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ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

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UNITED STATES OF AMERICA

NUCLEAR REGULATORY COMMISSION

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ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

(ACRS)

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METALLURGY AND REACTOR FUELS SUBCOMMITTEE

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WEDNESDAY

NOVEMBER 17, 2021

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The Subcommittee met via Video Teleconference, at 1:00 p.m. EST, Ronald Ballinger, Chairman, presiding.

COMMITTEE MEMBERS:

RONALD G. BALLINGER, Chair

DENNIS BLEY, Member

CHARLES H. BROWN, JR. Member

GREG HALNON, Member

DAVID PETTI, Member

JOY L. REMPE, Member

ACRS CONSULTANT:

STEPHEN SCHULTZ

DESIGNATED FEDERAL OFFICIAL:

ZENA ABDULLAHI

ALSO PRESENT:

MICHELLE BALES, RES

JAMES CORSON, RES

ALADAR CSONTOS, Public Participant

JOSEPH DONOGHUE, NRR

KIMBERLY WEBBER, RES

P R O C E E D I N G S

1:00 p.m.

CHAIR BALLINGER: The meeting will now come to order, this is a meeting of the Materials in Metallurgy and Reactor Fuels Subcommittee of the Advisory Committee on Reactor Safeguards. I'm Ron Ballinger, Chairman of today's Subcommittee meeting.

ACRS Members in attendance are Charles Brown, Greg Halnon, Joy Rempe, I have to go down here, Dave Petti, and if I've missed somebody I'm sure I'll hear about it.

We have our consultant also in attendance, Steven Schultz. There may be others that will chime in. Judging from the list of attendees, there's a fair amount of interest here.

The purpose of this meeting is for the Staff to brief the Subcommittee on the regulatory information letter RIL 2021-13, interpretation of research on fuel fragmentation, relocation and dispersal at high burnout.

The Subcommittee will hear presentations and buy and hold discussions with the research Staff on this matter. A number of other people have just chimed in, not yet, okay.

By way of background, the RIL is an update

to work in this area that depending on how old you are, it's been ongoing for at least 40 years and Steve Schultz says 50, related to cladding and brittle performance during LOCA.

And then more recently, in the early 2000s, evolving to fuel fragmentation and dispersal at high burnup.

There have been a number of documents that have been released, NUREGs, another RIL previous to this, 0801, and the latest to my knowledge fuel fragmentation relocation and dispersal was NUREG 2121.

The ACRS has also issued a number of letters related to this as well as embrittlement. The latest one related to draft final rule of 5046C, which is still under consideration by the Commission.

This RIL is a little bit unusual to my mind because it not only summarizes research that's been done in the past and does analysis on the results, but also in Appendix A suggests a model that might be used to accommodate that.

In effect, reset the burnup initiation time from about 65 gigawatt days for metric tons -- sorry, I'm getting old -- to around 55. So, there's a fair amount of meat in this that will be fruits for discussion.

The ACRS was established by statute and is governed by the Federal Advisory Committee Act, FACA. That means the Committee can only speak through its published letter reports. We hold Subcommittee and full Committee meetings to gather information to support our deliberations.

I might add that since it's a Subcommittee meeting, the opinions of the members are just that, personal opinions.

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

The interested parties who wish to provide comments can contact the office requesting time. I think we have had a request for a public comment from at least one member of the public.

Closed meeting transcripts are not posted to protect any information that might be proprietary. The Subcommittee will gather information, analyze relevant issues and facts, and formulate proposed positions.

The full Committee for the research is scheduled to be held during December full committee

meeting, which is scheduled for November 30th through December 3, 2021. The transcript of the meeting is being kept and will be made available as stated in the Federal Register notice through the COVID-19 pandemic.

Today's meeting is being held over Microsoft Teams. For NRC Staff and the stakeholder and public attendees, there's also an MS Teams telephone number that allows participation of the public to make comments in the comment period specified in the posted agenda.

When addressing the Subcommittee, participants should first identify themselves and speak with sufficient clarity and volume so that they may be readily heard. When not speaking, we request that participants mute their MS Teams microphone or phone number.

We will now proceed with the meeting. Let me call on I think Kim Webber hopefully? Yes, Kim Webber, the Director of the Division of Systems Analysis of the NRC's Research Office to deliver her opening remarks.

MS. WEBBER: Yes, thank you, Chair Ballinger, ACRS Members.

It's really a pleasure to be here. Just for the record, my name is Kim Webber, I'm the

Director of the Division of Systems Analysis and we're here to talk to you today about the research information letter, or RIL, that's related to fuel fragmentation, relocation, and dispersal, or FFRD.

The presentation is timely as it addresses the performance of high burnup fuel at a time when industry is interested in pursuing licensing of current fuel designs to higher burnups.

And as you can see and as you noted in your opening remarks, we have many industry representatives and members of the public who have interest in this topic.

So, it's good to see the broad interest and participation in today's meeting.

The Office of Nuclear Regulatory Research, or RES, has sponsored research of the behavior of high burnup under loss of coolant conditions for over two decades. I think you pointed out that the research has been ongoing for even longer than that.

