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UNITED STATES OF AMERICA

NUCLEAR REGULATORY COMMISSION

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ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

(ACRS)

+ + + + +

JOINT SUBCOMMITTEES ON METALLURGY & REACTOR FUELS

AND STRUCTURAL & SEISMIC ANALYSIS

+ + + + +

TUESDAY

JULY 20, 2021

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The Subcommittees met via Teleconference, at 2:00 p.m. EDT, Peter Riccardella, Chair, presiding.

COMMITTEE MEMBERS:

PETER RICCARDELLA, Chair

RONALD G. BALLINGER, Member

VICKI M. BIER, Member

DENNIS BLEY, Member

CHARLES H. BROWN, JR. Member

VESNA B. DIMITRIJEVIC, Member

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WALTER L. KIRCHNER, Member

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DAVID A. PETTI, Member

JOY L. REMPE, Member

MATTHEW W. SUNSERI, Member

ACRS CONSULTANT:

STEPHEN SCHULTZ

DESIGNATED FEDERAL OFFICIAL:

CHRISTOPHER BROWN

ALSO PRESENT:

RAJ IYENGAR, RES/DE/REB

DAVID RUDLAND, NRR/DNRL

PATRICK RAYNAUD, RES/DE/REB

DAVID DIJAMCO, NRR/DNRL/NVIB

SCOTT MOORE, ACRS

THOMAS DASHIELL, ACRS/PMDA

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P R O C E E D I N G S

(2:00 p.m.)

CHAIR RICCARDELLA: It is now 2 p.m. Eastern Time and the meeting will come to order.

This is a meeting of the Metallurgy and Reactor Fuels and Structural and Seismic Analysis Subcommittees of the Advisory Committee on Reactor Safeguards. I'm Pete Riccardella, chairman of today's session.

ACRS members in attendance are Joy Rempe, Dennis Bley, Jose March-Leuba, David Petti, Matthew Sunseri, Ron Ballinger, Vesna Dimitrijevic, Walt Kirchner, Vicki Bier, Gregory Halnon. Our consultant Steve Schultz is also on the phone.

Christopher Brown of the ACRS is the designated federal official for the meeting.

I did not call Charles Brown. Charles, are you here?

(No response.)

CHAIR RICCARDELLA: Evidently not.

During today's meeting the subcommittee will discuss NRC's perspectives on probabilistic fracture mechanics analysis and on a graded approach for PFM. The joint subcommittee will hear presentations by and hold discussions with the NRC

staff from NRR and Research and other interested persons regarding this matter.

The rules for participation in all ACRS meetings, including today's, were announced in the Federal Register on June 13th, 2019. The ACRS section of the USNRC public website provides a charter, bylaws, agenda, letter reports, and old transcripts of all full and subcommittee meetings, including slides presented there.

The meeting notice and agenda for this meeting were posted there. We have received no written statements or requests to make an oral statement from the public.

This subcommittee will gather information, analyze relevant issues and facts, and formulate proposed positions and actions as appropriate for deliberation by the full committee. Lists for participation in today's meeting have been announced as part of the notice of this meeting previously published in the Federal Register.

A transcript of the meeting is being kept and will be made available as stated in the Federal Register notice.

Due to the COVID pandemic, today's meeting is being held over Microsoft Teams for ACRS members

and NRC staff. There is also a telephone bridge line allowing participation of the public over the phone. When addressing the subcommittee, the participants should first identify themselves and speak with sufficient clarify and volume so that they may readily be heard.

When not speaking, we request that participants mute your computer or phone.

We will now proceed with the meeting. And I'd like to stop by calling on Raj Iyengar for opening remarks.

Raj, are you there?

MR. IYENGAR: Yes, I am, thank you. Can you hear me?

CHAIR RICCARDELLA: Yes, we can.

MR. IYENGAR: Okay. I really appreciate this opportunity to appear in front of you members and to let our staff provide a briefing on this very significant topic on probabilistic fracture mechanics and the application results of those for reactor component safety.

As you may all know, this topic people have been working on probabilistic fraction mechanics for several decades. There have been different kinds of tools available. But until recently, there has not

been a concerted effort to develop a strong basis for application of these tools in order to provide reasonable assurance of adequate protection for components.

I think the NRC staff from Research as well as from NRR joined forces to develop a PFM, probabilistic fraction mechanics guidance in early 2016. And that's been published by technical letter report on this topic in 2018. Since then we've gotten quite bit, a lot of feedback on that.

And as the subject of this endeavor, the staff had proposed to develop a probabilistic fraction mechanics regulatory guide for to better understand and provide better guidance for licensees when they use probabilistic fraction mechanics tools for license amendments, or relief requests, licensing actions.

So that I think we've done a pretty great collaboration between research and NRR, with the help of Sandia National Labs, to develop the current new technical basis document, as well as the reg guide that you'll hear being talked about.

And I did want to mention, throughout the process we've had several public interactions with our stakeholders. We've been keeping with our good principles of regulation, in particular with EPRI who

provided very constructive input and developed a white paper on a graded approach to PFM. Which you will see that some of the aspects were reflected in the current document.

The draft documents associated with the NUREG technical basis, NUREG and the draft reg guide are still under internal review, so we will not be able to make it public at this time. However, the staff was very open to providing some kind of considerations that we have in developing this regulatory guide.

Today we'll hear from our regulator NRR about why they believe NRC needs to be of some guidance and why at this time. We are going to save that thunder for Dave Rudland.

Then Research will, staff will present our latest perspectives on PFM analysis and on a graded approach for PFM. Research and NRR are presenting their thoughts of PFM guidance in regulatory application. As you know, that is the most important aspect of what we do.

We look forward to having a productive meeting and, hopefully, answering all your insightful questions to the best of our ability.

I actually want to commend our staff from

NRR as well as Research who really worked very hard in the last several years to make this happen.

With that, I'd like to turn this over to Dave Rudland to provide his thoughts on PFM.

Thank you.

MR. RUDLAND: Thanks, Raj. So, as Raj mentioned, my name is Dave Rudland and I am a senior technical advisor for materials in the Division of New and Renewed Licenses in NRR. And I'm going to provide today a couple of slides on the need for probabilistic fraction mechanics guidance.

And as Raj pointed out, this has been a long effort, a couple of year effort in developing this guidance and understanding what we think we need in our discussions with industry.

As the NRC has been transitioning from deterministic methodology to more risk-informed methodology, the staff had developed an integrated decision making process that includes the results from probabilistic fraction mechanics in terms of the change in risk to core damage frequency or large early release frequency. And coupling that with investigations in how it impacts safety margins, defense in depth, whether it meets the current regulations, and how performance monitoring is done

creates a integrated risk-informed solution. And it's important to point out that this is risk-informed and not risk-based.

In recent times, though, the agency has been trying to expand the use of risk beyond PRA and calculation of CDF by using more risk insights, and especially for passive component integrity where when you'd be talking about components that may not be actually modeled within the PRA. So, that's kind of what we're going to be focusing on today.

Through the course of this development in risk-informed space, the staff has developed applications, be it how to change license basis using risk-informed methodology or how to categorize SPCs in risk-informed space.

And with those, of course, they've also developed specific guidance, guidance that is directly related to the application in question. And also they've developed generic guidance.

As shown here, Regulatory Guide 1-200, which is one approved approach for determining if the technical adequacy of probabilistic fraction mechanics is sufficient to provide confidence in the result.

In addition to what I've shown here, there's other licensing actions that are being

considered, and guidance processing tools are still under development in those areas. And one of those areas if probabilistic fraction mechanics.

I think Raj alluded to it a bit, but for those that aren't familiar probabilistic fraction mechanics analyses are basically probabilistic analyses that leverage fraction mechanics and the uncertainties in their inputs and models in developing probabilities of failure. In PRA space, you know, you have initiating events, scenario, development, and consequence, probabilistic fraction mechanics can be used in determining initiating event frequencies.

But, typically, PFM is used more for requests for inspection relief, or determining LOCA frequencies in the calculation of leaks, or breaks, or other things. And it's those areas where we are, where we are lacking guidance.

If I can talk about the licensing reviews that I just mentioned and put them in more of a graphical form, you can see that on this, on this schematic. On the X factors it is kind of a reliance on licensees' PRA information, the risk information. And the Y axis is the acceptability of that PRA, those PRA results.

The processes that I talked about earlier

are here on the right-hand side where we have high reliance and high acceptability on those particular processes.

Over on the other end of the scale where we have relief requests for maybe relief from the SME code, we may not rely much on PRA information. We may use more qualitative risk arguments. And, therefore, the acceptability of any particular PRA is not as important to that review.

I'm going to be talking about stuff and we're going to be talking about stuff today that's kind of in the middle where we may be using risk outside the defined processes, or outside of formal risk-informed licensing basis processes, but may use probabilistic fraction mechanics. Those processes are still under development.

Recently, the staff has released LIC 206 which is integrated risk-informed decision making for licensing reviews where some guidance is from the staff on how they can try to use this outside of these normal processes. But in terms of PFM, there's currently no, no real guidance. And to make, to make decisions on requests that use this, we need really adequate and consistent information, and we need to make sure that we have confidence in the result.

Like Raj had mentioned also, PFM has been around for quite some time. And there have been submittals in the past, and successful submittals, that have used PFM. However, typically there's a very complex, lengthy review because these codes are very complex. There's a lot of different models on how uncertainties are being propagated that's very computer code-specific. The reviews can be very complex.

Many staff believe these codes are like black boxes where input's in and output's out without even knowing what's happening within the code. And that may be due to insufficient documentation, or insufficient vetting of the code and the input. And this all leads to very low confidence in the output.

And this becomes particularly an issue when we are, of course, using that as a basis for modifying or changing things like long (unintelligible) inspection programs.

Back when we first started this effort we had a public meeting with the industry to talk about PFM and kind of our thoughts and ideas and our position on what should kind of go into these analyses and what should be reported. And we presented this table which shows some of the past EPRI reports and

categories and which we think are important to discuss and to consider when using PFM in a regulatory submittal. And what we did was we kind of labeled what we thought -- whether we thought these things for these reports met the staff's position for acceptable PFM.

And as you can see, there's a lot of -- there's some yeses, some noes, a lot of partials. But what's consistent in here is that there was not much consistency across the reports, in a particular report or across many reports in terms of how the information was provided to the NRC.

There are a lot of hurdles still in PFM in moving forward. Now, the submittals that we've had with PFM are -- have been inconsistent, have been complex. The level of acceptability has been mixed also as we have considered PFM as a basis for a regulatory position.

This risk-informed decision making is still very much in process, in the process of being implemented at the agency, especially for the passive components that may not be modeled in traditional PRA. The PFM is just one part of this risk-informed decision making process, as I mentioned. And both the industry and the staff need to keep that in mind as we

are working through these kind of processes.

And we're still in the development, not just the PFM reg guide, but other processes in terms of how to use risk-informed for these types of components that are under development. But use of PFM for licensing is increasing rapidly. And especially recently we've been seeing more and more applications of using probabilistic fraction mechanics codes and unique codes in that fact to -- as a basis for trying to make a regulatory change.

And so, because of all this we really think that a PFM reg guide will help both the licensees as well as the staff to determine what is consistent and adequate information that needs to be supplied to the NRC when using this type of code for licensing applications.

So, that is all that I have. And with that, I will transfer the control over to Patrick Raynaud who will be giving some details about the draft guide.

CHAIR RICCARDELLA: Yes, thank you, David.

Members, are there any questions on David's presentation at this time? So let's then proceed.

MEMBER BLEY: Yeah. Pete, this is Dennis.

CHAIR RICCARDELLA: Hi, Dennis.

MEMBER BLEY: Early on your mentioned some of the problems with the uncertainty treatment and certain people not having a lot of confidence. Has that condition changed?

I know we have used this in some regulatory areas so far. Where do we stand right now on that side of things?

MR. RUDLAND: Well, I think the, you know, the applications in the past have been very inconsistent in how they have handled uncertainties and reported it to the staff. I think as the more and more it's being used, the better it is.

I think Raj pointed out that EPRI had published some thoughts on this in a white paper in terms of how to present uncertainties, how to present the results, what to present. And that's helped in the most recent applications. But I think, you know, to be consistent across the board, something like this kind of guidance is needed.

MEMBER BLEY: If we go back to the PTS work some years ago, --

MR. RUDLAND: Uh-huh.

MEMBER BLEY: -- this had been chased pretty hard at that time. Was it done more rigorously

there or is it just we've looked deeper into it since then?

MR. RUDLAND: Well, you know, I think especially with PTS it was a long process that took a lot of time to get to where we wanted to be. Right? So, it was not a, it was not a simple, short-term effort.

And through the multitude of iterations I think we got to the right place.

MEMBER BLEY: Okay. You're right, it took a long time.

MR. RUDLAND: Yeah. And there were a lot of good lessons learned that we've learned from that effort that set into the stuff we're going to see in this, in this draft guide.

MEMBER BLEY: Okay, thanks.

CHAIR RICCARDELLA: Thank you, David.

Patrick, are you ready to go?

MR. RAYNAUD: I am. Thank you.

I hope you can see my slides, for those of you who are on the Teams meeting. I think I got it right. Let me know if that's not the case.

CHAIR RICCARDELLA: Some of us aren't getting slides. So, I would appreciate it if you would just tell which slide you're on.

MR. RAYNAUD: Of course.

CHAIR RICCARDELLA: Thank you.

MR. RAYNAUD: So, right now I'm just on the cover slides. And I want to introduce myself.

I'm Patrick Raynaud. I'm a senior materials engineer in the Reactor Engineering Branch in the Division of Engineering and Research. And I've been aiding the project to develop the PFM guidance for the NRC side since late 2016 or somewhere about there.

And today is our first time speaking to the ACRS. And I'm going to present some of the research perspectives on PFM analyses and some detailed thoughts on a graded approach for PFM.

I'm on Slide 2. I just want to highlight the objectives today.

First, you know, we want to describe, as I said, our perspectives on the analytical steps that could be used to create high-performance PFM demonstrations for regulatory purposes, and to demonstrate that you have an adequate solution to a technical problem that would be relevant for a regulatory application.

And then we want to describe what a graded approach for PFM analysis and documentation could look

like when you consider a number of factors such as the safety significance of a particular problem that you were trying to solve, and the complexity of that problem, as well as of the tools that you're using to solve that problem.

Now, a few things that -- a few disclaimers for today is that, you know, the slides I'm showing today are all pre-decisional content that's not yet an official position of the NRC. And nothing presented here is completely final since they're still under internal review and could change. And so this content is not intended to be guidance, final guidance on what constitutes an acceptable approach for PFM submittals to the NRC. Hopefully, we'll get there soon.

So, my presentation has two parts today. I'm on Slide 3. First I'm going to present the analytical steps in a PFM demonstration. And then I'm going to focus on this graded approach that we have been discussing so far.

Slide No. 4.

