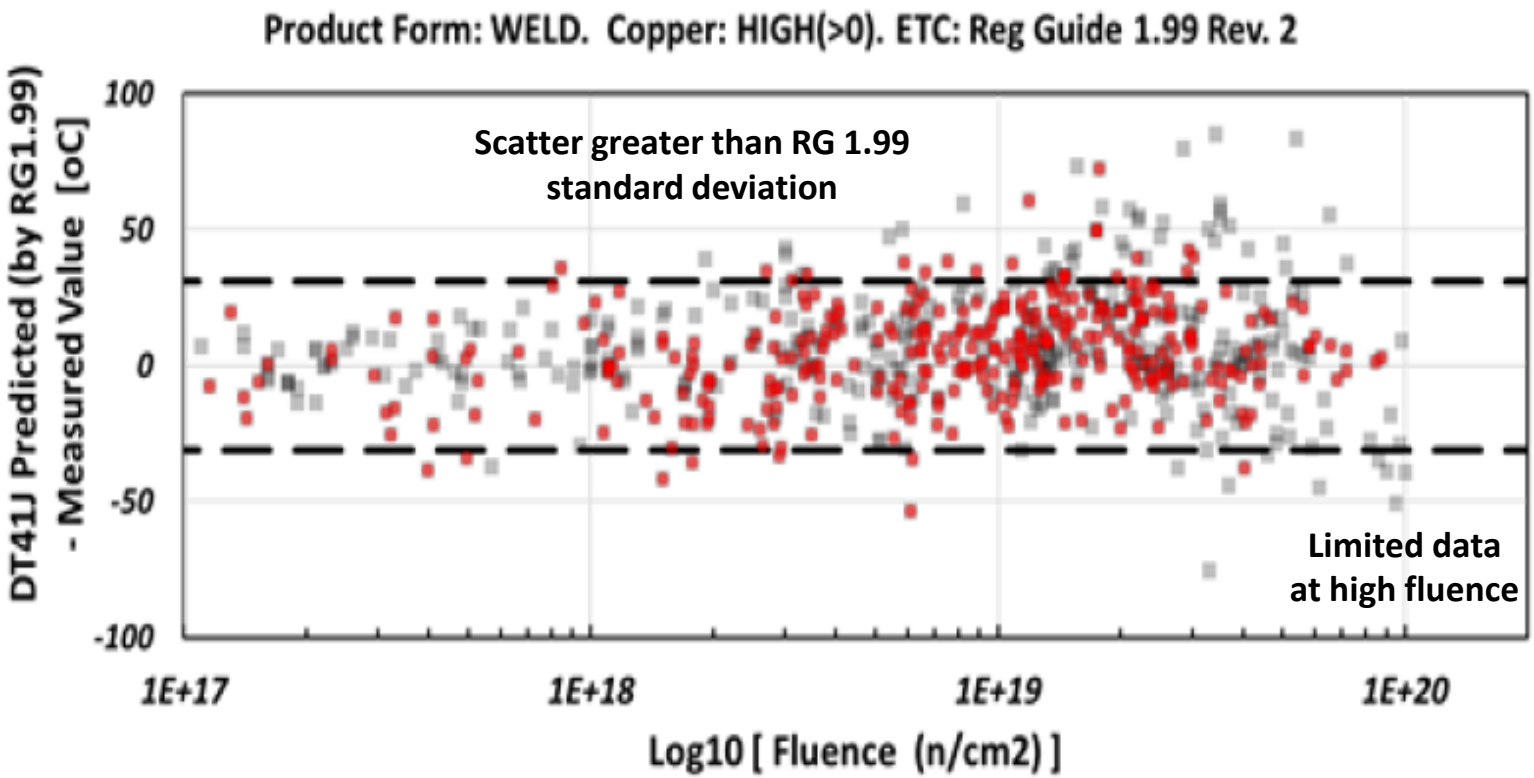
Issue – ETC



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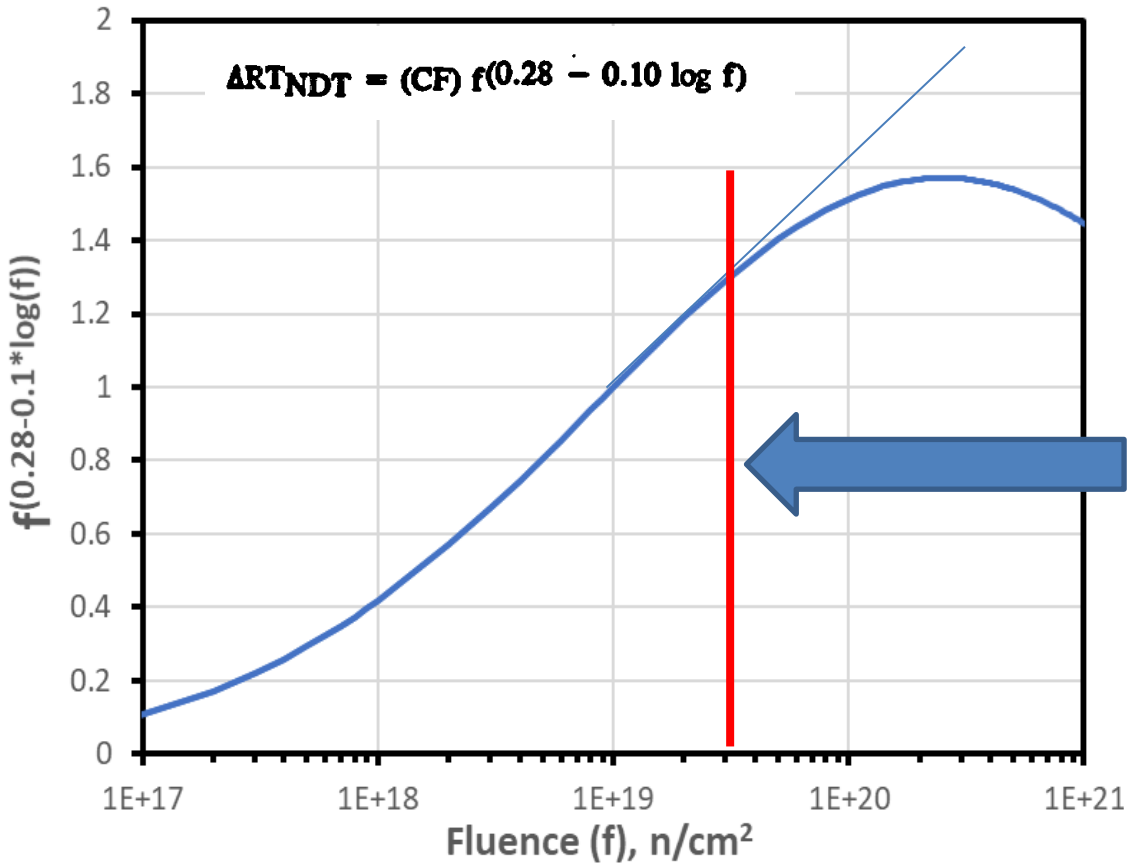
Issue – ETC Fluence Function