I'll start with describing at a high level what we think are the necessary analytical steps in a probabilistic fraction mechanics demonstration. And really if you look at that in the chart that we have

here, we have three big parts.

We have a planning stage, an analysis stage, and a synthesis stage. And there are five steps in total.

So, the first part, planning, only has one step. And I'm going to go into each one of these five steps in the subsequent slides in more detail.

But the major step there is to translate your regulatory requirements into an analysis plan and decide what you need to do and how before you launch into it.

The second major part is to perform an analysis. And here we have three main steps.

First, you need to characterize the model input uncertainty. And that is essentially how you are going to represent your inputs that might have random values.

The second big step is to estimate your quantities of interest -- you'll see this acronym often, Q of I's, throughout my slides -- and the uncertainty that is associated with those quantities of interest.

And the last step, which you may or may not need, depending on your situation, is to conduct sensitivity studies to assess the credibility of your

modeling assumptions and to better understand how your problem changes depending on those assumptions.

The last part of the analysis would be to synthesize your results and to draw conclusions from your analysis.

And one thing that I really want to emphasize here is that we believe that this is a recursive process, you know, or an iterative process where, you know, you might have some thoughts, initial thoughts on an analysis and perform those analyses. And then based on your results you may often have to revisit some of your initial assumptions or initial modeling choices to refine your results and get a result that is more defensible, perhaps, for whatever you're trying to prove or demonstrate as part of that regulatory analysis.

So now I'm moving on to Slide 5. And I'm going to go into each one of these five steps in some more detail.

So, the first big step is, as I mentioned, to translate the regulatory requirements into an analysis plan. And here we have come up with four actions that you may have to perform.

First you need to look at your regulatory context and, you know, how your PFM analysis is going

to be used to support a decision on a regulatory action. And by that we mean how is the technical basis using PFM going to be input to the regulatory decision.

And, specifically, here what might be important is what criteria are going to be used to support a proposed regulatory action. There may be cases where the criteria are well-known. If it's a specific regulation that you're trying to demonstrate that you meet, or maybe the criteria are not so well-defined and then, you know, the criteria would need to be described and justified.

The second action here would be to define the quantity of interest and how it relates to what our model or PFM code can provide as output, and then to compare that also to the acceptance criteria. So, specifically we're looking at mapping what quantities are used to show that a regulatory requirement might be satisfied, how they're mapped onto specific outputs of our PFM code or model.

And we want to make sure that our model is able to predict the needed and relevant quantities.

The third action would be to -- and it's related to the third one -- to the second one, is to determine the suitability of the probabilistic

fraction mechanics code to the specific application. What we mean here is that you want to be sure you have a code that is able to model the relevant physics for the problem that you're trying to solve, in the appropriate ranges, and that it has all the necessary physics and numerical and computational features that are needed to solve your problem.

And the fourth and final action of this first big step is to identify the key elements of the problem that might impact your analysis choices. For example, if your model is very computationally extensive, what simplifications may you need to take in order to be able to solve your problem in a reasonable time or in a way that doesn't require, you know, a supercomputer.

So, now I'm on Slide 6.

And the second big step, which is the first step of the analysis portion of our grand scheme here, is to characterize the model input uncertainty.

So, first of all two actions here. The first action is to identify which model inputs are going to be characterized as uncertain or random. And then, also, if you are separating aleatory and epistemic uncertainty, how are you going to categorize the uncertainty for each one of these inputs?

And the second action here is to specify probability distributions for those uncertain or random inputs in order to be able to then represent them in a numerical way and propagate those uncertainties through your model.

And so, typically this is done by choosing probability distributions of which there are a great number, and setting their parameters, perhaps getting into data and so, and then to propagate that uncertainty to estimate your quantities of interest for your problem.

The third step is to actually estimate the quantity of interest and the associated uncertainty. Four main actions here.

The first one is to select the sampling scheme that you're going to use to propagate your uncertainty through your model. There are many choices there. The simplest, or the simplest in terms of numerical implementation might be simple random sampling using Monte Carlo methods. But there are many different ways to sample an input space.

And the goal here is, obviously, to get a good estimate of your quantity of interest and be able to characterize the uncertainty associated with that quantity of interest.

The second action is to assess the sampling uncertainty, which is also performing statistical conversions analysis. You want to assess that the quantity of interest that you've calculated by propagating uncertainties through your model is sufficiently converged to give a solution to your problem given the sampling scheme that you've chosen.

And you may, as part of that iterative process that I alluded to earlier, you may need to adjust that sampling scheme if initially you don't have a converged enough solution. That might be adding samples, looking at different random seeds, or completely changing your sampling strategies, maybe using more advanced sampling strategies if you're dealing with, for example, very low probability, if that's where you need to sample more in the tails of distributions to see certain things happen and have more reliable outputs.

The third action, which may or may not be needed depending on your case, is to conduct sensitivity analyses to determine the input uncertainty importance. Sensitivity analyses are analyses that correlate the uncertainty of inputs with the uncertainty of outputs and help you understand which inputs drive most of the uncertainty in your

outputs of interest. And so this is essentially akin to identifying the problem drivers.

This can also help you confirm that your model is behaving as expected. You may find that some input distributions may need to be refined to get better convergence on your final estimation of the quantities of interest that you need.

You may also be able to identify which assumptions in your modeling assumptions may be candidates for sensitivity studies, so you're making a distinction between sensitivity analyses, which is understanding how uncertainty propagations are modeled, and sensitivity studies which are more like "what if" analyses if you change your model or if you change a distribution.

And also you can, by identifying the problem drivers, you can identify which are the best candidates for more targeted, more advanced sampling methods like importance sampling, for example, for those that drive the problem.

And the final action in this Step 3 is to conduct output uncertainty analysis. And by the way, I think there was a typo in one of my slides, so that title might be different than what you have from the slides that we sent earlier.

So, the title here is conduct output uncertainty analysis. And the goal is to provide a final estimate and the associated uncertainty of the quantities of interest. And, as always, it's very helpful to visualize results when possible from a reader perspective.

The fourth step, which is the last step of the analysis portion in our scheme, is to perform sensitivity studies, meaning "what if" analyses to assess the credibility of some of the modeling assumptions that you may have made.

And there are two actions here. First of all, to choose which sensitivity studies are going to be performed. And that means identifying important assumptions that need further scrutiny and need to be better understood, and to understand what happens if we change these importance assumptions.

And the second action is to actually conduct those sensitivity studies and summarize and present the results.

There are many ways to perform sensitivity studies. But in any case, there are common elements to pretty much any method you use. You need a reference case, maybe your baseline case. And then you're going to have perturbations from there, maybe

change a model, change some input distributions. And then you're going to compare the output of these new realizations of your model, where you've changed something, to the reference case and understand the differences, see if there are differences or not, and whether those changes are significant.

And that can help build confidence in showing that perhaps the overall model is behaving as expected, or to cover the various options that you may need to cover to represent operational occurrences and such.

The final step is to draw conclusions from our analyses.

MEMBER KIRCHNER: Patrick, this is Walt Kirchner.

MR. RAYNAUD: Yes.

MEMBER KIRCHNER: Before you go on could you just, you know, you had sensitivity analyses previously when we were looking at estimating, you know, your quantity of interest and such. What are the difference, what's the difference in the sensitivity analyses done before this step? I guess it was in Step 3.

MR. RAYNAUD: Uh-huh.

MEMBER KIRCHNER: Just is it at a micro-

level so to speak? Or in Step 3 you also were doing sensitivity analyses. So, this looks like a more macro look at functions.

CHAIR RICCARDELLA: You may mean the difference between sensitivity analyses and sensitivity studies. Maybe you could clarify.

MR. RAYNAUD: Correct. Correct. And I was going to reinforce that. Perhaps I didn't make the point enough.

There is a difference between sensitivity analysis and sensitivity study. And I know for me it took me a long time to realize that there was a difference. But sensitivity analysis really is about understanding what input uncertainty has a large influence on the output uncertainty.

So, essentially it's studying the relationship between input uncertainty and output uncertainty.

Whereas sensitivity studies is, you know, given that relationship, if I change something how does the output change?

So, again, it's studying the relationship between uncertainties versus doing "what if" analyses, you know, what if I change a model, what if I change a distribution, what if I change values for this

parameter or that one.

So, they're two different things in our scheme here. Two different types of analyses.

MEMBER KIRCHNER: Okay, thank you. Yes, in my simplistic world the first one is more a micro at separate model levels, or material selections, or whatever you're looking at. And this last step to me is more at a macro level: you know, how does it impact the overall results.

But I thank you for the clarification.

MR. RAYNAUD: You're welcome.

And they're definitely intimately related. But they are, down in the detail of how you perform these, they are different and they provide different insights.

Okay, so unless you have more questions, I'll continue.

So, we were on Slide No. 9 and our fifth step of our scheme to perform PFM analyses.

And this last step is to draw conclusions from analysis results. And, you know, two actions here.

First, we're going to interpret the results we have by synthesizing the information that was gathered in the previous steps. And then we're

going to try to draw conclusion. We may be able to draw final conclusions by comparing to our acceptance criteria, or we may realize that we need additional analyses or to refine our analyses to create a more complete evidence package to be able to draw our conclusions.

And the second actions, which is very much related to what I just said, is to iterate on the analysis process and to refine the model results. You know, in many cases you will need to provide more than one final analysis because PFM is very complex and there are so many moving parts that, you know, this iterative process and providing a more complete picture of how the model behaves and how the results change for different assumptions can be very important in PFM space.

So, I'll move on now to the second part of my presentation which has to do with thoughts on our graded approach. That's Slide No. 10.

And, first, before I dive into any details I want to highlight some overarching, higher level concepts.

And the first thing I want to really emphasize, and Dave before me alluded to that, is that PFM is generally complex. You know, if you could

solve problems deterministically, that is, obviously, much simpler and perhaps the first thing that everyone tries, and that we have been doing for quite some time.

So, when you're dealing with something as complex or potentially as complex as probabilistic fraction mechanics, the depth and the breadth of the analyses that you're going to perform, and perhaps how much you're going to have to document those things, can depend on a number of factors, which is why it does make sense to take a graded approach.

And, you know, I think this was discussed in previous public meetings as far as maybe around 2018 or so, in particular with EPRI who brought some of these concepts up. And so I want to credit our stakeholder feedback for putting us onto this path.

So, the graded approach not only applies to how you perform your PFM analyses, but of course how you document them to present an evidence package in a regulatory context that is something that is going to be reviewed and scrutinized by the NRC.

The general principles that sort of guided our thoughts here are that if you have higher safety significant of the application at hand, higher complexity, or higher degree of novelty associated

with, you know, the regulatory request for application or the codes and tools that are used to perform the analyses, then that probably is going to translate into having to perform more analyses, have a more complete documentation package. And, ultimately, it will mean a higher burden to create a more defensible and rigorous evidence package.

And so what we've done to try to develop a graded approach or some thoughts on a graded approach is come up with all the main topics that we think need to be addressed in a probabilistic fraction mechanics analysis and submittal context. And we came up with eight of those, which I'll list in a second.

And then for each, we came up with some categorization schemes and recommendations or thoughts on what might be needed for analysis or documentation.

So, the eight broad topics that we came up with are:

First, software QA and V&V; then models; then inputs; then uncertainty propagation; then convergence; then sensitivity analyses; then quantity of interest uncertainty characterization, and; finally, sensitivity studies.

So, I'm going to go into some detail for each one of these. I have some pretty detailed tables

so that once you have all the slides, you have all the information. But I may not cover everything in detail because I think it would just be a lot of reading off and talking. So, I'll try to highlight some of the higher level distinctions we made.

CHAIR RICCARDELLA: Just a general comment for my colleagues from someone who's been involved in a lot of probabilistic fraction mechanics analyses. And one of the things that's unique, I think, about fraction mechanics that makes it so amenable to this technique is we generally see much more scatter, much more input scatter in the material properties in fraction mechanics than we do in other strength of materials type applications.

And I think that, you know, growth rates, for example, you could see orders, an order of magnitude difference, you know, in essentially the same property from different samples that are tested. And maybe not quite an order of magnitude, but on the fracture toughness you see much more scatter in that property than you would see in, for example, the tensile test, yield strength or tensile strength.

So that's one of the things, I think, that has led to probabilistic fraction mechanics being used so much.

MR. RAYNAUD: Thank you for that.

So, I'm going to go to my Slide 11. And I'm going to go through each one of these eight topics and present our current thoughts which are, again, decisional not final, can still change, but our current thoughts on our categorization and our graded approach for these different topics.

Start with on Slide No. 11 our thoughts on a graded approach for software quality assurance and verification and validation.

First of all, let me just state that in general safety demonstrations for the NRC usually require that a QA program be in place. So, that's sort of a prerequisite thought. And we also believe that because of the complexity of probabilistic fraction mechanics and all the intricacies of this potential graded approach, if that's where we end up, presubmittal meetings and discussions between applicants and the NRC would probably be very useful to make sure everybody's sort of on the same page as to, you know, where we fall within this, you know, rather complex graded approach.

So, when it comes to quality assurance and V&V our categories are labeled QV-1, which stands for QA and V&V-1, through QV-3. And, essentially, our

criteria here to determine which category you are in are still with how familiar we are with the code. And when I say "we," I mean the NRC in this case.

So, you know, the base case is if you have an NRC-approved code that's exercised within its validated range, previously approved, et cetera, then, you know, the path in terms of documentation of the code might be pretty simple and pretty basic. Just show that your -- that the code works for the application basically.

And then as you move away from that, for example if you use the code outside of its previously validated and accepted range, then you may have to provide additional evidence that, you know, the code is still applicable for what you are doing, and so on.

If you then modify a previously NRC-approved code, then you know there would be probably some questions and some documentation that would be helpful about what's changed and what kind of V&V and QA did you perform on those changes, and what documentation is available for that.

The second category for QA and V&V is QV-2, would be for commercial off-the-shelf software designed specifically for the purpose of the application. I don't think there are many such PFM

codes that are specifically, you know, off-the-shelf available for purchase. I can't think of any, but there may be some.

And the final category, QV-3, is if you have a completely new and custom code. And then, obviously, you know, much more documentation and description of the QA and V&V would probably be needed to instill confidence and show that the code behaves as expected and so on.

So, the next big topic that we have is models. And for this we have categories that we labeled M-1 through M-5. And I really want to emphasize that it's possible that in a large PFM software tool different models could belong to different categories. Because we sort of tied these categories to the QA and V&V categories that I just discussed previously.

So, for example, the easiest category, M-1, would be if you used a model from an approved NRC code within its validated range, then, you know, presumably we're familiar with it, we've reviewed it, we've accepted. So, the path is pretty easy to show that, to give us confidence that this works.

Conversely, if you start using that same model outside of its validated range, then we'd want

to perhaps understand, you know, a demonstration of why these models are still applicable in this new range of application, and so on.

If you take a model from an NRC code but you change it then, obviously, more description of the changes would be needed.