Fluence function begins to "flatten" at the same fluence level underprediction occurs in Slide 8

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Surveillance Capsule Delays

- Appendix H to 10 CFR Part 50 requires periodic monitoring of changes in fracture toughness caused by neutron embrittlement
  - ASTM standard (E185-82) allows final capsule fluence to be 2X RPV "design" fluence – plants change (intended 40-year) design fluence to current license length (e.g., 60 or 80 years)
  - ASTM standard (for 40 years) permits holding last capsule without testing

- Commission finding ("Perry decision" NRC Administrative Letter 97-04) that staff review of requests to change capsule withdrawal schedules is limited to verification of conformance with the ASTM standard (i.e., not based on technical or safety considerations)
  - Capsule withdraw and testing repeatedly delayed in some cases to achieve higher fluence

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License Renewal

- Regulations are unchanged; surveillance program addressed in guidance
  - Guidance provides flexibility for licensees to demonstrate adequate management of RPV embrittlement due to varying plant-specific circumstances

- Aging Management Program XI.M31, "Reactor Vessel Material Surveillance"
  - Continues reliance on Appendix H program using ASTM E185-82
  - GALL Report (NUREG-1801, Rev. 1) for license renewal (40 to 60 years)
    - "shall have at least one capsule with a projected neutron fluence equal to or exceeding the 60-year peak reactor vessel wall neutron fluence prior to the end of the period of extended operation"
    - Describes use of reconstituted specimens and use of operating restrictions (neutron flux, spectrum, irradiation temperature, etc.)
  - GALL-SLR Report (NUREG-2191) for subsequent license renewal (60 to 80 years)
    - "withdrawal and testing of at least one capsule . . . with a neutron fluence of the capsule between one and two times the peak neutron fluence of interest at the end of the subsequent period of extended operation" – or data from a prior tested capsule
    - Specifies – "it is not acceptable to redirect or postpone the withdrawal and testing of that capsule to achieve a higher neutron fluence that meets the neutron fluence criterion for the subsequent period of extended operation"

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License Renewal in Practice

- Licensees have changed capsule withdrawal schedules prior to application for license renewal or subsequent license renewal
  - Change is evaluated under current approach of "conformance verification"
- (Updated) current licensing basis surveillance program for license renewal/subsequent license renewal is then consistent with the program in GALL/GALL-SLR

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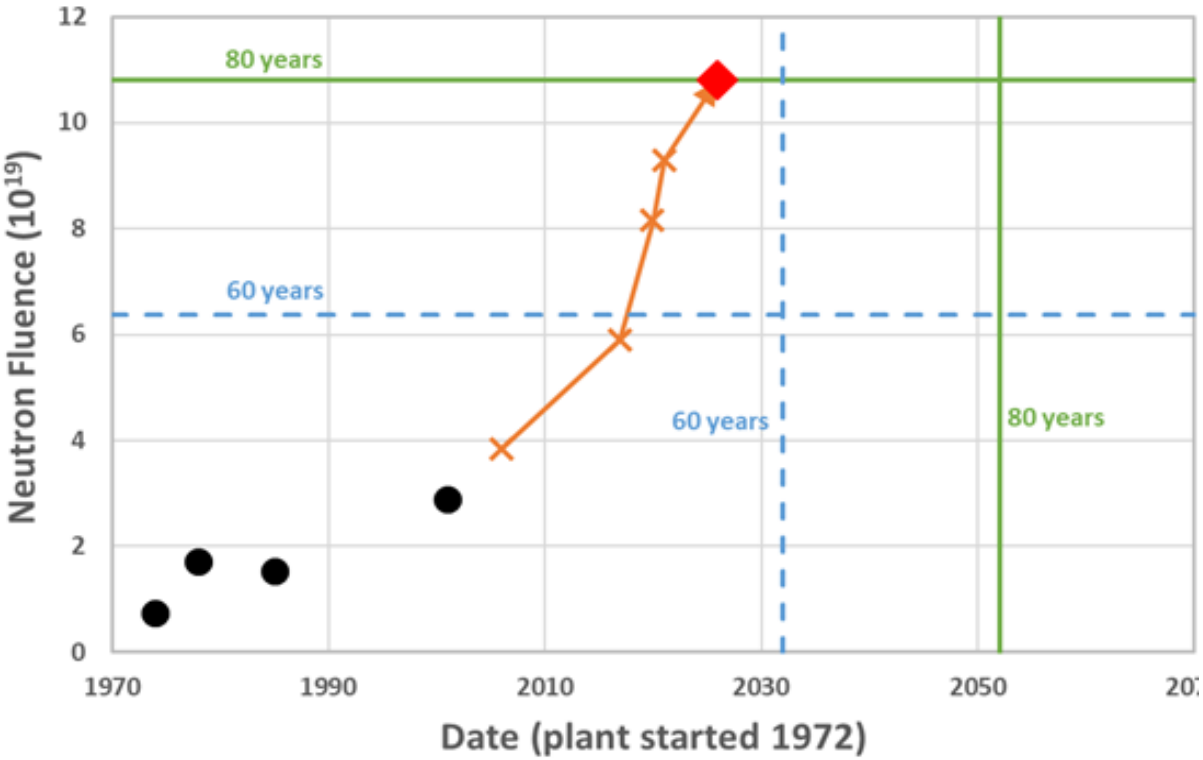
Issue – Appendix H

Performance Monitoring



Capsule withdrawal schedule changes include delays in both time and/or fluence

Many licensees have delayed capsules (time and/or fluence), some recent examples:

Plant	Capsule #	# of times delayed
Turkey Point	5	4
Robinson	5	2
Surry U1	5	2
Surry U2	5	2
North Anna U1	4	2
North Anna U2	4	2
St. Lucie U2	4	1
Point Beach	5	1