If you take a well-established model that, but that's not from an NRC code, maybe it's a published model or something that others have used extensively in other codes, or maybe something from the ASME code, something that's widely accepted but it hasn't been previously put into an approved software, then, you know, obviously we'd probably want to understand exactly how that was done and see some QA and V&V trace of how that -- what data was used and how well the model predicts and such. So, obviously, the documentation starts to increase.

And, of course, if it's a first-of-a-kind model, which is our final category, M-5, that, you know, brand new, never published, just something completely new for a new phenomenon that has occurred then, obviously, really detailed documentation and perhaps sensitivity studies and analyses to show how the model behaves, and such, may be needed to instill the right level of confidence.

So, again, quite a wide range. And you can see this progression from what we're most familiar with to something completely novel with, you know, an increased emphasis on more documentation and more analyses and data analysis to show that the model is behaving correctly and that we can have confidence in that software.

Topic inputs in this one is it's a little bit more complicated. So, I'm on Slide 13. And here we're looking to determine our categories we thought about what types of inputs we might have. And some inputs in a code might be deterministic, meaning a single value was provided. And others might be random inputs or uncertainty inputs.

So, we made that distinction in our categories when we numbered them I-1, for input one, through I-4, for input four. But then we have a D for deterministic and an R for random after those. And depending on whether you have a deterministic or a random input, obviously, you know, the type of documentation you may need to provide may be different because those models are inherently different -- or those inputs are inherently different in how they are characterized.

And then we focused on how important is

this input with regards to the output that we're interested in? And then how well do we know the characteristics of that input?

So, in our I-1 category, you know, it's something that you know very well and, on top of that, has low importance with regards to the output. And in that case, you know, you may need very little documentation. Just list your values and that's it, or your distributions.

But as you increase the importance that that input has on the output, and to know that by the way, that's where sensitivity analysis may come into play. And so, the more important the input is and the less knowledge about that input you have, then the more uncertainty you have.

So, if you have a lot of uncertainty on something that's really important with regards to your quantities of interest and your output, obviously, you know, more scrutiny would be placed on such an input value. And so more and more documentation and analyses to show that the input representation covers, you know, all the possibility -- well, "all" is a big word -- but, you know, the relevant possibilities would definitely be of interest in that case.

And, yes, one other important thing that

I want to say here is that every input you have may fall in a different category, much like every model you have in your overall code might fall in a different category. So, there's a real detailed work of categorization here that has to happen so that you make sure that you're doing, you know, what you should do but not too much or too little. And so it really takes some care. And that's why I think, you know, a lot of discussion, interactions with the NRC perhaps would be helpful.

The next big topic is uncertainty propagation. I'm on Slide 14.

And here, you know, we alluded to this iterative process in your PFM analysis overall where you might have to run several analyses within the scope of your entire demonstration. Well, here, for instance, your propagation may be different analyses that you're going to run using different sampling schemes, different features of how you model the uncertainty and propagate it, might mean that different analyses in your overall package and demonstration might fall into different categories.

So, here we have categories UP, sensor uncertainty propagation 1 through 2-Bravo. And, you know, here we sort of left the QA and V&V aspects

aside and we focused more about on what the specifics of that analysis might be, and what you might have to document in those cases.

So, if you just run a very straightforward Monte Carlo analysis, you know, obviously it would be relevant to describe what methods specifically you used for uncertainty propagation. You know, was it simple random sampling? Did you use Latin hypercube sampling? You know, you might want to describe your sample sizes, your random seeds, what type of pseudo-random number generator you used, and so on. If you separated aleatory and epistemic uncertainties, how did you do that? If you used importance sampling, how did you do that, and what regions of the input space and why?

But then, you know, in some cases if your model is very computationally extensive, you may only run a handful of realizations and then fit a model through that output, essentially create a surrogate model. Some people believe this is machine learning. And in that case, you know, you'd be bumped into the next category because now you're using a more advanced feature, something a little bit more complex that adds maybe some uncertainty to the overall methodology.

And so, you know, we'd want to hear about

that surrogate model and how you implemented it, and what are the assumptions, approximations, and how did you validate it?

If you use a surrogate model for sensitivity analyses specifically, you know, once again we would want to hear about that because you could use a surrogate model for the overall uncertainty propagation, or maybe only, for instance, to the analyses or sensitivity studies. So, it depends on what you used the surrogate model for, and we'd be looking for descriptions of what was done specifically.

A broad topic -- I'm on Slide 15 -- is convergence. And, first, let me say that here I'm really talking about statistical and probabilistic convergence.

And so, you know, we assume that temporal and spatial conversions, if you have finite element model, for example, as part of your fraction mechanics calculation, that that part of the convergence, the discretization convergence, pretty much has to be achieved for you to have valid results.

So that's, that's sort of a prerequisite, if you want to think of it that way. Otherwise, your results really can't be valid. But once you have

valid discretization convergence, and good enough, then you want to looks at statistical convergence. And here is really what we focused on when we looked at our graded approach.

And once again, much like for uncertainty propagation, you know, you could fall into different categories for each one of the analyses you do as part of your overall evidence package.

And here the criteria we used to come up with our categories focused on how close you might be to an acceptance criterion so, you know, how much margin you have essentially, and how simple your analysis is over all.

So that category SC, which stands for statistical convergence, SC-1, which is the lowest category would mean, you know, you meet your acceptance criteria with plenty of margin, and you haven't done anything fancy: no importance sampling, no surrogate models. In that case, you know, what you've done is relatively simple and there are some pretty simple methods, perhaps, to show that you've achieved statistical convergence.

Or, you know, if you really have a ton of margin, maybe you don't even really need to focus too much on statistical convergence at all.

But then as you get closer to your acceptance criteria, or if you use some more advanced methods, like importance sampling or surrogate models, or if you separate aleatory and epistemic uncertainty, then, you know, we definitely want to hear more about how you assessed your statistical convergence. There are many ways to do this.

You know, if you're still relatively far from your acceptance criteria that your analyses are using more advanced methods, you could demonstrate statistical convergence just using one method of your choice. There are many to choose from.

But as you get closer to your acceptance criteria, it would be a good idea to use more than one method to assess your statistical convergence.

So, that's kind of the gist of how we came up with our categories here in our graded approach.

The next big topic is sensitivity analyses. So, again, this is understanding the relationship between the uncertainty and the inputs, and the uncertainty and the outputs. And here for sensitivity analysis we have six categories labeled SA-1 through SA-6.

And these categories are very much tied to which QA and V&V category your software falls in from

the very first category I discussed. So, you know, if you're in the category of an approved code with, you know, within the previously validated ranges, presumably we know that code well and you may not even need sensitivity analysis in some cases.

However, as you start getting further away from that, you know, if you have a code that's a modified previously approved code, or a first-of-a-kind code, and also as you improve the number of independence input variables that go into your software, that means you're essentially increasing the complexity, as well as getting further away from what we previously approved and what we know well.

So then, you know, we'd want to hear a lot more about how you did your sensitivity analysis. Was it local, global? What were the quantities of interest that you looked at? You know, what sampling scheme were your sensitivity analyses done for? And what were the results, you know, what were the most important inputs that you identified and how much of the variance could be explained by those, and so on.

If you separated aleatory and epistemic, obviously you would, you know, maybe want to study the sensitivity analyses for both things. And the more variables you have, independent variables as inputs to

your model, the more relevant and important the analyses might be to narrow down, you know, which inputs you really need to study and reply to the solutions for, and so on.

And so, those are the kinds of things that I think are important features of an analysis and that really need to be explained so that you can show how you built more and more evidence and confidence into your final result.

The next big topic is quantity of interest uncertainty characterization. And we often refer to this as output uncertainty characterization. So our categories are labeled O-1 through O-3. "O" stands for output.

And here we focus on, you know, how far are you from the acceptance criteria? And then if you're close, you know, how strong is your basis and your confidence on your input distributions and uncertainty classification?

And, you know, I would say the less margin you have and the less certainty you have about your inputs, the less knowledge you have about your inputs, the more you're going to want to study the output uncertainty.

I'm hearing a lot of echo in the line.

So, anyway, you know, in any case for at the lowest level you're going to want to give a best estimate of your quantity of interest and the uncertainty that you calculated, perhaps represent that graphically. How you calculated your best estimate is important.

You know, did you separate, for example, aleatory and epistemic uncertainty?

And what is the fraction in each of those uncertainties?

And, you know, try to summarize what the major assumptions were that went into the output that you got and into the uncertainty, and what effect did each of those assumptions have on the uncertainty?

And, you know, again, once you get closer and closer to your acceptance criteria we're going to want to have a stronger explanation, if you will, of why your uncertainty that you calculated, you know, you know it well enough to be confident that you're not going to exceed your criteria.

The last topic now that we have is sensitivity studies. And, again, this is studies where you're going to change something in reference to a base analysis that you performed, perhaps change some models, change property of uncertainty, change

how you represent some distributions, and so on, and look at the outcome, the result on -- look at how that changes your results.

And here we have six categories from SS-1 to SS-6. SS stands for sensitivity studies. And these categories are very much tied to which category of QA and V&V you were in earlier on.

And if you're in, you know, category QV-1 where we know your code really well, you know, you may not even need to do sensitivity studies. You may be able to summarize what's been done previously.

However, as you move away from that, if you have an approved code but the quantities of interest that you're looking at were not previously documented or studied or approved in any way, then, you know, you want to provide more information on what sensitivity studies you might have done.

If you have a very limited number of independent variables in your code, you may not need as many sensitivity studies or you may not need them at all. It depends on exactly the specifics, you know, how different is your code from a previously approved code.

However, if you have a code that's newer and you have a great number of independent variables,

then you're going to definitely want to perform and document some more sensitivity studies. And the goal here is to, you know, explain what your assumptions were, what the impacts they had, or what impacts they had on the final results of your study. And try to describe, you know, what questions might arise, what "what ifs" might arise with regards to your specific problem, and how you address those via sensitivity studies.

So, that covers the eight major categories of PFM analysis that we envision. And, honestly, there's a lot of intricate detail in these graded approaches that we tried to come up with. So, you know, it's a lot to deliver in the short amount of time that I share, but we still have some time for questions.

I'll just go to my last slide really quick to highlight some of our next steps before maybe we can have some discussion.

Our next steps with regards to this project overall would be to publish some draft regulatory guidance, as well as a draft technical basis NUREG for public comment. And, of course, gather and address the comments that we receive

If we feel like public meetings might be

needed to, you know, to gather additional feedback or have discussions with our stakeholders, of course we will organize some. And, you know, we expect that perhaps once these documents actually are out and finalized at the draft level, that maybe ACRS might want to be able to discuss the various specifics of those documents. So, of course, we're always available for that.

And that ends my presentation for today.

Hello?

CHAIR RICCARDELLA: Yes, this is Pete. I'm sorry. I had my microphone on mute.

I have sort of a general comment/question. There seems to me that in a graded approach something should depend, the amount of detail you get into and the amount of validation, it depends on the results and how the results are going to be used.

And I think there's a difference in my experience between if you want to make a quantitative statement of comparison to some acceptance criteria, like 10 to the minus 5th, or a delta risk of 10 to the minus 6th, you know, sort of the Reg Guide 1.174 type of criteria, versus more of a qualitative use of PFM results such as comparing two actions, action A versus action B. It might be hydro test versus some form of

inspection. Or it might be different types of inspections.

And that qualitative use of PFM results is, to me, a useful, risk-informed approach that should be considered, you know. If A, if option A turns out to be an order of magnitude better than option B, say, and then you do sensitivity studies and you change some of the input assumptions, and maybe the absolute probabilistic results change by an order of magnitude, but option A always comes out better than option B, you've demonstrated something that's pretty useful that I think that kind of a use of PFM should be included somehow in a graded approach.

MR. RAYNAUD: I do have some thoughts on that.

I think, first of all, I agree. But I think, ultimately, you know, my understanding of what we're trying to do or show here is that we need to have confidence in the results and the codes used. And to do that, to be able to believe, you know, the types of arguments that you've just described, even if they're qualitative in nature, we need to have high confidence that, indeed, the code that was used produced results that we believe.

And I think that's a big focus of what

we're trying to do here. It is very rigorous and perhaps demanding, but it really has the ultimate goal of removing this feeling of the black box that has been described, and instilling confidence in the reviewers and the public that, yes, these results that show these qualitative differences can be believed.

CHAIR RICCARDELLA: Uh-huh.

MEMBER BALLINGER: Are you all set, Pete?

CHAIR RICCARDELLA: Yeah.

MEMBER BALLINGER: Yeah, this is Ron Ballinger. In reading through this, it was sort of like reading the old sections of the ASME code before it was computerized and you had a hard copy, and you had to have 27 fingers to locate yourself into various places in the document to feed things through.

This thing kind of cries out for a set of examples that could be included which would give somebody that wants to use this a little bit of initial direction.

Maybe I'm not using the right terminology, but it just seems like there should be examples in an appendix or something like that that says, you know, this is a simple one and this is a complex one, that kind of illustrates where the nub of the problem is likely to be.

DR. RAYNAUD: Yeah, I understand that. We, in fact, have drafted two reports that illustrate some of the concepts that we have here. You know, we're limited to the tools that we have, which are NRC tools, at least the ones we're familiar with that we can really use to the full extent that we want to, and so it's a little bit hard to go through the graded approach, but we do have some draft reports in the works that are pretty much ready to go.

When the guidance is issued for public comment, we'll post those as well, that at least illustrate concrete examples with a fictional problem of how you solve a PFM analysis and, you know, what the documentation might look like and so on, and I know you haven't seen that yet.

MEMBER BALLINGER: Yeah, so that would be very instructive, and these are referenced specifically in 1382?

DR. RAYNAUD: 13 --

MEMBER BALLINGER: Or whatever the NUREG turns out to be?

DR. RAYNAUD: Oh, I don't know if there are specific references yet because nothing being public, you know, it's hard to reference nonpublic things, but, yes, we can certainly add that in. We do

have the reports in a draft version.

MR. RUDLAND: And Ron, this is Dave Rudland. If we do, you know, have a public meeting once these are released, it might be a good idea for us to go through those at the public meeting so that you can see the examples and how they work.

MEMBER BALLINGER: Yeah, that's probably an excellent idea. I mean, I remember a workshop that Pete and I went to on xLPR, enough said.

DR. RAYNAUD: I was actually going to mention xLPR, which of course is one of the NRC's main probabilistic fracture mechanics codes for piping.

There have been a great number of publications related to that code, including a lot on sensitivity studies, sensitivity analyses, and so on that could also be a basis for drawing examples.

MEMBER BALLINGER: Yeah, those, I'm assuming that in this NUREG, there will be a set of, what do you want to call it, references, not just references, but a bibliography of sources that a user could go to which would include some of the things that you just mentioned.

DR. RAYNAUD: We can make sure that that's there.

MR. RUDLAND: But realize, Ron, that xLPR,

and FAVOR for that matter, you know, the staff are very, very familiar with those codes, and very, very familiar with, you know, the bases, and so it would not --

It might not be as useful to use those codes as examples of how to step through this because, you know, the basis is really for new or unique codes, you know, where it might be more complex to use the regulatory guide.

MEMBER BALLINGER: Yeah, I would think of xLPR or FAVOR as what I would call a dead ringer example, and then another example would be, you know, I don't know, use another acronym, the killer example, the one that's the most complicated.

CHAIR RICCARDELLA: Well, I would guess xLPR and FAVOR are all in the one category --

(Simultaneous speaking.)

MR. RUDLAND: That's correct, yeah.

DR. RAYNAUD: So, you know, a lot of the documentation, the QA and V&V documentation that exists for both of those codes, but especially for xLPR because it's a more modern code, and as a result, the standards that were used in developing all of the documentation are more up to today's standards, you can see that that documentation is extensive.

You know, we're talking I don't even know how many reports and thousands of pages. Obviously, that's not really something that is realistically reviewable, you know, within a licensing submittal.

It's just too much, but I think that type of rigor that was performed there and that exists, it would be nice if that sort of thing existed for very complex new codes that we've never heard of such that if we have specific questions or needed to see specific parts of the V&V and QA, that that paper trace exists, and I think that's been one of the things that's been very hard to get to in past PFM reviews.

MR. MOORE: Chairman Riccardella, Members Bier and Dimitrijevic have their hands raised.

CHAIR RICCARDELLA: Oh, okay, I'm sorry. I didn't see that. Vicki, would you want to --

MEMBER BIER: Sure, I can go first. I have a couple of questions that are mainly kind of to understand the context for this.

You mentioned that some of these components that would be analyzed this way might be passive components that wouldn't even appear in the PRA, but just kind of a what if this failed, you know, how likely is that and do we need to worry about it.

Could this also be used for components that are in there, like for, you know, getting fragilities for seismic PRA or would you imagine that would be a different process?

DR. RAYNAUD: Dave, do you want to try and take that one?

MR. RUDLAND: We're talking specifically here about fracture mechanics types of codes, but there's no reason why the process that we have here couldn't be applied to other probabilistic style codes.

MEMBER BIER: Okay.

MR. RUDLAND: Yeah, I don't see why not, but this particular regulatory guide is really focused just on the probabilistic fracture mechanics codes, yeah.

MEMBER BIER: So, I guess the question I have which, you know, may be my lack of familiarity with the context, but there's a very sophisticated discussion about kind of all of the inputs and complexities that could go into the analysis, you know, epistemic versus aleatory uncertainties and how they would be treated, et cetera, but there seems to be relatively little discussion of what happens to the output of the analysis.

And, you know, part of that is, okay, fine, you get a distribution of whatever that then, you know, goes to the decision makers the same like any other probabilistic result, but the thing that I'm wondering is are there dependencies between the results of analyses for different components?

So, for instance, I don't know, a valve versus a tank, or a pipe in one orientation versus a pipe in another orientation that may be positively correlated like they're likely to fail in the same circumstances, or they may be negatively correlated. The factors that would lead one to fail would make it less risky for the other component.

And am I just thinking too far downstream and this would be done for, you know, a single component in isolation or do we need some guidance to deal with those things as well?

DR. RAYNAUD: I think the answer, at least in my mind, is that there's no true limitation. You know, I think we're often thinking about single component because that's what we've done to date and what we're more familiar with, but I don't see any reason why a modeling tool couldn't be developed to model interactions between components --

MEMBER BIER: Got it.

DR. RAYNAUD: -- and so forth.

MEMBER BIER: Okay, but that's not in the current practice very much, and therefore doesn't feature largely in this guidance, is that fair?

DR. RAYNAUD: I think that's true. I would look to Dave to confirm.

MR. RUDLAND: Yeah, if you don't mind, Patrick. Yeah, so, you know, as I mentioned in my little intro stuff, you know, typically we -- you know, the way that we've done PRAs is we've had guidance on, you know, how to conduct a good PRA analysis or how to conduct a good PFM analysis.

But then for problem-specific issues, for instance if we needed to develop some kind of criteria for a leak before a break, for instance, there would be separate guidance on how to, you know, on what the acceptance criteria would be, what the interactions would be.

That would have to be in separate guidance because this is really just focused on how to do the analyses, and how you apply the analyses to any specific problem would have to be in different guidance.

MEMBER BIER: Okay, I guess the one thing I would say is that there may -- if you eventually

envision that kind of interaction, there may need to be a lot more information carried forward from the details of the analysis to support that eventually.

MR. RUDLAND: Yeah, and I really, I totally agree, and especially as you mentioned for these components that really aren't even modeled in PRA. There's a lot of thought that needs to go into, you know, how do you apply these risk insights, you know, in determining the safety of these particular components, and what the interactions are, and, you know, are there isolable (phonetic) systems that you need to consider and things like that.

MEMBER BIER: Yeah, okay.

MR. RUDLAND: Yeah.

MEMBER BIER: Thank you.

CHAIR RICCARDELLA: Vesna, did you want to ask a question?

MEMBER DIMITRIJEVIC: Yes, I did not ask a question. I wanted to make the comment actually to support, Pete, what you said.

Well, the PRA especially, but I have met the fracture mechanics code many times in my life, you know, pressurized (unintelligible), the risk-informed ISI where we had the Westinghouse code using fracture mechanics, and an EPRI code using deterministic

results, and then I worked in internal flooding, those guides.

So, there is many places you can use fracture mechanics in the PRA, but the point that Pete was making is that, you know, the risk informed in this case is not usually that risk.

What is happening here is actually what is much more important. How are those results used? So, let me -- I would say that case based like, say, on the vessel, fracture mechanics analysis of the probability to fail the vessel.

So, in all PRAs, the number for that was less than ten to the minus six and it was not considered in the PRA. Then, the PRAs started coming with much lower numbers, and suddenly ten to the minus six would dominate the results, then suddenly the new number of ten to the minus six that's showing up is not really justification for either one of those numbers.

So, now how important it is to have a good fracture mechanic model to calculate this less than one in a million or less than one in hundred millions, and it's very important in calculating that.

So, obviously it would be much easier to prove that something is less than some value than

getting a specific number like 6.2, you know, in minus seven or something, and that could be the goal for this.

The other thing is that when you calculate delta risk results, delta risk results are very -- to calculate the importance of anything. This number is the same in each CBI (phonetic) for a lot of -- and so it doesn't really matter what it is because the delta risk disappear.

So, this is extremely -- so I think that this is extremely important. If you did not change any factor reaching part of this number, but possibly what is very not likely to happen, then you can change factor between impact, the vessel fail probability.

In that case, it's completely irrelevant what that number, as long as it's not challenging safety goal. It will disappear in every delta risk Reg Guide 1174 application.

Similarly to large LOCA, like if you want to see like the fracture mechanics code be applicable to large LOCA, then obviously the large LOCA is also small, not as small as the vessel, but you have a choice between using the expert opinion, right, versus trying to use the fracture mechanics code. In that case, you only have to evaluate where the

uncertainties are higher.

So, the use of fracture mechanics in the PRA is often going to be very specific and limited. It has to prove the smaller uncertain value. It has to account for uncertainties, whether it's the deterministic inputs, or the expert opinion, or just to define the important factors that impact something.

So, you said one thing which is really extremely true. This is so complex that it can just be -- defining exact application is what may be your risk-informed input.

When you say, you know, safety-significant, risk-informed input is defining what type of application and what should be proved in that application.

That's my opinion and I think Pete brought that to say qualitative, but it's not always qualitative. You can just prove envelope. You know, it's smaller than this.

You can prove the factors which will not impact that in the risk-informed applications, or you can prove that uncertainties will lead to this is higher than currently used. That was my take on some of those things.

DR. RAYNAUD: Thank you.

CHAIR RICCARDELLA: Like anything, there's a trade off. As you expand the rigor, you expand the complexity of the analysis. You extend the time and the cost, and I think, you know, the two examples that Ron just mentioned, FAVOR and xLPR, are an example.

I mean, look at the time and the cost that went into developing those codes and, you know, you're going to see perhaps less use to PFM because it just turns out not to be cost effective to do it, but that's why I'm suggesting some simpler criteria if you're just looking for a qualitative result, but that's just my opinion.

Are there any other members that want to comment? We have one more presentation, but I think maybe we'll take a break before that. Is there any other members that have any comments on it?

MEMBER KIRCHNER: Pete, this is Walt. I was trying to think through after listening to you and Vesna in particular, and also Vicki's comments.

I wonder, Patrick, you and your colleagues, have you thought about how this might be applied to new materials through advanced reactors that may be operating at higher temperatures, and hence the overall, I'll just say qualitatively, the probability of something like a pressure primary

vessel rupture or fracture could be much higher?

CHAIR RICCARDELLA: Or, Walt, like graphite, which we just heard has to be analyzed in the probabilistic method, right?

MEMBER KIRCHNER: Yeah, or composites. I often think about graphite composites as pressure vessels, or other internal structures like to house control rods or boron carbide absorbers so that you get the metal out of the system, but you introduce new materials and new challenges.

So, Patrick, have you been thinking about -- this morning, we had a very nice presentation on Division 5 of the boiler and pressure vessel code. Are you thinking along those lines to how this might play out to supplement a risk-informed application for an advanced high-temperature vessel?

DR. RAYNAUD: Yeah, so I guess what I want to emphasize is that, you know, what we're thinking about here is not really tied to any specific technology, I mean, other than fracture mechanics.

But, you know, if you have the correct models to model different temperature ranges, different materials, different phenomena that might lead to failures where fracture mechanics can be used, then we believe that what we proposing here is general

enough.

And it's really focused more on statistical methods and stuff much more than the detail of which fracture mechanics model you're using, so it is extensible to these other classes of problems and materials that you've described.

MR. RUDLAND: Yeah, this is Dave Rudland from the staff I could just comment also. You know, it's really highly dependent on the information that you have and the uncertainties that you've developed and your confidence in those, right?

So, for these high-temperature materials where we know there's not a lot of data quite yet, right, I think it would be more difficult to apply these types of techniques because you wouldn't have as much confidence in the results because of the lack of data.

You can make some approximations, and of course adjust acceptance criteria based on that, but, you know, as the industry develops more and more data on the different materials, I think these applications and the application of these types of tools will become more useful.

CHAIR RICCARDELLA: Okay, so it's approaching 3:30. We have one more presentation.

David Dijamco, do you think you can get your presentation done in a half hour or so?

MR. DIJAMCO: Oh, yes, I think I can, Pete, so, yeah.

CHAIR RICCARDELLA: So, would it be okay to take --

MR. DIJAMCO: Mine's only ten minutes or so.

CHAIR RICCARDELLA: All right, so let's take about a ten-minute break. It's 3:30. We'll break until 3:40 and then we'll reconvene, okay?

MEMBER KIRCHNER: Could you afford 15 minutes, Pete --

CHAIR RICCARDELLA: Okay.

MEMBER KIRCHNER: -- for the break?

CHAIR RICCARDELLA: I can. We may end up staying a little bit past 4:00, but that's okay.

MEMBER KIRCHNER: Thank you.

CHAIR RICCARDELLA: All right, so we're on recess until, I have to keep converting the time, until 3:45.

(Whereupon, the above-entitled matter went off the record at 3:29 p.m. and resumed at 3:45 p.m.)

CHAIR RICCARDELLA: Okay, so it's 3:45 Eastern Time and we will resume the meeting. David,

are you ready to go?

MR. DIJAMCO: I'm ready to go.

CHAIR RICCARDELLA: Okay.

MR. DIJAMCO: Okay, so, good afternoon, everybody, and good afternoon, Dr. Riccardella. It's good to hear from you.

So, for those who don't know me, my name is Dave Dijamco. I'm from the Office of Nuclear Reactor Regulation from the Vessels and Internals Branch, and I'm going to talk about the use of the PFM guidance from a technical reviewer's perspective.

So, the NRC received a submittal from Vogtle using PFM probabilistic fracture mechanics as a technical basis, and so we had a chance to pilot this guidance, which I want to emphasize it's still in an unpublished draft and pre-decisional form, but we had a chance to pilot this guidance during the review of the Vogtle submittal.

And so the objective of this presentation I would say is kind of the, is the more informal of the three presentations, which is basically for me to just share my thoughts on questions like how to review when, where to focus, of course, in the guidance, and other questions such as how is the guidance helpful or what did we learn from its use.

CHAIR RICCARDELLA: David, I take it this was the operating units and Vogtle 1 and 2, not 3 and 4?

MR. DIJAMCO: That's correct. That's correct, yeah.

CHAIR RICCARDELLA: Thank you.

MR. DIJAMCO: 1 and 2, yeah.

MEMBER BLEY: David, it's Dennis Bley. You folks used the guidance. Was it available for the folks at Vogtle or did they use it?

MR. DIJAMCO: No, I believe they were not available for the Vogtle folks.

MEMBER BLEY: Okay.

MR. DIJAMCO: It was just internally available to the NRC.

MEMBER BLEY: So, we have a case where they did it on their own and then you applied the guidance when you reviewed it. It would be interesting --

(Simultaneous speaking.)

MR. DIJAMCO: I believe so, to some extent. I believe -- I applied it to what was there.

MEMBER BLEY: Okay.

MR. RUDLAND: This is Dave Rudland. The Vogtle staff had the EPRI white paper that they used.

They followed the EPRI white paper, which was kind of the basis for some of the categorizations that Patrick talked about.

MEMBER BLEY: Okay, thanks.

MR. DIJAMCO: So, I just wanted to give a quick background. So, EPRI initiated an NDE optimization program that sought to increase the inservice inspection intervals of certain class one and class two components from ten to 30 years, and EPRI issued a series of publicly available reports as a result of this effort, and so each of these EPRI reports is for a specific component.

For example, that first report, 14590, it's for steam generator nozzles. The second report is for pressurizer vessel shell wells and so forth, and, of course, the centerpiece in all of this is probabilistic fracture mechanics.

And this slide just gives you just a very, very high level view of what the submittal was about. It was basically an alternative request to increase the ISI interval of steam generator welds and nozzles from ten to 30 years, and it referenced the first of that report I showed in the previous slide, that 14590, as the technical basis.

And I just provided here some basic

information about the submittal and the NRC safety evaluation. All of these documents are available in ADAMS.

And I just wanted to mention also that there were actually three more submittals that came in after Vogtle which referenced each of the other three EPRI reports that are shown on the previous slide. Another thing to note is that the NRC did not review any of the EPRI reports for generic use.

So, what's this EPRI report 14590? So, again, it's the reference technical basis for the Vogtle submittal, and the specific components were steam generator nozzle to vessel welds and nozzle inside radii.

As expected, because it's PFM based, it was extensive. It was nearly 200 pages, lots of technical topics, and in fact, PFM is only one of several chapters.