Not all plants have delayed withdrawal of capsules

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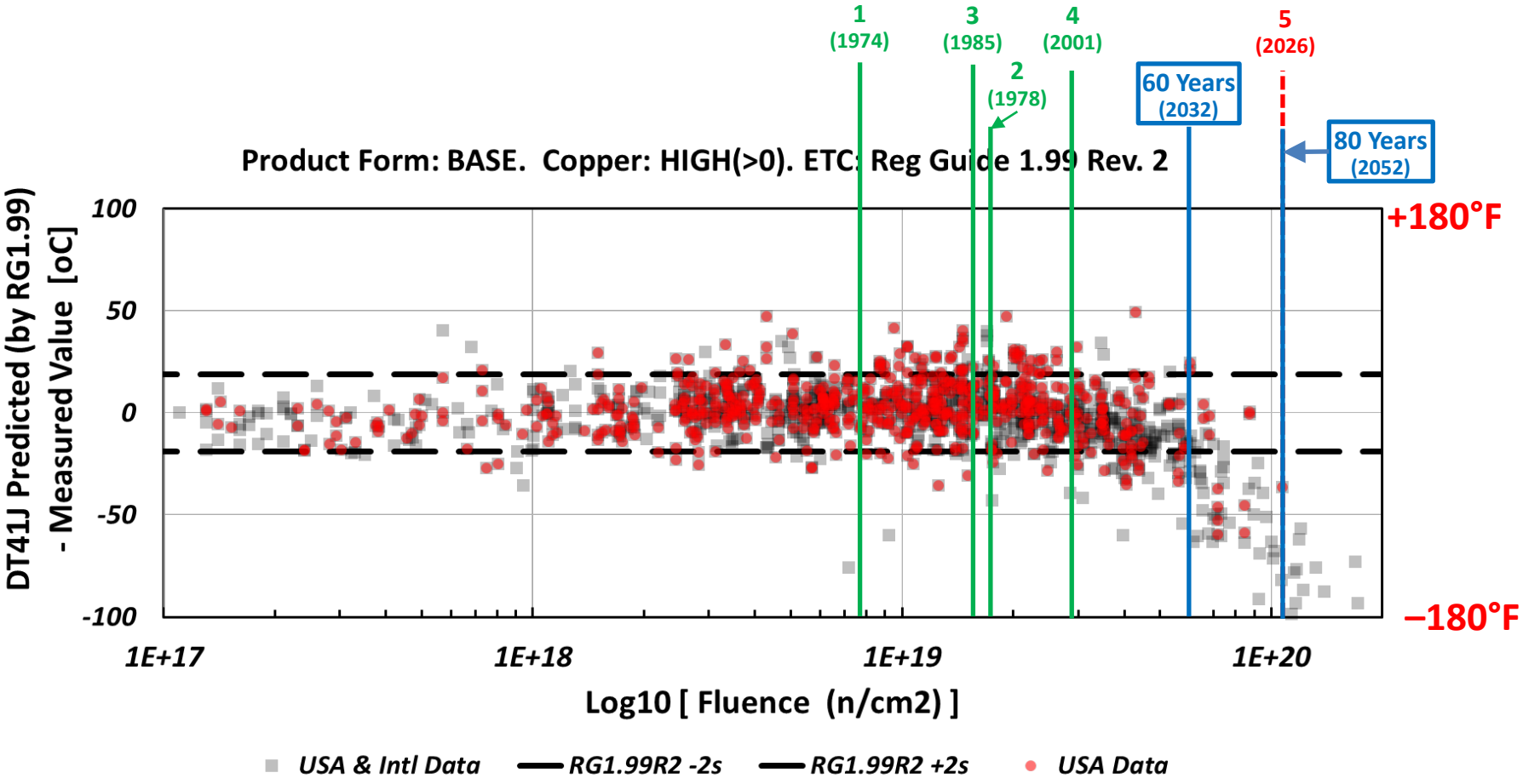
Potential Impact of Issue



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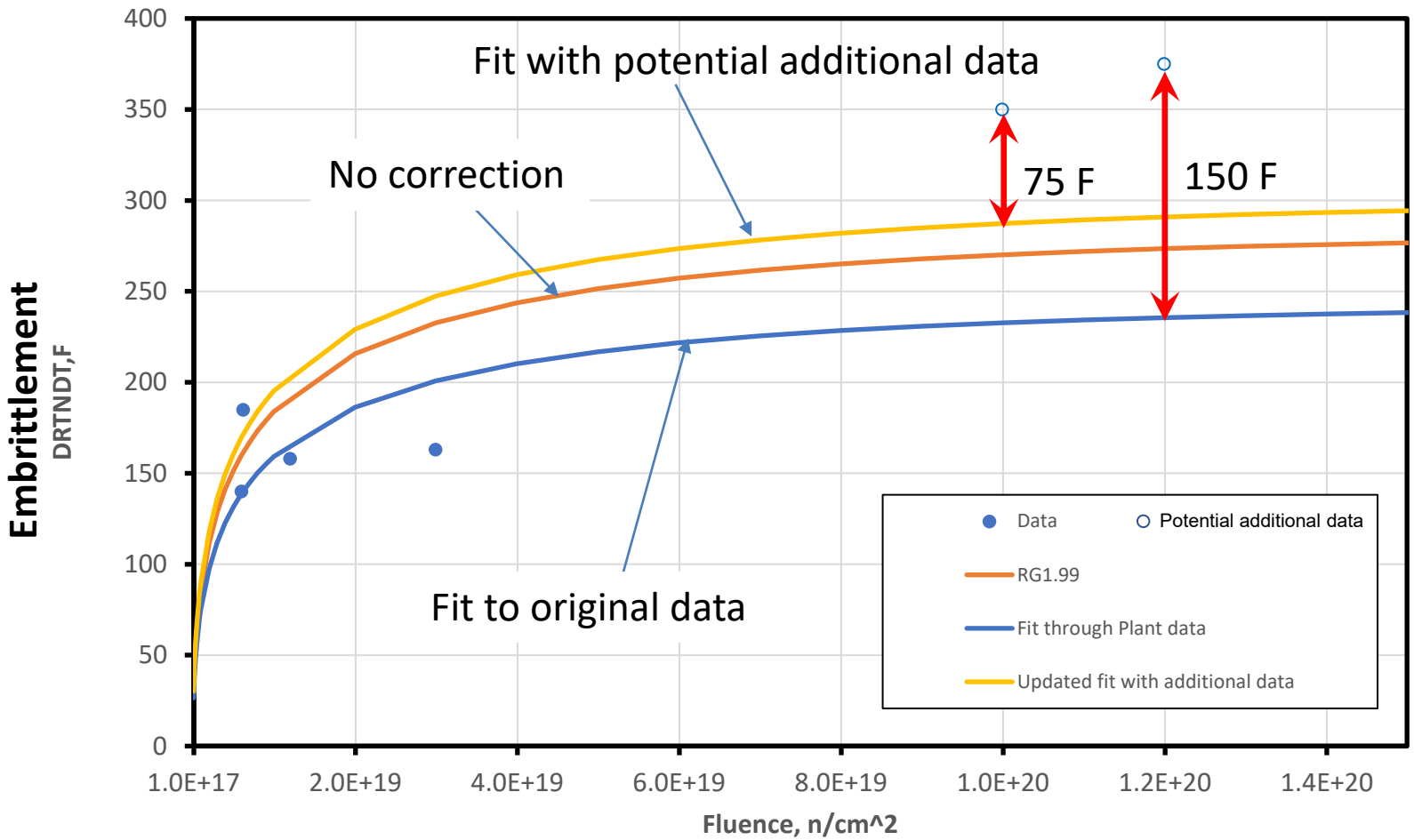
Potential Impact of Issue