And so this is what my brain looked like after going over the report. I call it my spaghetti brain because of all of these crisscrossing concepts and topics.

So, my background is in mostly deterministic analysis. Coming into the review, I did have a little bit of knowledge of PFM.

So, even though some of these concepts like degradation mechanisms, finite models, convergence and things like that, they were familiar to me, but I just wasn't sure how to approach the review.

So, the main question in my mind as a technical reviewer was how do I review this thing? And, of course, the PFM guidance, which I took to mean the draft guidance and the draft NUREG, they suggested an approach, or maybe it's better to say that I inferred an approach from looking over the guidance.

So, how did the guidance help? So, at the time of the Vogtle review, the details of the graded approach that Patrick talked about were still under development.

And as Patrick had mentioned, they are still under current internal review, but the guidance at that time had enough of a framework for me to work with, especially the sections on the suggested content of PFM submittals.

And I just wanted to note here the EPRI white paper that Dave Rudland mentioned earlier, and that was also on PFM submittals. It's publicly available and that was very helpful in crafting the draft graded approach.

And so this brings me to the first thought that I wanted to share, which is that the guidance helped me put a framework around various topics, and thus organizing my review, and these are the topics that are covered in the guidance which Patrick talked about in detail in his presentation.

And so again, this is, you know, my spaghetti brain without the guidance and into a well-ordered path with the guidance.

And this is the actual outline of the safety evaluation for the Vogtle submittal. I'm not going to go through each one of these. The point here is just to show that many of the topics that I've kind of mentioned in the previous slides made it into the safety evaluation.

So, I think there's an observation to be made here, which is that I think there was an overall efficiency gained in the submittal and review process. The guidance will help the industry prepare submittals that have a consistent level of quality, which in turn helps the NRC review the submittals.

And there's nothing really new in this process. One example that I can think of that's relevant in the (unintelligible) is the use of Reg Guide 1.99, Revision 2, to determine the embrittlement

levels of reactor pressure vessel materials.

The second thought that I wanted to share was that the guidance helped me understand sensitivity analysis and sensitivity studies and their importance in interpreting results.

And so the PFM results for the base cases were actually pretty far from the acceptance criteria, but those base cases were based on a representative configuration rather than a bounding configuration.

So, I felt that during the review, that I needed to understand the impact of the most important input parameters, and the SA and SS helped me in doing that, and both of these topics are covered well in the draft guide and the draft NUREG.

The third thought that I wanted to share was that the guidance supports knowledge management. If you're just coming up to speed on PFM like I was, and in many ways, I still am, I think the guidance is a good learning tool.

For example, the draft chapter four of the NUREG contains a compendium of methods for establishing confidence in a PFM analysis, so it talks about things like uncertainty, convergence, acceptance methods, things like that.

And I think this is a boom to all

stakeholders, especially as we move more and more towards risk-informed decision making, of course of which PFM is only a part as Dave Rudland mentioned during his talk, but it could be an important part.

MEMBER BLEY: David?

MR. DIJAMCO: Yes?

MEMBER BLEY: Coming to this without a real strong background in probabilistic fracture mechanics as many people probably will, were there areas where you were hoping for more help than you found in the guidance, or if there were some of those, did they get factored into the current version of the guidance?

MR. DIJAMCO: I think were -- so, at that time, you know, that version of the guidance that was available when I reviewed Vogtle and as I mentioned, you know, again for me, I'm mostly deterministic, but when I needed help, you know, there were others in the staff that I went to, especially, and he's here right now, Dave Rudland, and so I think where I lacked the knowledge and the proper confidence to review it, you know, I consulted with the right people.

MR. RUDLAND: Can I just comment also that in addition to what Dave has mentioned, we also, especially for this particular request, held an audit

of the probabilistic fracture mechanics code, which was a unique code just for this application, to gain further knowledge about how the code works, and the quality assurance, and the validation and verification.

So, that wasn't necessarily in the submittal because we were able to hold this virtual basically audit of the code to understand it a little better, and that also helps us to understand it if we're not familiar with it.

MEMBER BLEY: Thank you for that.

MEMBER KIRCHNER: To the two Davids, this is Walt Kirchner. Are there a lot of probabilistic fracture mechanics codes out there? Is each a one-off case or is there, besides the NRC codes, are there, quote, unquote, industry standards that most applicants would turn to?

MR. DIJAMCO: How do you feel about that, Dave? I mean --

MR. RUDLAND: Well, I'll tell you, you know, there is the hopes of these larger codes like FAVOR and xLPR, that they would be generic enough to be used for a lot of applications.

What we're finding is that I think the industry prefers to develop specific codes for their

particular applications. So, we're seeing that more and more, that they're more, I don't want to say one-offs, but at least applicable to only a certain set of components.

CHAIR RICCARDELLA: You know, Walt, I think a lot of these industry codes though, they kind of have a common kernel, you know, the Monte Carlo sampling, and it's just that they adapt the input and the output and maybe the fracture mechanics models to the specific problem, but a lot of them are based on a common routine. At least I know when we do that, we have one common Monte Carlo sampling approach.

MR. RUDLAND: Yeah, and I agree with Pete, and I think that was one of the reasons why we put into our graded approach, you know, a previously approved or approved as the use code that's been modified, because a lot of times, they'll do that. They'll just change a model or this, that, or the other thing, and apply it to something different, so.

MEMBER KIRCHNER: Thank you.

MR. DIJAMCO: Okay, actually that was my last slide. That's pretty much all I have, but I just wanted to make kind of a couple of final remarks.

So, you know, I just shared the thoughts of just one reviewer. As Dave mentioned earlier, Dave

Rudland, we have been getting PFM submittals recently, and I think we do expect to get more and more PFM submittals, and so I think having the guidance is very timely.

And I think as these submittals come in, I think it will be interesting to hear the perspectives of other reviewers.

CHAIR RICCARDELLA: So, David, just one technical question. You mentioned Reg Guide 1.99. I don't see how that came into play on this Vogtle submittal since it's not in a radiation zone. What was the reference to Reg Guide 1.99?

MR. DIJAMCO: Pete, I was just referring to the process of using or having a regulatory guide to, you know, guidance for the industry, and really for the industry and NRC to help the submittal and review process. That's kind of the analogy there. That's just one example of how, you know, the use of reg guidance is --

CHAIR RICCARDELLA: Yeah.

MR. DIJAMCO: -- has been used in the past.

CHAIR RICCARDELLA: Obsolete though it may be.

MR. DIJAMCO: Correct, correct, that's

right, yeah.

CHAIR RICCARDELLA: I couldn't help but get in that dig.

(Laughter.)

MR. DIJAMCO: Right, no, I understand.

MEMBER BALLINGER: Obsolete, but still used.

MR. DIJAMCO: It's still used, yeah.

CHAIR RICCARDELLA: Okay, that's a subject for another day, right?

(Laughter.)

MR. DIJAMCO: That's all I had, so.

CHAIR RICCARDELLA: Okay, well, thank you for the presentation, David. Are there any other member comments or discussion? Okay, hearing none, we will turn to public comments. Is the bridge line open now and unmuted?

MR. DASHIELL: The bridge line is open for public comments.

CHAIR RICCARDELLA: Thank you, Thomas. So, do we have any comments from the public? If so, please state your name and make your comment.

DR. COFIE: Dr. Riccardella, this is Nat Cofie here. Can you hear me?

CHAIR RICCARDELLA: Yes, I hear you, Nat.

How are you doing?

DR. COFIE: I'm doing good, Dr. Pete. Thank you for this meeting. You know, I've learned a lot. I just have a simple question for Patrick and maybe Dr. Rudland.

They mentioned, you know, codes by, you know, classification, NRC-approved codes. I heard something like that. What constitutes an NRC-approved code? Is there a database or somewhere that one could go and find out what codes for PFM have been approved by the NRC? Is it a code that has gone through an audit? What constitutes an NRC-approved code?

DR. RAYNAUD: I can take that and Dave can add to it. For now, obviously NRC's own codes, so FAVOR and XLPR, and we're looking specifically for codes where a safety evaluation report would have been written for that code or for that code in a specific application.

CHAIR RICCARDELLA: So, that's significant. If the code has been used for an application and that application was approved, then that constitutes and NRC-approved code?

DR. RAYNAUD: I wouldn't say that.

MR. RUDLAND: I would say as long as it's used in the exact same application, then, yeah, but if

not, then it would have to go to the different, the next step down where --

CHAIR RICCARDELLA: It would be one of those modified categories.

MR. RUDLAND: Yeah.

DR. RAYNAUD: Exactly.

MR. RUDLAND: Because again, the first application of any code, we're going to do like we did with the Vogtle and have an audit or something like that to really understand the workings of the code, so I think the bulk is going to happen in the first types of review.

MR. MOORE: Mr. Chairman, does the court reporter need the caller's name?

CHAIR RICCARDELLA: Yes, Nat, do you want to give your name and spell it? I can do it.

DR. COFIE: Oh, my name?

CHAIR RICCARDELLA: It's Nathaniel Cofie, C-O-F-I-E.

MR. MOORE: Thank you.

CHAIR RICCARDELLA: Are there any other comments?

DR. HARRINGTON: Pete, this is Craig Harrington.

CHAIR RICCARDELLA: Oh, hi, Craig, how are

you?

DR. HARRINGTON: I'm fine. How are you? I just wanted to add onto the comments that you and Dave made a minute ago about other codes. The distinction between like an xLPR or the more one-off codes like were used for Vogtle or some of these other activities.

I think to the extent that industry can use an existing code like an xLPR for a new application, they're certainly going to do that because of the benefits of it having some degree of preapproval and, you know, all of that.

But back to that first category that Patrick talked about of planning the analysis and the steps to ensure that your quantities of interest are adequately addressed by the code, these probabilistic fracture mechanics analyses are complex enough and they're nuanced enough that very often even with the range of flexibility that we tried to build into xLPR, it still doesn't quite get to exactly the place that you might want it or need it to go.

And so I think that drives these one-off codes, not a preference by industry, but just that it's that complex of a problem that it's very hard to solve every probabilistic fracture mechanics problem

with a broad brush tool.

And even with xLPR, for any of the analyses that we're doing, we end up tweaking little things or making small adjustments possibly to tailor it to the specific need at hand, so I just wanted to make that clarification.

CHAIR RICCARDELLA: Thank you very much for your input, Craig. Is there anybody else out there that would like to make a comment?

Well, with that and no further comments from the members, I thank everyone for a very interesting series of presentations and a very informative session, and the meeting is adjourned.

(Whereupon, the above-entitled matter went off the record at 4:07 p.m.)

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Need for Probabilistic Fracture Mechanics Guidance

Remarks by

David L. Rudland, Ph.D.
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Advisory Committee on Reactor Safeguards
Meeting of the Subcommittee on Metallurgy & Reactor Fuels
July 20, 2021

Integrated Decision Making

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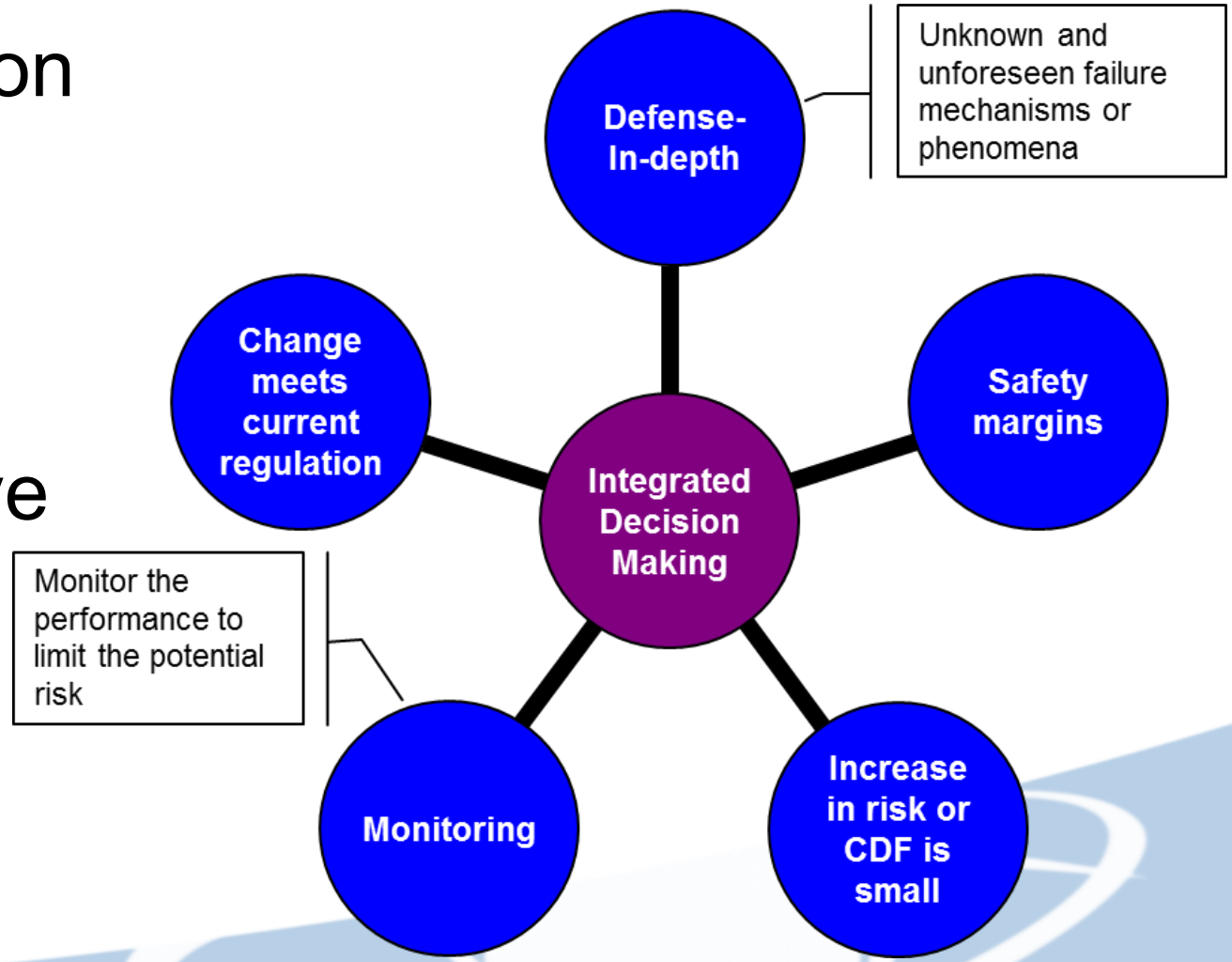
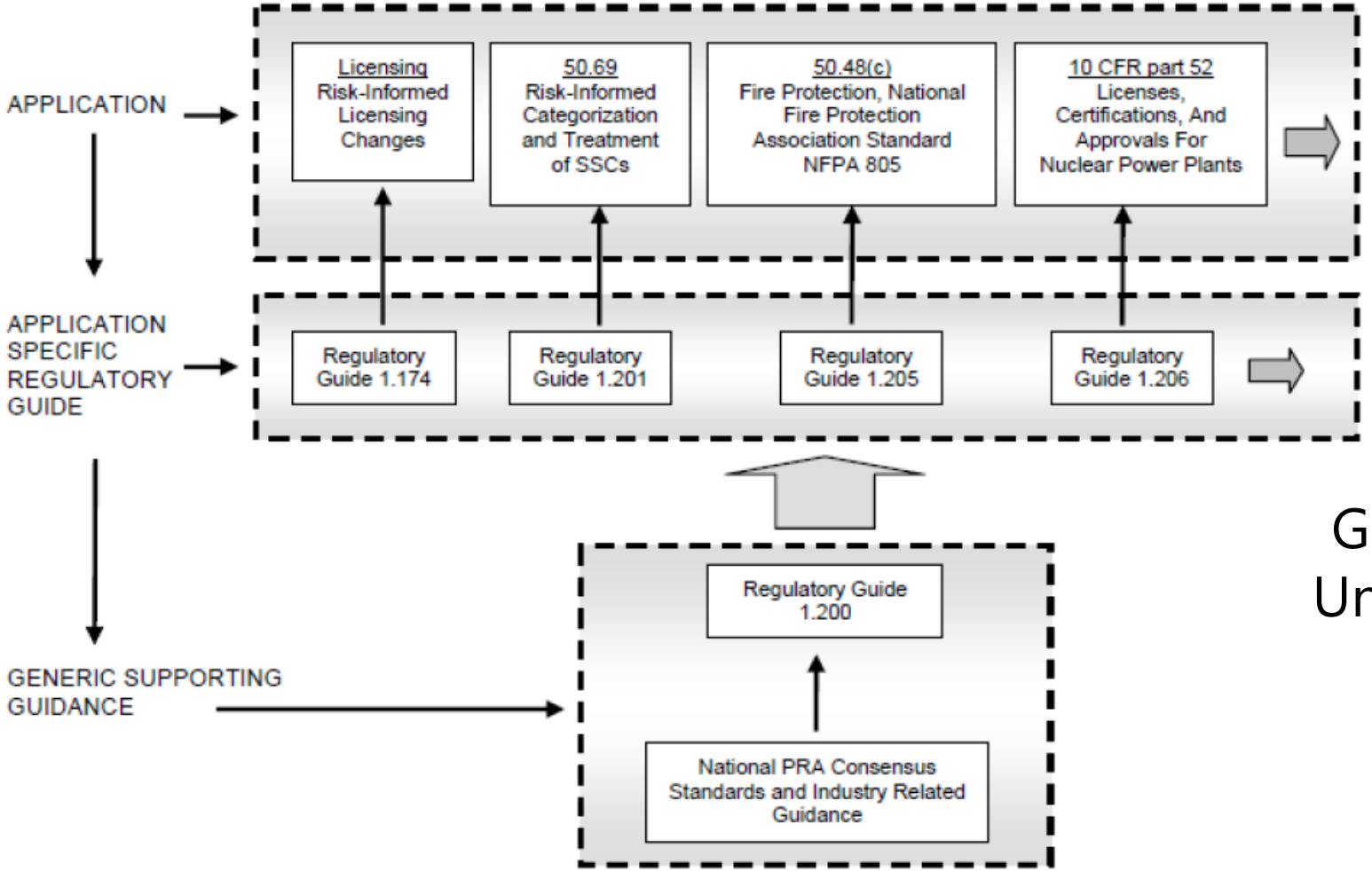
- Objective is integrated decision making
- Key is risk informed not risk based
- Use of risk insights for passive component integrity