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Risk-informed Analysis

- Considered combined effects of surveillance and embrittlement predictions
- Leveraged 5 principles of risk-informed decision making
- Targeted sample of plant data used, but much plant specific information not available

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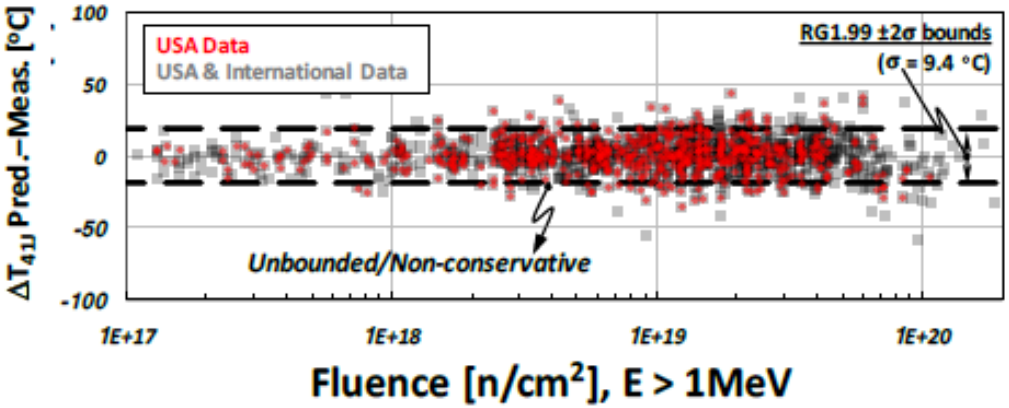
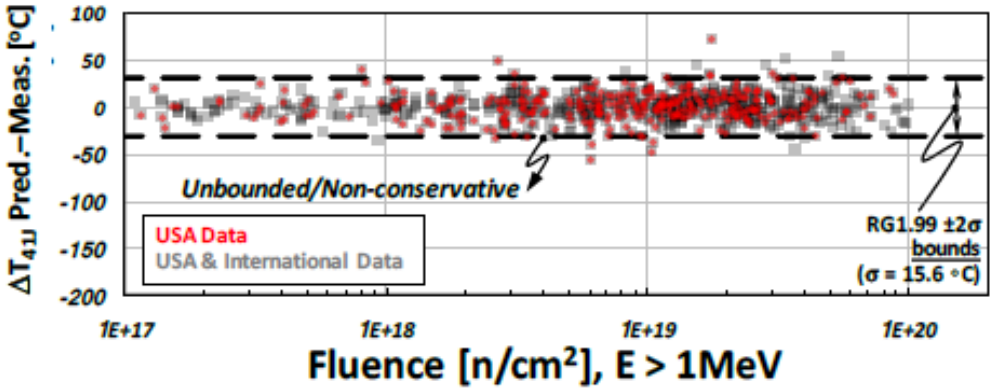
Analysis Assumptions

- Comparisons based on ASTM E900-15 ETC
- The NRC staff found that the ASTM E900-15 ETC provided the most accurate characterization of this database*

Plates and Forgings



Welds



*"Basis for a Potential Alternative to Revision 2 of Regulatory Guide 1.99," TLR-RES/DE/CIB-2020-11, ML20345A003

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Analysis Assumptions – Fleet Impact Study

- A targeted sample of 21 plants
- Emphasis on high fluence plants, with a few low Cu plants and BWRs to round out
- Determined changes in adjusted reference temperature resulting from switching ETCs – "embrittlement shift delta" (ESD)
- Results used to benchmark ESD range of risk analysis

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Results – Fleet Impact Study

- There is a tendency for material reference temperatures to increase when switching from RG 1.99 to ASTM E900-15.
- Base materials are more likely to see increases in reference temperatures than weld materials.
- Only a handful of plant limiting materials will have ESDs > 50 °F, and these tend to be at fluences ~6×10^{19} n/cm^2 .
- Range of ESDs assumed in risk study bounds fleet impact findings.

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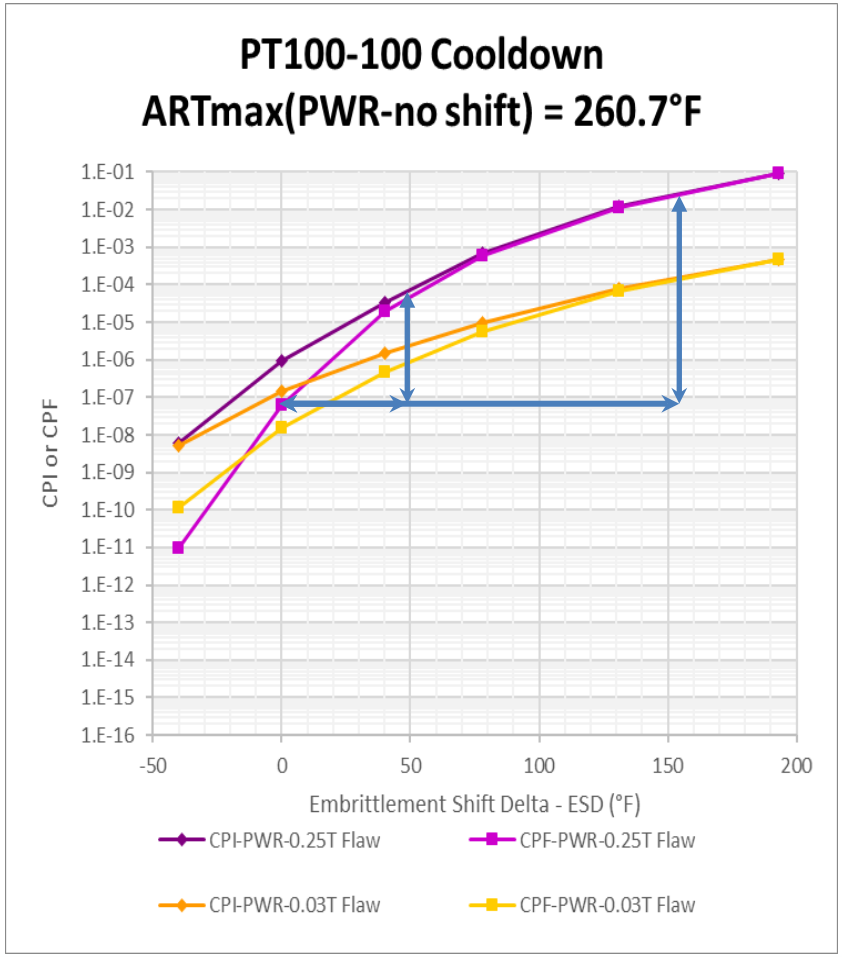
Risk of Failure



ESD represents the underprediction of ΔRT_{NDT}

Large Uncertainties:

- Unknown frequency of transient
- Actual plant fluence variations
- Are these analyses bounding?
  - Unknown plant-specific considerations
- How much protection do administrative and other operational limits provide against violating the PT limit?

"RG 1.99 Revision 2 Update FAVOR Scoping Study," May 6, 2021, TLR RES/DE/CIB-2020-09, Rev. 1, ML21126A326

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Through-Wall Crack Frequency Results

Transient Type	Shallow Flaw	1/4T Flaw	Comment
BWR P-T Limit Cooldowns	CPF ≤ $1x10^{-6}$ for all ESDs	CPF ≥ $1x10^{-6}$ for ESD > 40 °F	BWRs must cooldown on saturation curve, so cooldown on licensed limits not plausible.
BWR Saturation Cooldown	CPF ≤ $1x10^{-6}$ for all ESDs	CPF ≤ $1x10^{-6}$ for all ESDs	
BWR Leak Test, Cooldown rate ≤ 50 °F/hour	CPF ≤ $1x10^{-6}$ for all ESDs	CPF ≥ $1x10^{-6}$ for ESD > 100 °F	Additional information is desired to determine if high cooldown rates are possible, or ASME Code action will be pursued to prohibit.
BWR Leak Test, Cooldown rate > 50 °F/hour	CPF ≤ $1x10^{-6}$ for all ESDs	CPF ≥ $1x10^{-6}$ for ESD > 100 °F	
PWR P-T Limit Cooldowns	CPF >$1x10^{-6}$ for ESDs ≥ 50 °F	CPF > $1x10^{-6}$ for ESD ≥ 20 °F	Additional information on event frequencies is desired to confirm TWCF< $1x10^{-6}$ /year.
PWR Cooldown, Actual Transients	CPF < $1x10^{-6}$ for most transients	n/a	

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Pressurized Thermal Shock Considerations

- 10 CFR 50.61 uses ETC from RG 1.99
- RT_{PTS} from 10 CFR 50.61 might be impacted
  - Limits of 270 °F for plates, forgings, and axial weld materials, and 300 °F for circumferential weld materials
- However, through-wall crack frequency calculated with corrected embrittlement less than $1x10^{-6}$ for all cases investigated

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Safety Margins

- Uncertainties in risk calculations are high and increasing with time
- Even though the risk appears low, resolving these issues will help maintain the fundamental safety principles that are the basis of plant design and operation
- Safety margins, as provided by regulations and current license bases, provide reasonable assurance against brittle fracture

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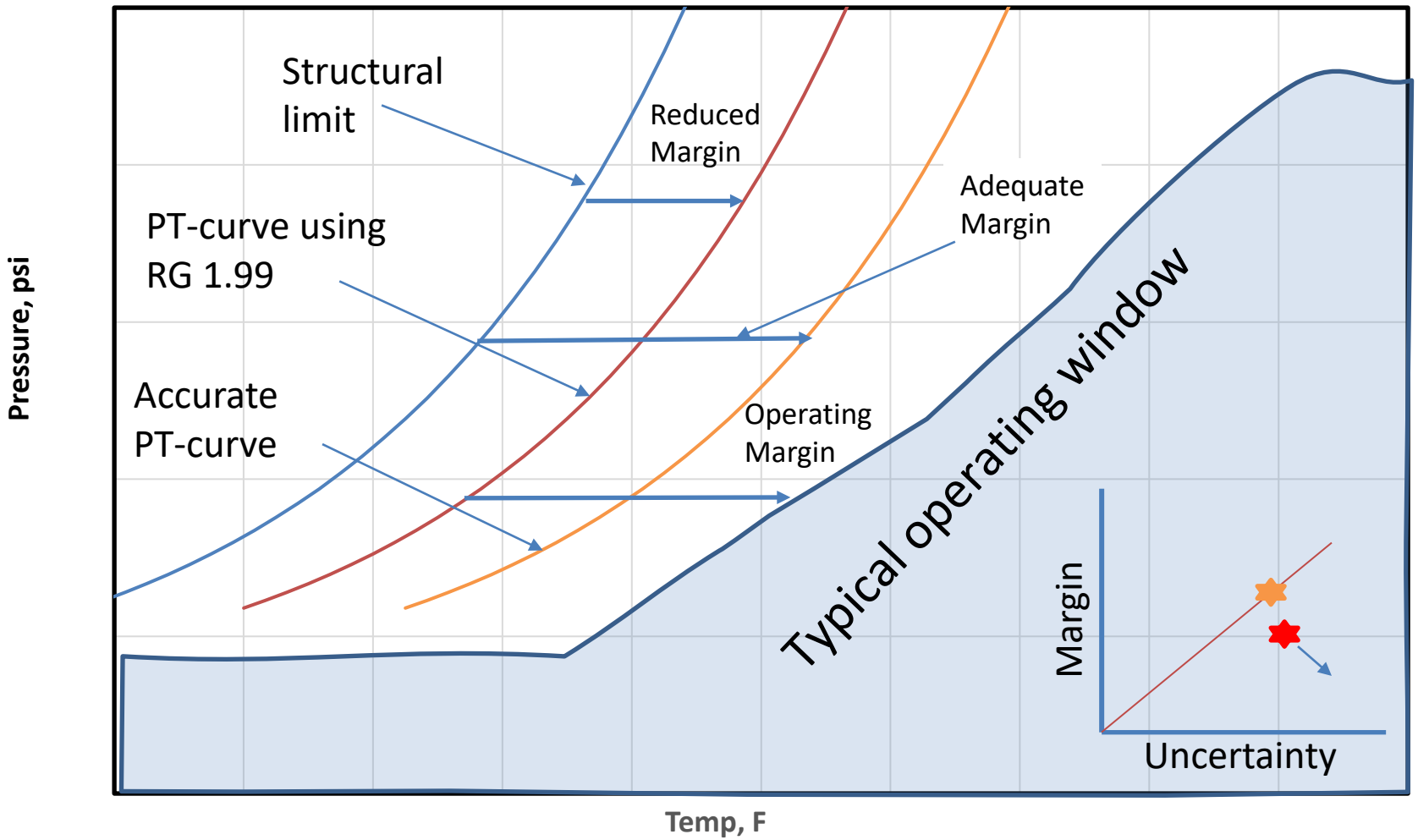
Safety Margins Illustration



Uncertainties increasing due to lack of surveillance, but margin is less due to embrittlement underprediction

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Performance Monitoring

- Performance monitoring ensures
  - Analysis results remain valid with time
  - No unexpected (or unmodelled) adverse safety issue occurs
- Delaying capsule withdrawal for an extended period with the possibility of no future data represents a lack of performance monitoring

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Analysis Summary

- With the current state of knowledge, a generalized analysis suggests the overall risk of brittle fracture is low
- The uncertainty in these results is high and increases with time
  - Plant specific details not considered
- Under certain conditions, safety margins are impacted and are decreasing as uncertainty increases
- Delaying capsules at high fluence represents a lack of sufficient performance monitoring
- Issues are plants with fluences > $6x10^{19}$ n/cm^2

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Who is Impacted?