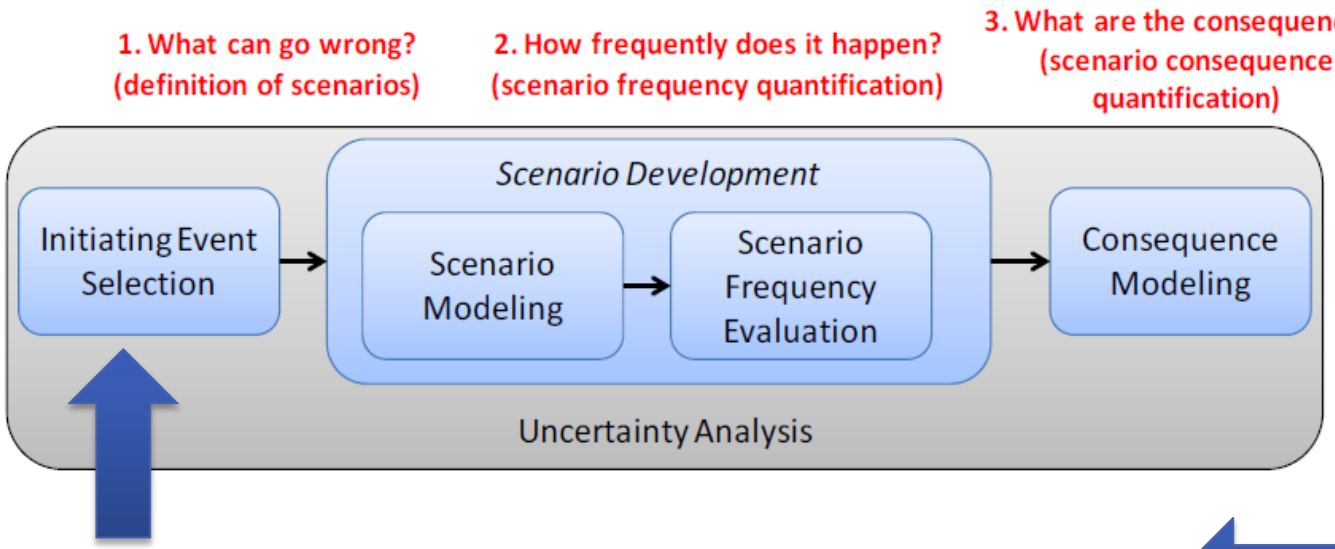
Risk-Informed Licensing



Other licensing actions

Guidance/Process Under development

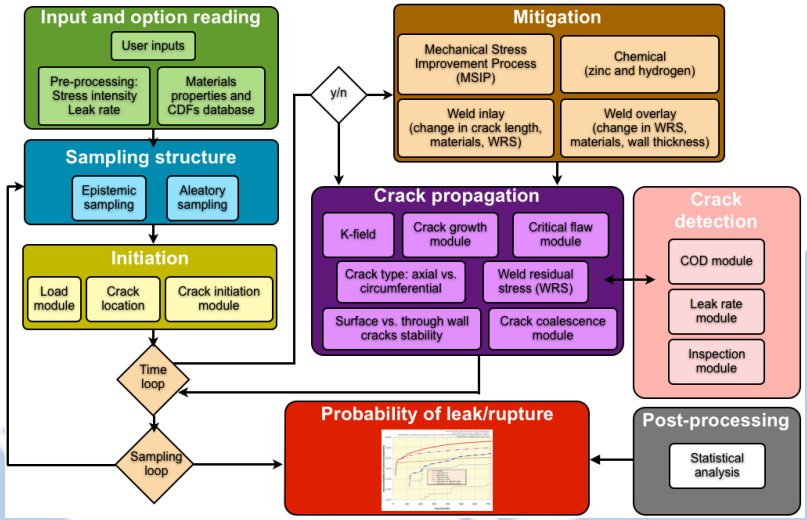
Use of Probabilistic Fracture Mechanics



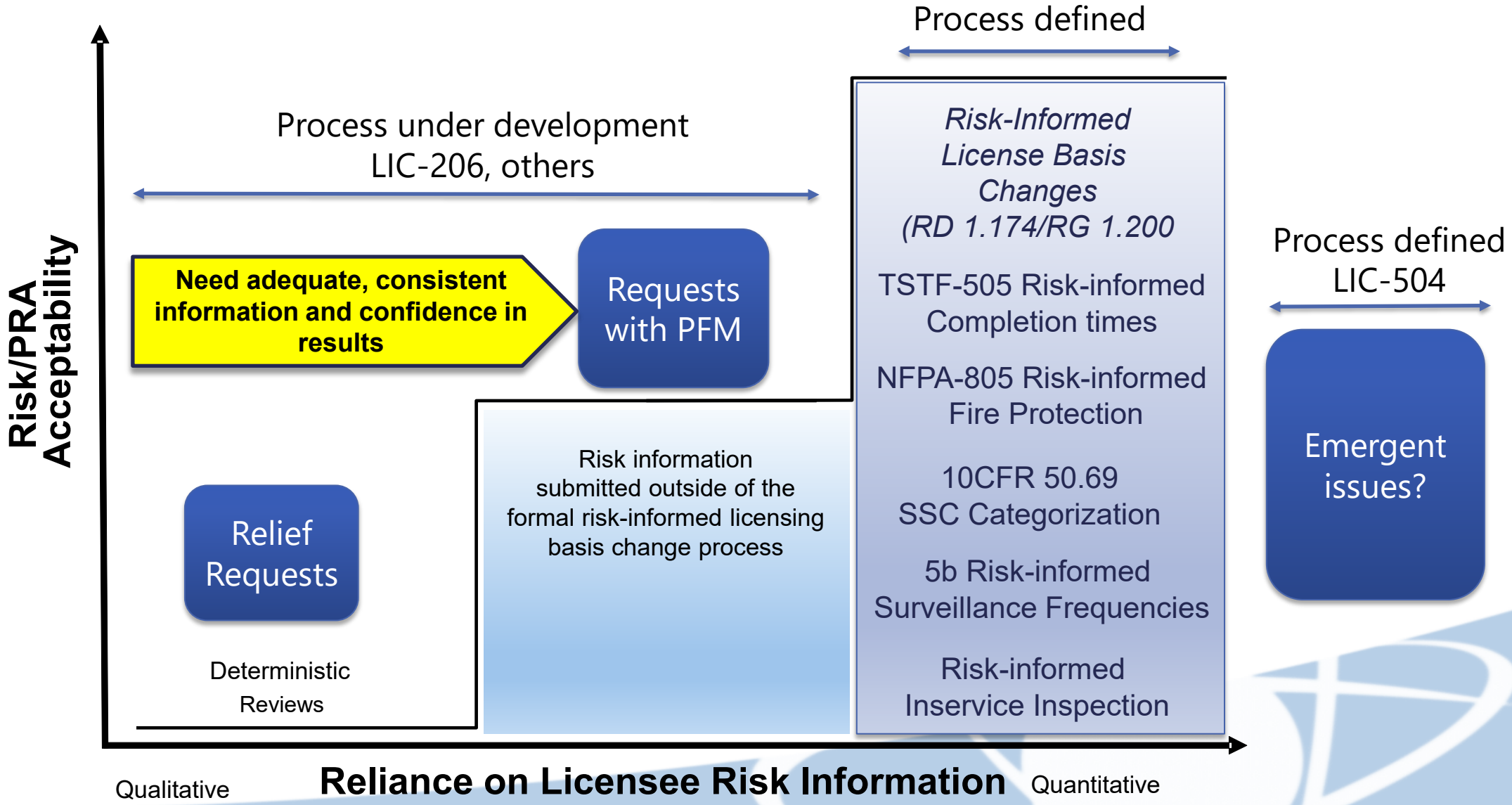
Probabilistic Fracture Mechanics (PFM) is being used

- Requests for Inspection Relief
- LOCA Frequencies
- LBB
- Others?

- Inputs to PRA
- Change in Inspection Schedule – eliminate inspections?
- Estimate LOCA Frequency
- Leak-before-break



Licensing Reviews and Emergent Issues



PFM – Past Regulatory Issues

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- Difficult for NRC staff to reproduce or verify PFM calculations
  - Complex regulatory review
  - 'Black Box' codes with insufficient vetting of inputs and code: low confidence in outputs
- Challenges where PFM was proposed as regulatory basis for long term inspection programs under NRC rulemaking

Are these topics sufficient relative to staff position on PFM, Yes, No, Partial								
Report	Models	Inputs	Uncertainties	V&V	Convergence	Sensitivity studies	Input Importance	Other Risk arguments
MRP-105	Partial	Partial	Partial	Partial	No	Partial	No	No
MRP-116	Partial	No	Partial	Partial	No	Partial	No	No
MRP-362, Rev. 1	Yes	Yes	Partial	Partial	no	Yes	Partial	No
MRP-335, Rev. 3-A	Partial	Partial	Partial	Partial	No	Partial	No	No
MRP-395	Partial	Partial	Partial	Partial	One paragraph	Yes, but limitations	No	Yes, but not acceptable (1) ignore leakage through weld (2) ignore BAC

PFM Hurdles and Path Forward

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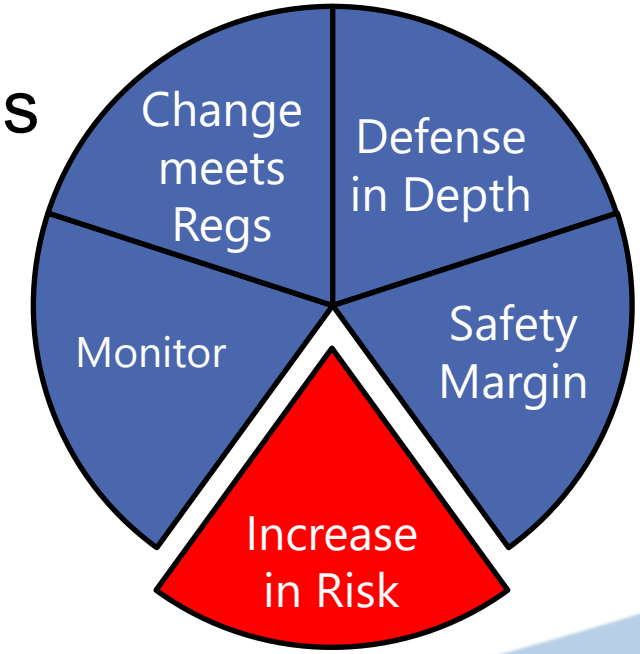
- PFM submittals and level of acceptability have been inconsistent
- Risk-informed decision making is still in the process of being implemented throughout all agency activities
- PFM results are only one part of risk-informed decision making
- Some license processes under development
- Use of PFM for licensing is increasing rapidly



- PFM Regulatory Guide will provide for consistent and adequate information for licensing application reviews

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RES Perspectives on PFM Analyses and on a Graded Approach for PFM

Remarks by

Patrick A. C. Raynaud, Ph.D.