- Embrittlement Underprediction

Percentage of Fleet Surpassing Fluence Levels			Percentage of PWRs Surpassing Fluence Levels	
Year\Fluence	6×10^{19} n/cm^2	8×10^{19} n/cm^2	6×10^{19} n/cm^2	8×10^{19} n/cm^2
60 years	6%	0%	9%	0%
80 years	22%	10%	34%	15%

  - Plant specific details (e.g., limiting material, etc.) may contribute to which plants are impacted
  - More work is needed to determine which plants are impacted

- Lack of Surveillance Data
  - Any plant renewing license that chooses to delay last capsule

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Staff Goals

- Currently, regulations are sufficient for reasonable assurance of adequate protection against brittle fracture of vessel
- Staff wants to ensure continued reasonable assurance in long-term operation
  - Provide remedies for the identified issues with RPV surveillance requirements and embrittlement predictions, on a risk-informed, performance basis
- Do not impact those plants that are not adversely affected by the issues
  - Plant-specific surveillance data that covers end of license fluence level
  - Projected fluence at end of license < ~3×10^{19} n/cm^2

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Options Being Considered to Meet Goal

- Plant-specific action
- Focused regulatory action
- Generic communication
- No action

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Summary

- High confidence that currently operating plants remain safe, and recent licensing actions remain valid
- Issue will eventually (after about 10 years for PTS and 23 years for P-T limits) impact the staff confidence in the integrity of the reactor pressure vessel in long-term operation, i.e., both safety margins and performance monitoring may be impacted
- Further work is needed to determine which plants are impacted by this issue
- Proactively ensure continued reasonable assurance though a risk-informed, performance-based solution
  - Staff is considering options – desires focused solution to only those conditions adversely impacted by this issue

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Thank You

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RPV Embrittlement Monitoring and Prediction in Long-Term Operation

October 2021 EPRI MRP Technical Brief

Elliot J. Long
Principal Technical Leader

NRC Public meeting on RPV Integrity
October 18, 2021

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Presentation Outline*

- **Future Sources of High Fluence Capsule Data**
  - PWR Coordinated Reactor Vessel Surveillance Program (CRVSP)
    - MRP-326, Revision 1
  - PWR Supplemental Surveillance Program (PSSP)
    - MRP-412
- **Review of Prior EPRI MRP Conclusions from the November 2019 ACRS Meeting**
  - Potential to impact plant Pressure-Temperature (P-T) limit curves

*Note that BWR Units have an NRC approved Integrated Surveillance Program (ISP) for up to 60 years for the U.S. BWR Fleet (BWRVIP-86, Rev. 1-A). The implementation plan for Subsequent License Renewal (SLR) has also been accepted by NRC, with the highest BWR Unit projected *not* to exceed the threshold for fluence of 6×10^{19} n/cm^2 (E>1.0 MeV) as described in this report (BWRVIP-321-A). See Slide 12 for more details.

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Update to the CRVSP, MRP-326, Revision 1

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Coordinated PWR Reactor Vessel Surveillance Program (CRVSP)

- Materials Issue Being Addressed:
  - Optimize the U.S. PWR surveillance capsule withdrawal schedules to increase the amount of high-fluence ($f > 3.0 \times 10^{19}$ n/cm^2) surveillance data which can be used to inform development of embrittlement trend correlations (ETCs) applicable for RPV operation to high fluence (60+ years).
- Objectives of the Project
  - Revision 0 (2011): Review the reactor vessel surveillance programs (RVSPs) of the operating U.S. PWR fleet and recommend changes to selected RVSP withdrawal schedules in order to increase the amount of high fluence surveillance data by 2025.
  - Revision 1 (2021): Review of how we did, what has occurred, what's left to do, and when it is most likely to happen across the US fleet
- Updates to the evaluation include
  - Evaluated capsules withdrawn since 2011
  - Future capsule pull schedules
  - Capsule fluence values
  - Analysis of closed (or to be closed) plants

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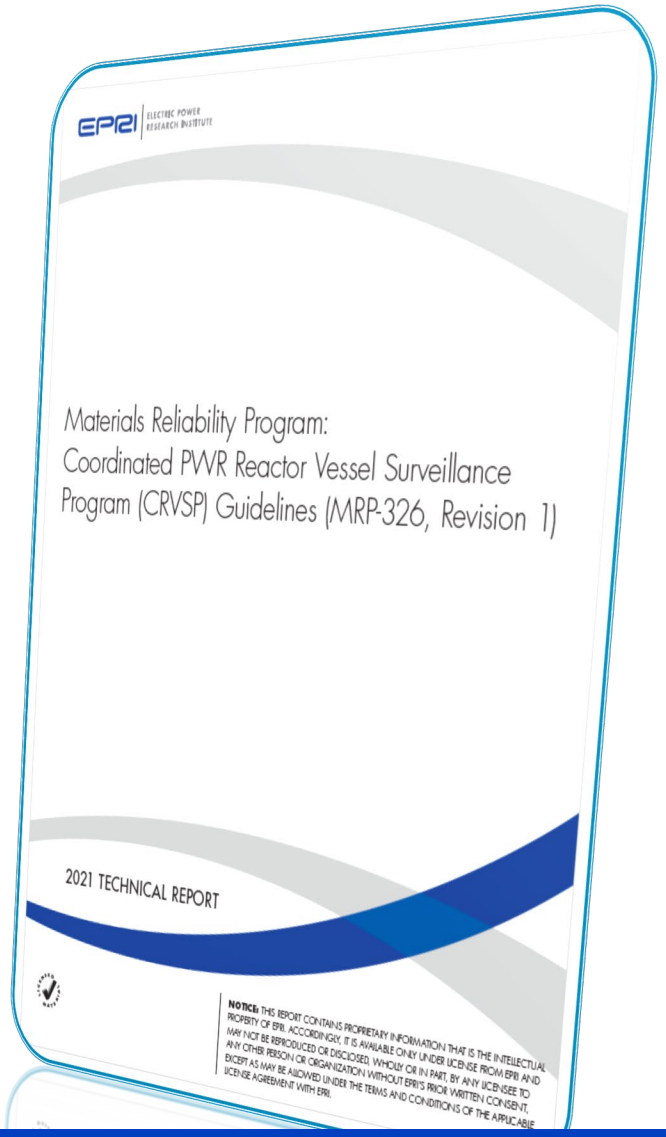
Update to the CRVSP, MRP-326, Revision 1