Senior Materials Engineer
Division of Engineering
Office of Nuclear Regulatory Research

Advisory Committee on Reactor Safeguards
Meeting of the Subcommittee on Metallurgy & Reactor Fuels
July 20, 2021

Objectives and Disclaimers

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The goals of this presentation are:

1. Describe NRC/RES current perspectives on the analytical steps that could be used to create a high-confidence PFM demonstration for the purpose of demonstrating an adequate solution to a technical problem

2. Describe what a graded approach for PFM analyses and documentation might look like when considering the safety significance and the complexity of a given problem

Disclaimers:

1. All content shown in these slides is pre-decisional and does not represent an official position of the NRC

2. None of the ideas presented here are final

3. This content is not intended to be guidance on what constitutes an acceptable approach for PFM submittals to the NRC

Outline

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- **Part 1: Analytical steps in a probabilistic fracture mechanics demonstration**

- **Part 2: Detailed thoughts on a graded approach for PFM**

Analytical steps in a probabilistic fracture mechanics demonstration

	Step	Action
Plan	**1**. Translate regulatory requirements into an analysis plan	• Define the regulatory context • Define the QoI and how it relates to the model output and acceptance criteria • Determine the suitability of the PFM code for the application • Identify key elements of the problem that impact analysis choices
Analyze	**2**. Characterize model input uncertainty	• Identify uncertain model inputs • Specify probability distributions on uncertain inputs
	3. Estimate QoIs and their associated uncertainty	• Select a sampling scheme • Assess sampling uncertainty • Conduct sensitivity analysis • Conduct output uncertainty analysis
	4. Conduct sensitivity studies to assess the credibility of modeling assumptions	• Determine a set of sensitivity studies • Conduct sensitivity studies and present results
Synthesize	**5**. Draw conclusions From analysis results	• Interpret analysis results • Iterate on the analysis process to refine model results

Analysis results inconclusive, refinements needed.

Step 1: Translation of Regulatory Requirements into an Analysis Plan

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- Action 1: Define the Regulatory Context
  - How will PFM analyses will be used as a technical basis for a regulatory action?
  - What criteria will be used to support a proposed regulatory action?

- Action 2: Define the Quantity of Interest and How it Relates to the Model Output and Acceptance Criteria
  - Map regulatory requirements onto specific model outputs
  - Ensure that the model is predicting appropriate and relevant quantities

- Action 3: Determine the Suitability of the Probabilistic Fracture Mechanics Code for the Specific Application
  - Determine whether a specific PFM code is suitable for the application of interest
  - Identify any potential limitations of the code with regard to the application

- Action 4: Identify Key Elements of the Problem that Impact Analysis Choices
  - Identify key elements of the PFM application that will determine how to conduct the analysis
  - Example: simplifications to a model because of computational limitations or because the problem is inherently not complex

Step 2: Model Input Uncertainty Characterization

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- Action 1: Identify Uncertain Model Inputs
  - Determine which model inputs are treated with uncertainty
  - Determine the type of uncertainty (aleatory or epistemic) for each input

- Action 2: Specify Probability Distributions on Uncertain Inputs
  - Uncertainty in model inputs is represented through probability distributions
  - Uncertainty is propagated forward to the model outputs to estimate and quantify uncertainty in QoIs

Step 3: Estimation of Quantity of Interest and Associated Uncertainty

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- Action 1: Select a Sampling Scheme for Sampling Uncertain Model Inputs
  - Select a method for propagating uncertainty in the model inputs through the model
  - Goal is to estimate the QoI and the associated uncertainty

- Action 2: Assess Sampling Uncertainty: Statistical Convergence Analysis
  - Assess the statistical convergence of QoI estimates from model outputs given a sampling scheme

- Action 3: Conduct Sensitivity Analyses to Determine Input Uncertainty Importance
  - Identify problem drivers
  - Confirm that the model is behaving as expected
  - Identify inputs that may need refinement before final estimation of the QoI
  - Identify assumptions may be candidates for sensitivity studies (Step 4)
  - Identify candidates for more targeted sampling methods such as importance sampling

- Action 4: Conduct Output Uncertainty Analysis
  - Provide a final estimate, with associated uncertainty, of the QoI
  - Visualize results

Step 4: Sensitivity Studies to Assess the Credibility of Modeling Assumptions

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- Action 1: Determine a Set of Sensitivity Studies
  - Identify important assumptions that merit further scrutiny
  - Understand what might happen if these assumptions were changed

- Action 2: Conduct Sensitivity Studies and Present Results
  - Many different options for sensitivity studies, but same common elements
    - Reference realization (or baseline case) with a documentation of the QoI
    - One or several modified realizations illustrating the concept that needs to be represented
    - Comparison between the reference realization and the modified realization(s)
    - Comparison criterion to decide whether the change is significant
    - Conclusion, including potential consequences

Step 5: Draw Conclusions from Analysis Results

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- Action 1: Interpret Analysis Results
  - Synthesize the information gathered in Steps 1 through 4
  - Draw conclusions from the information
    - May be able to directly compare PFM results with an acceptance criterion
    - May need several analyses to create an evidence package

- Action 2: Iterate on the Analysis Process to Refine Model Results
  - Determine whether additional analyses are required to draw informative conclusions from the modeling
  - If results inconclusive, many possible paths:
    - Changing or clarifying aspects of the PFM code
    - Refining the input uncertainty distributions
    - Choosing a different sampling scheme or increasing the number of model realizations
    - Adding more sensitivity studies to address existing limitations

Detailed thoughts on a graded approach for PFM

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- PFM is complex
- The depth and breadth of a PFM analysis might vary widely depending on several factors
- It makes sense to take a graded approach…
  - …for PFM analyses themselves
  - …for the level of detail to be presented as part of an evidence package
- General Principles
  - Higher safety significance
  - Higher complexity
  - Higher level of novelty

- Topics Covered
  - Software QA and V&V
  - Models
  - Inputs
  - Uncertainty Propagation
  - Convergence
  - Sensitivity Analyses
  - QoI Uncertainty Characterization
  - Sensitivity Studies

- More analyses, more documentation
- Higher burden to create defensible and rigorous evidence

Software QA and V&V

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- Safety demonstrations for the NRC usually require that a QA program be in place
- Pre-submittal meetings are very useful to help ensure that everyone agrees on the graded approach path

Category	Description	Graded Approach
QV-1	NRC-approved code	
QV-1A	Exercised within validated range	Demonstrate code applicability within the validated range.
		Describe features of the specific application where the code is validated and applicable (i.e., areas of known code capability).
QV-1B	Exercised outside of validated range	Provide evidence for the applicability of the code to the specific application with respect to the areas of unknown code capability.
		Describe features of the specific application where the code has not been previously validated and applied (i.e., areas of unknown code capability).
QV-1C	Modified	Give an SQA summary and V&V description for modified portions of the code.
		Demonstrate that the code was not "broken" as a result of changes.
		Make detailed documentation available for further review upon request.
QV-2	Commercial off-the-shelf software designed for the specific purpose of the application	Demonstrate code applicability.
		Describe the software and its pedigree.
		Make software and documentation available for review upon request.
QV-3	Custom code	Summarize the SQA program and its implementation.
		Provide a basic description of the measures for quality assurance, including V&V of the PFM analysis code as applied in the subject report.
		For very simple applications, possibly provide the source code instead of standardized SQA and V&V.
		Include separate deterministic fracture mechanics analyses to support other validation results, as appropriate for a given application.

Models

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- Models could be addressed with the following graded approach
- Each model in a given PFM tool could potentially be categorized differently

Category	Description	Graded Approach
M-1	Model from a code in category QV-1A or QV-1B within the same validated range	Reference existing documentation for that model in the NRC-approved code, demonstrate that the current range of the model is within the previously approved and validated range, and demonstrate that the model functions as intended in the new software.
M-2	Model from a code in category QV-1A or QV-1B outside the validated range	See M-1, except demonstrate validity of the model for the new applicability range (document a comparison of model predictions for the entire new range to applicable supporting data, including quantitative goodness-of-fit analyses).
M-3	Model derived from a category M-1 or M-2 model	See M-2, and include a detailed description of changes to the M-1 or M-2 model, with justification for the validity of the new model.
M-4	Well-established model not previously part of an NRC-approved code	Describe gaps and limitations in the code capabilities for the analysis, combined with a strategy for mitigating identified gaps and communicating any remaining issues or risks.
		Describe the model(s) applied in the PFM analysis code in sufficient detail so a competent analyst familiar with the relevant subject area could independently implement the model(s) from the documentation alone. Model forms can either be theoretical, semiempirical, or empirical.
		Establish a basis for all significant aspects of the model(s). This may consist of raw data or published references. Document or reference any algorithms or numerical methods (e.g., root-finding, optimization) needed to implement the model(s). Discuss any significant assumptions, approximations, and simplifications made, including their potential impacts on the analysis.
		Identify important uncertainties or conservatisms.
		Describe the computational expense of the model and how that might affect analysis choices.
M-5	First-of-a-kind model not yet published in a peer-reviewed journal	See M-4, and perform and document model sensitivity studies to understand trends in the model, as compared to expected model behavior and to the data used to develop the model, and describe model maturity and the status of the technical basis.

Inputs

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Category	Graded Approach
I-1D	List input value.
I-1R	List input distribution type and parameters. If applicable, list uncertainty classification (aleatory or epistemic).
I-2D	List input value. If there is a lack of data, justify the use of expert judgment.
I-2R	List input distribution type and parameters. If applicable, list uncertainty classification (aleatory or epistemic). If there is a lack of data, justify the use of expert judgment.
I-3D	List input value. State the rationale for setting the input to a deterministic value. For each deterministic input, give the rationale (method and data) for the selection of its numerical value, along with any known conservatisms in that numerical value and the rationale for such conservatisms. Reference documents that contain the foundation for input choices. Explain the correlations between inputs and how they are modeled, and verify that correlated inputs remain consistent and physically valid. Describe any sensitivity analyses/studies performed to show that the input or its classification does not have a significant effect on the QoI.
I-3R	List input distribution type and parameters. If applicable, list uncertainty classification (aleatory or epistemic). If relevant, classify uncertain inputs as aleatory or epistemic and give the corresponding rationale. For each uncertain input, describe both its distribution parameter values and its distributional form. Give the rationale (method and data) for selecting each distribution, including any known conservatisms in the specified input distributions and the rationale for the conservatism. Detail the distributional fitting method, including interpolation, extrapolation, distribution truncation, and curve fitting. Reference documents that contain the foundation for input choices. Explain the correlations between inputs and how they are modeled, and verify that correlated inputs remain consistent and physically valid. Describe any sensitivity analyses/studies performed to show that the input or its classification does not have a significant effect on the QoI.
I-4D	See I-3D. If there is a lack of data, justify the use of expert judgment.
I-4R	See I-3R. If there is a lack of data, justify the use of expert judgment.

Input Category	Low Knowledge of Input Characteristics		High Knowledge of Input Characteristics	
	Deterministic	Uncertain	Deterministic	Uncertain
High Importance	I-4D	I-4R	I-3D	I-3R
Low Importance	I-2D	I-2R	I-1D	I-1R

Uncertainty Propagation

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- Each analysis within a larger PFM demonstration could potentially fall in a different category

Category	Description	Graded Approach
UP-1	Analysis does not employ a surrogate model	Give the method for uncertainty propagation and describe the simulation framework.
		If Monte Carlo sampling is used, describe the finalized sampling scheme and rationale for the sampling scheme, including sampling method, sample size, the pseudo-random number generation method, and the random seeds used.
		Describe the approach for maintaining separation of aleatory and epistemic uncertainties, if applicable.
		If importance sampling is used to oversample important regions of the input space, justify the choice of importance distribution.
UP-2	Analysis does employ a surrogate model	See UP-1 and describe the form of the surrogate model(s), any approximations or assumptions, the method used for fitting the surrogate, and the validation process for the surrogate model.
UP-2A	Surrogate model used for sensitivity analysis	See UP-2 and describe the features of the different surrogate models used.
UP-2B	Surrogate model is used for uncertainty propagation	See UP-2 and quantify the magnitude of error associated with the surrogate model approximation and include as additional uncertainty in the estimation of the QoI.

Convergence

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- Discretization convergence should be achieved to have valid results
- Statistical convergence graded approach for each analysis within PFM demonstration

Category	Description	Graded Approach
SC-1	[Acceptance criteria met with at least one order of magnitude margin] AND [no importance sampling AND no surrogate models used]	No sampling uncertainty characterization recommended as long as the uncertainty is sufficiently small relative to the margin.
SC-2A	[Acceptance criteria met with at least one order of magnitude margin] AND [use of importance sampling OR surrogate models OR both]	Describe the approach used for assessing statistical convergence, with one method needed for sampling uncertainty characterization.
		Explain the approach used for characterizing sampling uncertainty.
		Justify why the sampling uncertainty is small enough for the intended purpose (i.e., why statistical convergence is sufficient for the intended purpose).
		Describe how sampling uncertainty is used in the interpretation of the results.
SC-2B	[Acceptance criteria met with at least one order of magnitude margin] AND [use of importance sampling OR surrogate models OR both]] AND [separation of aleatory and epistemic uncertainties is implemented in the PFM code]	See SC-2A, and distinguish between epistemic and aleatory means and standard deviations.
SC-3A	[Acceptance criteria met with less than one order of magnitude margin]	See SC-2A, and provide two different methods for sampling uncertainty characterization.
SC-3B	[Acceptance criteria met with less than one order of magnitude margin] AND [separation of aleatory and epistemic uncertainties is implemented in the PFM code]	See SC-3A and give a sample size convergence analysis for both the aleatory and epistemic sample sizes.

Sensitivity Analyses

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Category	Description	Sensitivity Analysis Needed?	Graded Approach
SA-1	Previously approved code (QV-1, QV-1A) with same QoI and same inputs	No	Describe important input and measure of input importance from previous use.
SA-2	Previously approved code (QV-1, QV-1A) with different QoI	Yes	Explain the methods used for sensitivity analysis, including any initial screening and model approximations and assumptions.
			State whether a local or global sensitivity analysis approach is used.
			Give the QoI used for the sensitivity analysis.
			For a global sensitivity analysis, describe the sampling scheme along with the rationale for selection, including the sampling technique, number of model realizations, and random seed for the model realizations.
			Provide the results of the sensitivity analysis, including the most important model inputs identified; a measure of the input importance, such as the variance explained by the most important inputs; and relevant graphical summaries of the sensitivity analysis results.
SA-3	Modified approved code with limited independent variables (e.g., <5, determined on a case-by-case basis)	Yes	Describe analyses, important input, and measure of input importance.
SA-4	Modified approved code with many independent variables (e.g., >5, determined on a case-by-case basis)	Yes	See SA-2.
SA-5	First-of-a-kind code with limited independent variables (e.g., <5, determined on a case-by-case basis)	Yes	Describe the analyses, important input, and measure of input importance and include additional documentation.
SA-6	First-of-a-kind code with many independent variables (e.g., >5, determined on a case-by-case basis)	Yes, with submodel SA as appropriate	See SA-2.
			Indicate how the sensitivity analysis results informed future uncertainty propagation for estimation of the QoI and associated uncertainty.
			State whether the results of the sensitivity analysis are consistent with the expected important inputs based on expert judgment.