- Current high fluence capsule withdrawal results
  - 16 out of 30 CRVSP Capsules are tested or planned to be tested
  - There are 14 remaining CRVSP Capsules
    - Half of these are not planned to be tested (i.e., due to plant shutdown) or will be delayed beyond 2025
- Summary of available high fluence data
  - 48 U.S. capsules have been tested at $f > 3.0 \times 10^{19}$ n/cm^2
    - 4 of these are $f > 8.0 \times 10^{19}$ n/cm^2
  - By 2025, the remaining 7 planned CRVSP capsules will be tested at $f > 3.0 \times 10^{19}$ n/cm^2
    - 2 of these are predicted to be $f > 8.0 \times 10^{19}$ n/cm^2
- PSSP withdrawal schedule update
  - Farley 1 Capsule P to be withdrawn in Spring 2027
  - Shearon Harris Capsule P in Fall 2028



There are no NEI 03-08 requirements of any kind associated with this report revision

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PWR Supplemental Surveillance Program (PSSP)

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PWR Supplemental Surveillance Program (PSSP)

- Materials Issue Being Addressed:
  - Additional high-fluence ($f > 5.0 \times 10^{19}$ n/cm^2) surveillance data is needed to inform development of embrittlement trend correlations (ETCs) applicable for RPV operation to high fluence (60+ years).
- Objectives of the Project:
  - Fill projected gaps in the tested surveillance capsule database
  - Inform future ETCs using actual RPV surveillance materials from commercial PWRs (not test reactor data)
- End game: Irradiate two supplemental surveillance capsules for ~10 total years before withdrawal, testing, evaluation and publication of capsule test reports
  - These two surveillance capsules have 288 Charpy Specimens from 27 unique plates, forgings and welds
  - The data generated from these capsules will ultimately yield 24 new transition temperature shift results and 3 additional upper shelf energy results
    - Fluences levels of the to be evaluated specimens will range from ~4.5E+19 up to ~1.2E+20 (n/cm^2)

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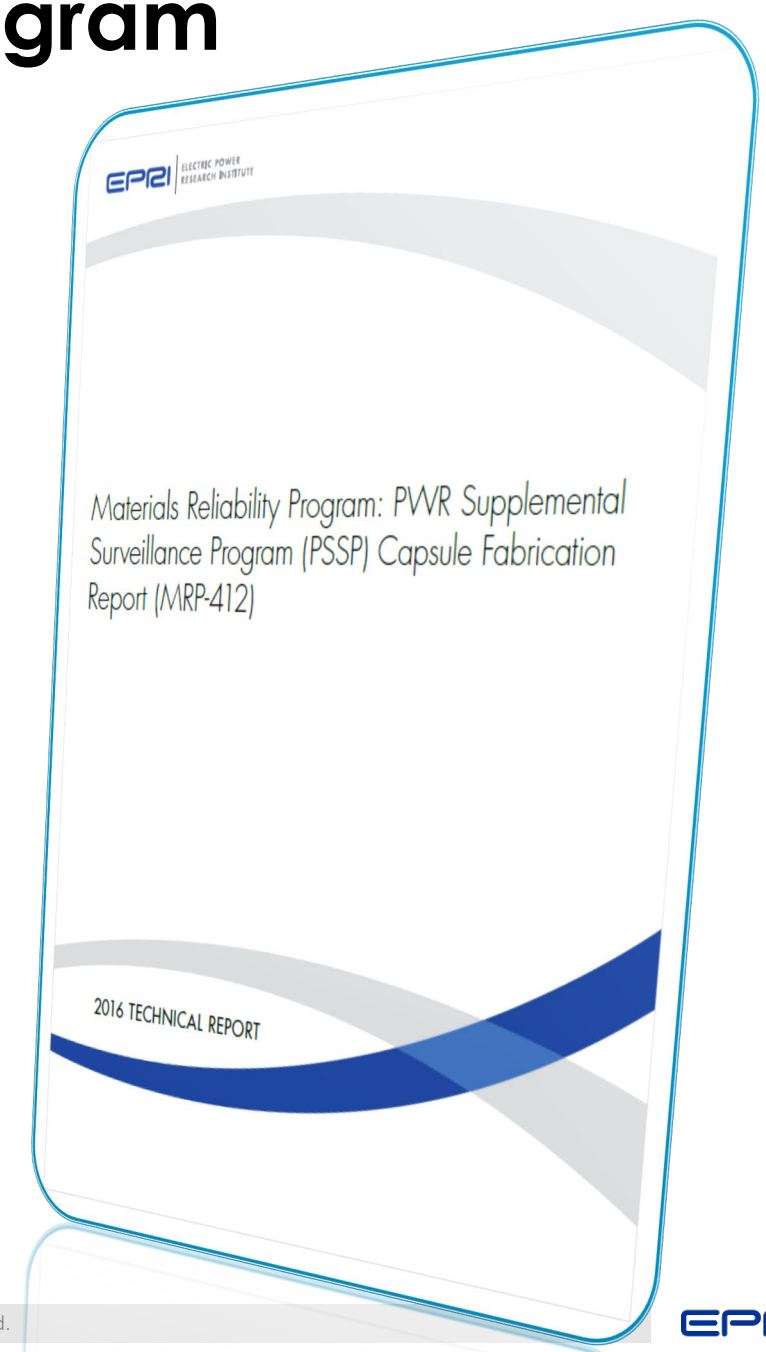
PWR Supplemental Surveillance Program

- Project History
  - Program designed and fabricated 2 supplemental surveillance capsules containing previously-irradiated, reconstituted PWR materials
  - EPRI MRP sponsored the fabrication of these 2 surveillance capsules:
    - ALA-P; 14 materials (Host: Farley 1), inserted October 2016
    - CQL-P; 13 materials (Host: Shearon Harris), inserted April 2018
  - MRP-412 (PSSP Capsule Fabrication report) was published in 2016



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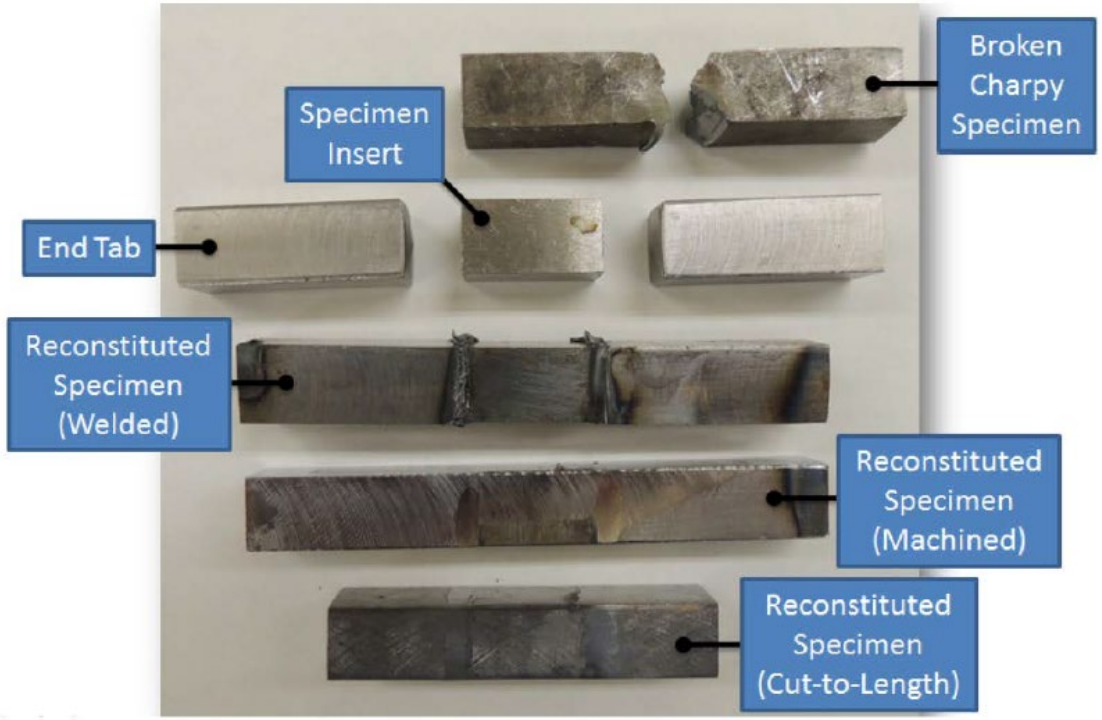
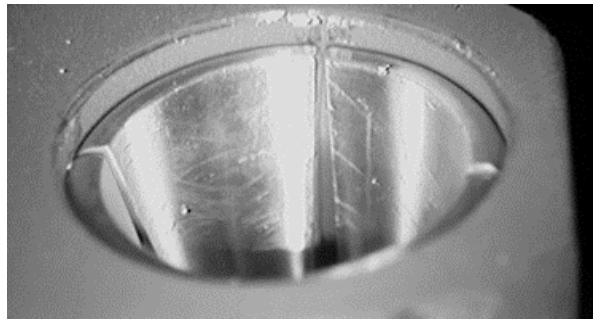
PWR Supplemental Surveillance Program

- Current Project Status and Timeline
  - Farley 1 Capsule P to be withdrawn in Spring 2027; Shearon Harris in Fall 2028 per MRP-326,R1
  - Testing of surveillance capsules and data evaluation in 2028-2030
  - Anticipated Project Deliverable Date:
    - Capsule report within ~18 months of each capsules' withdrawal date (2 reports total)
  - Data evaluation and impact on future ETCs in 2030-2032





PSSP Capsule seated in its holder

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Prior EPRI Conclusions on the Potential Revision of RG1.99R2

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Conclusions from the EPRI Presentation to the ACRS in November 2019

- EPRI MRP previously presented on the potential revision of RG1.99R2 to the ACRS in Nov. 2019
- The conclusions from that meeting (shown at right) have not changed
- **<u>If</u>** a future revision to RG.199R2 is implemented, ASTM E900-15 remains the preferred ETC model (today)
- It is understood that for fluence values below 6E+19 n/cm^2, RG1.99R2 remains adequate for predicting RPV embrittlement
- The next slide details when certain plant designs will see that fluence level at 1/4T

Conclusions and Recommendations

- Changing the USE prediction model in RG1.99 would result in negligible safety benefit but would cause a significant reanalysis burden on the fleet
- ASTM E900-15 is the preferred alternative ΔT_{41J} prediction formula
- Because RG1.99 is used for embrittlement predictions performed to show compliance with 10CFR50, Appendix G, the appropriate metric for assessing the need for plants to adopt a new ΔT_{41J} prediction model is the RPV 1/4T fluence, since that is the fluence upon which operating limits are based per ASME XI Appendix G
  - BWRs do not reach the threshold of concern through 80 years of operation and can be exempted from the burden of adopting a new ΔT_{41J} shift prediction model
  - PWR adoption of a new shift prediction model would appropriately be based on a 1/4T fluence metric
- Because embrittlement prediction models have significant impact on the RPV operating envelop, it will be helpful to plants considering SLR for the regulator to identify the shift model that will be adopted in RG1.99R3, and guidance for consideration of surveillance data

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What *surface* fluence = 6E+19 @ 1/4T and 3/4T?

- The chart at right was developed using the current fluence attenuation formula from RG1.99R2*
- It is understood that the 3-Loop Westinghouse design has the highest surface fluence at end-of-life
- SLR plants' most limiting surface fluence values are also summarized herein
- Only Plant 'A' will hit a 1/4T fluence of 6E+19 n/cm^2 for 80-years
  - This is currently predicted to occur well into the SLR operating period

Design	RPV Maker	Vessel T (in)	Surface Fluence Needed to Reach 6E+19 @	
			1/4T (E+19)	3/4T (E+19)
WEC 2-Loop	B&W/CE	6.5	8.86	19.3
WEC 3-Loop/Smaller CE	CE	7.875	9.62	24.8
B&W NSSS	B&W	8.44	9.96	27.4
WEC 4-Loop	RDM	8.45	9.96	27.5
WEC 4-Loop	B&W	8.5	9.99	27.7
WEC 4-Loop/Larger CE	CE	8.625	10.1	28.3
CE - Special	CE	8.79	10.2	29.2
CE - Sys80	CE	11.2	11.7	45

Plant	Design	EFPY	Surface Fluence (E+19)	Potentially Impacted?
A	WEC 3-Loop	72	10.8	at ~65 EFPY
B	WEC 3-Loop	68	7.26	No
C	Smaller CE	72	6.56	No
D	WEC 3-Loop	72	7.34	No
E	WEC 2-Loop	72	7.80	No
F	B&W	72	2.02	No

***BWR plants are not shown as they will *never* reach these fluence levels in any reasonable operational time-frame [BWR SLR Plant 70 EFPY surface fluence < 5E+18 n/cm^2]**

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