QoI Uncertainty Characterization

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Category	Description	Graded Approach
O-1	Acceptance criteria met with at least one order of magnitude margin	Give a measure of the best estimate and uncertainty in the QoI.
		Include a graphical display of the output uncertainty.
		Describe how the best estimate and its uncertainty were calculated, including a clear description of the types of uncertainty (e.g., input, sampling, epistemic) being summarized.
		Summarize key uncertainties considered in the analysis and any major assumptions, conservatisms, or simplifications that were included and assess (qualitative or quantitative) their effect on the analysis conclusions.
O-2A	Acceptance criteria met with less than one order of magnitude margin and a strong basis for input distributions and uncertainty classification	See O-1 and provide the reasoning behind a strong basis.
O-2B	Acceptance criteria met with less than one order of magnitude margin and no strong basis for input distributions or uncertainty classification, or both	See O-1.
		Include a sensitivity analysis (if important inputs are unknown) and sensitivity studies for any inputs that do not have a strong basis.
O-3	O-1, O-2A, or O-2B and potential unknowns	See O-1, and provide the reasoning behind a strong basis. Describe potential unknowns and their possible effect on analysis results.
		OR
		Include a sensitivity analysis (if important inputs are unknown) and sensitivity studies for any inputs that do not have a strong basis.

Sensitivity Studies

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Category	Description	Sensitivity Study Needed?	Graded Approach
SS-1	Category QV-1A code with same QoI	No	Summarize sensitivity studies conducted in prior approval.
SS-2	Category QV-1A code with different QoI	Limited, focused on inputs related to QoI	Summarize past sensitivity studies conducted in prior approval and current sensitivity studies.
SS-3	Category QV-1B or QV-1C code with limited independent variables (e.g., <5, determined on a case-by-case basis)	Limited, focused on impact of modification	Summarize past and current sensitivity studies.
SS-4	Category QV-1B or QV-1C code with many independent variables (e.g., >5, determined on a case-by-case basis)	Yes, focused on inputs related to QoI	Summarize past and current sensitivity studies. List the uncertain assumptions that are considered for sensitivity studies. State the impact and conclusion of each sensitivity study. Give the rationale for why certain assumptions were or were not considered for sensitivity studies. Provide the specific question(s) each sensitivity study is attempting to answer. Describe a reference realization. Describe how each sensitivity study is translated into model realizations, and compare the study and the reference realization. List changes to the code and the QA procedure used.
SS-5	Category QV-2 or QV-3 code with limited independent variables (e.g., <5, determined on a case by case basis)	Yes	See SS-4.
SS-6	Category QV-2 or QV-3 code with many independent variables (e.g., >5, determined on a case by case basis)	Yes, model and input studies	See SS-4.

Next Steps

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- NRC will publish draft regulatory guidance and an accompanying draft technical basis NUREG, both for public comments
- NRC will gather public comments on the draft guidance and draft NUREG
- NRC will address all comments received
- Public meetings may take place, if needed
- At least one more ACRS briefing on the topic of PFM and PFM regulatory guidance is expected in the future

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Use of PFM Guidance

A technical reviewer's perspective

July 20, 2021

David Dijamco
Office of Nuclear Reactor Regulation
Vessels and Internals Branch

Objective

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The NRC received a submittal from Vogtle using PFM as technical basis; pilot the PFM guidance (unpublished, draft, pre-decisional) during the review of this submittal.

Objective of this presentation is to share thoughts on:

- How the review went (with a focus on the draft guidance).
- How was the draft guidance helpful? What did we learn from its use?

Background

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EPRI initiated an NDE optimization program that sought to increase the inservice inspection (ISI) intervals of certain Class 1/Class 2 components from 10 to 30 years. Issued a series of publicly available reports as a result of this effort:

- EPRI report 14590 (ML19347B107) – steam generator nozzles
- EPRI report 15905 (ML21021A271) – pressurizer vessel shell welds
- EPRI report 15906 (ML20225A141) – steam generator vessel shell welds
- EPRI report 18473 (ML21091A014) – BWR RHR heat exchanger welds and nozzles

Center piece is probabilistic fracture mechanics (PFM).

Vogtle Units 1 and 2 submittal

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- Alternative request to increase the ISI interval of steam generator welds and nozzles from 10 to 30 years. Referenced EPRI report 14590 as technical basis.
- Submittal:

  ML19347B105 – Dec. 2019

  ML20253A311 – revised/supplemented Sept. 2020
- NRC safety evaluation:

  ML20352A155 – Jan. 2021

Note: The NRC did not review EPRI report 14590 and the other EPRI reports for generic use.

EPRI Report 14590

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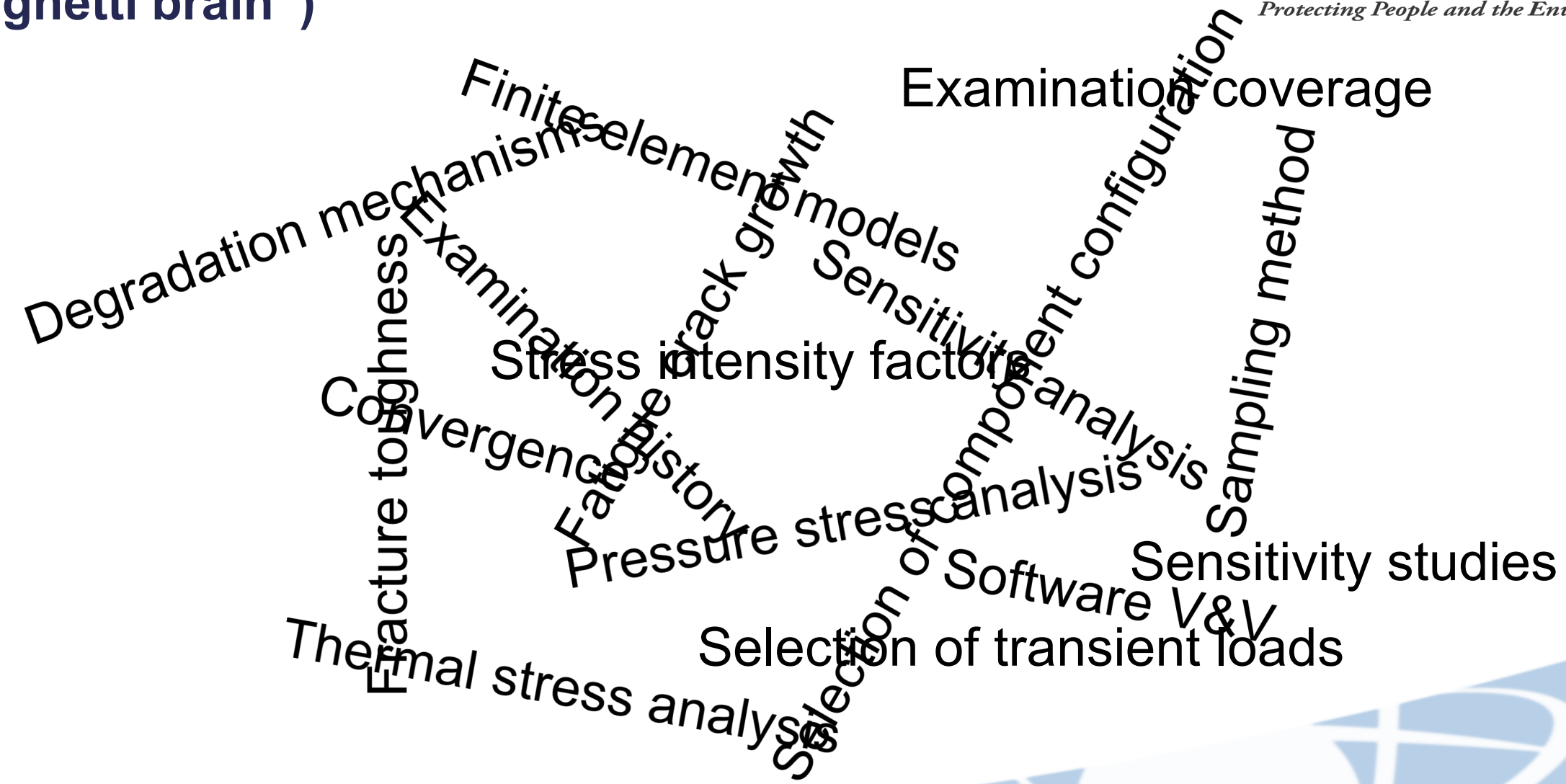
- Referenced technical basis for the Vogtle submittal for steam generator nozzle-to-vessel welds and nozzle inside radii

- Extensive report, nearly 200 pages, lots of technical topics (PFM is only one of several chapters)

My brain after going over EPRI Report 14590 ("spaghetti brain")



Main question as a technical reviewer was:

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How do I review the submittal???

PFM Guidance

Draft Regulatory Guide + Draft NUREG-7278

(both unpublished, still under internal review)

How did the guidance help?

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- At the time of the Vogtle review, details of graded approach were still under development (and are currently under internal review)

- But it had enough of a framework for me to work with, especially the sections on the suggested content of PFM submittals.

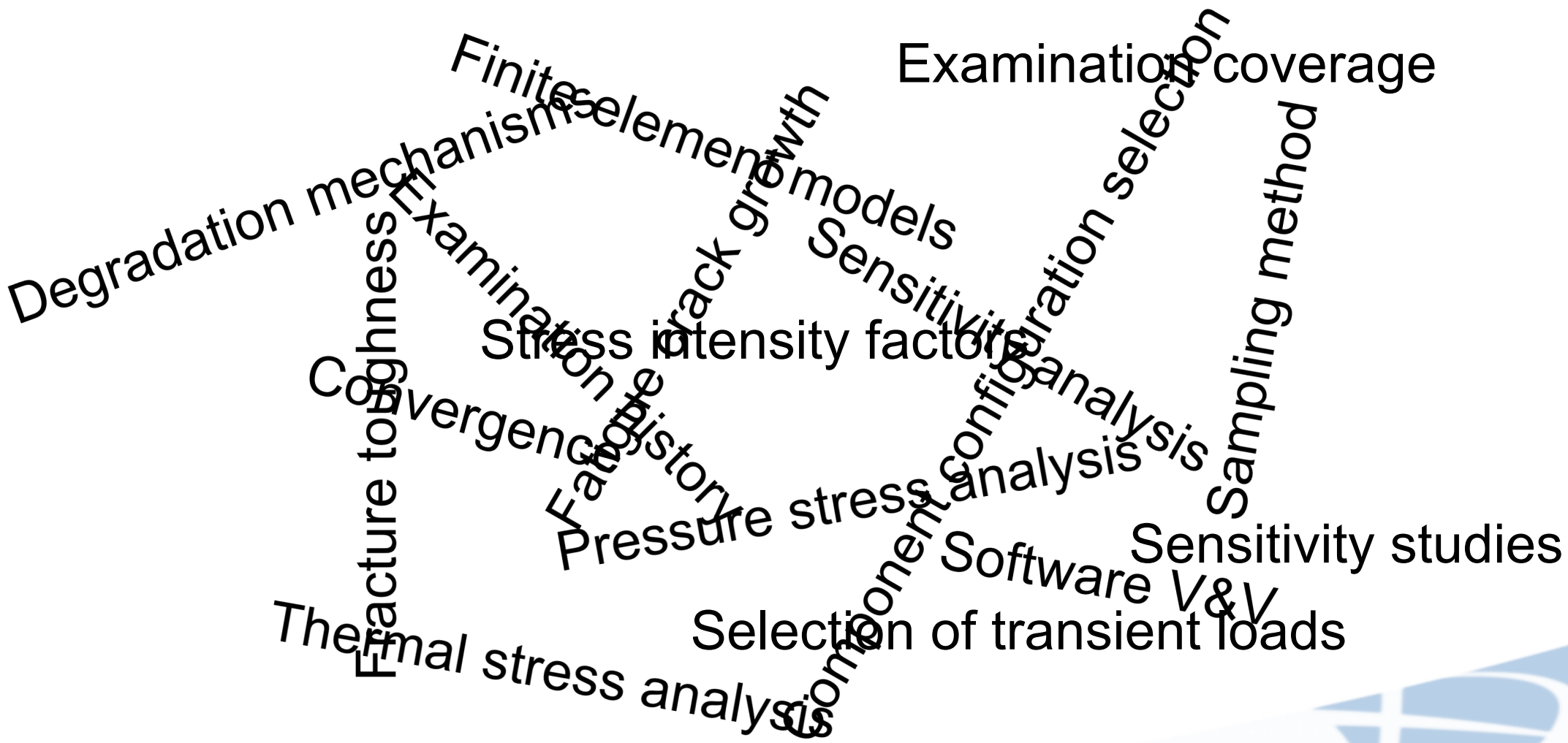
  (Note: EPRI white paper on PFM submittals (ML19241A545, publicly available) was very helpful in crafting the draft graded approach.)

1. The (draft, pre-decisional) PFM guidance helped me put a framework around the various topics, thus organizing my review.

Topics covered in the guidance

- Models
- Inputs
- Uncertainties
- Sensitivity analyses
- Sensitivity studies
- Convergence
- Software V& V

Without PFM Guidance



With PFM Guidance

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Degradation mechanisms
- Fatigue crack growth

Component configuration selection

Stress analysis
- Selection of transients
- Finite element models
- Pressure stress analysis
- Thermal stress analysis

Deterministic fracture mechanics
- Stress intensity factors
- Fracture toughness

Probabilistic fracture mechanics
- Examination coverage
- Sensitivity studies
- Sensitivity analysis
- Sampling method
- Convergence

Software V&V

Outline of safety evaluation of the Vogtle submittal

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- 3.8.1 Overall PFM Approach (acceptance criteria, sampling method, etc.)
- 3.8.2 Parameters most significant to PFM results
- 3.8.3 Stress analysis
- 3.8.4 Fracture toughness
- 3.8.5 Flaw density
- 3.8.6 Fatigue crack growth rate
- 3.8.7 ISI & examination coverage
- 3.8.8 Other considerations (probability of detection, SIF models, V&V, etc.)
- 3.8.9 PFM results relevant to Vogtle's request

Overall efficiency gained in submittal/review process

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The (draft, pre-decisional) PFM guidance…

- helps the industry prepare submittals that have a consistent level of quality
- helps the NRC review the submittals

2. The (draft, pre-decisional) PFM guidance helped me understand sensitivity analysis (SA) and sensitivity studies (SS) and their importance in the interpreting the PFM results.

Both the (draft, pre-decisional) regulatory guide and (draft, unpublished) NUREG-7278 cover these topics.

3. The (draft, pre-decisional) PFM guidance supports knowledge management.

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- Draft Chapter 4 of NUREG-7278 contains a compendium of methods for establishing confidence in a PFM analysis

- A boon to all stakeholders, especially as we move more and more toward RIDM of which PFM is only a part, but it's an important part.