Over the last 10 years, the research has increasingly focused on FFRD so today you'll hear from the Staff about recent research which addresses phenomena in which high burnup fuel has been observed to fragment, relocate within the fuel rod, and disperse into the coolant under loss of coolant

conditions.

The RIL is an NRC document and specifically an Office of Research document that communicates research findings between the Staff in RES and other offices. In this particular case, the RIL summarizes and communicates to NRR the available research on FFRD.

And it provides insights regarding the bases for empirical limits. In the past, RILS have been used to support the development of regulatory guidance and for this situation, the determination to develop guidance associated with high burnup and/or FFRD lies with NRR.

My Staff have worked very closely with their counterparts in NRR to discuss the body of research and the information that you will hear in today's presentation.

We hope that in some way this will help the licensing reviews of high burnup fuel in the future. Before turning the presentation over to the Staff, I want to say a few words about the third phase of the cladding integrity program, or SCIP-III.

The SCIP-III program is one example of a timely research investment that resulted in findings that directly address the open regulatory safety

questions. It's a multi-party international research program that allows NRC to accomplish complex research in a highly leveraged way, both in terms of cost and expertise.

For some topics addressed in the RIL, the Staff incorporated conservatisms or stop short of proposing a specific limit due to limited information in the research. Many of these topics are being investigated in the SCIP-III program, of which NRC is a member.

The research conducted under the SCIP program is proprietary to the members involved in that program, however, the NRC sought permission from the SCIP-III Management board, which granted our request very recently to site-specific SCIP-III results in the RIL.

And so prior to a week or two ago, this information was not yet available to be published and discussed publicly.

But we're grateful to the program and to the Management Board because it enables us to make the RIL publicly available, providing maximal transparency about the research on this important topic.

And so with that, I'd like to turn the presentation over to Michelle Bales.

MS. BALES: Thank you, Kim, I appreciate those introductory remarks from both the Chairman and from Kim. I'm going to now share my screen for the presentation. Can you see the presentation?

CHAIR BALLINGER: Very well.

MS. BALES: Okay, perfect. My name is Michelle Bales and I will be starting the presentation today and then turning it over to colleague who also works with me in the Office of Research in a few slides.

So, I'll today be presenting the research information letter 2021-13. It's an interpretation of research on fuel fragmentation, relocation, and dispersal at high burnup.

The controls are a little bit different than I expected. Today's presentation, I'll start with a brief regulatory history of FFRD at NRC, some of which has been mentioned in the introductory remarks.

I'll then spend some time talking about the program cited in the RIL and the peer review process that we used. I'm then going to speak to the outcome of the RIL, in other words what the RIL makes possible in terms of safety analysis.

And after doing that, I will go back and

speak about each empirical threshold and the basis for it as documented in the research information letter. There are a few other matters that we'll cover at the end and then we will be wrapping up.

So, first, FFRD history at the NRC. The first mention of fuel relocation and dispersal in a regulatory context was in 2008 with the issuance of RIL 0801.

This RIL was written just after fuel dispersal was first observed in the Halden Reactor Project on a road with over 90 gigawatts of data per time.

The RIL 0801 discussed axial fuel relocation and the loss of fuel particles through a rupture opening, and recommended further research in these areas. However, at that time it was documented expected phenomena were occurring at burnups well above current operating limits.

In 2012, the Staff conducted an extensive literature review and published NUREG 2121. This literature review captured the results of over 90 LOCA tests performed in 8 different programs over 35 years.

Putting all of that information together, the Staff concluded that the occurrence of FFRD couldn't be precluded during the LOCA and really

required additional research.

In 2015 the Staff was in the middle of rulemaking for loss of coolant accidents in the 5046C rulemaking. And the Staff wrote a secy informing the Commission that we did not plan to include or address FFRD in that rulemaking.

But SECY also documented the Staff's evaluation of FFRD and our basis for not including FFRD in the proposed rulemaking.

At that time, the Staff also concluded that immediate regulatory action was not needed to address FFRD, however, as stated in that SECY, the conclusion was closely linked to existing fuel design limits and assumptions on how high burnup fuel would be operated.

That brings us to today where the Staff has written a new research information letter to document the interpretation of fuel fragmentation, relocation, and dispersal at high burnup.

We choose to do this now because industry is pursuing extension of fuel design limits and also because a large body of research has become available. Documenting NRC's interpretation of available FFRD research provides regulatory predictability and technical review consistency.

So, now I'll go into a little bit of background on the program cited in the RIL and the peer review process used. With this illustration, I want to communicate that we've learned a lot about FFRD since the 2015 SECY.

The 2015 SECY is shown on this bottom timeline and you can see that both the SCIP-III program and a program at Oak Ridge started and finished since the SECY was issued.

The circles that you see are scaled to the size of the program and the shading indicates whether results have been public prior to the RIL, or solid shading indicates that results are in the public domain.

As Kim mentioned in her introductory remarks, prior to the RIL, the SCIP-III data was completely proprietary towards members and therefore, the publication of this RIL marks the first time this information will be in the public domain.

MEMBER REMPE: Michelle, this is Joy. If you'll go back a slide? Again, there's a lack of reduction in prototypic-ness when you go out of pile, isn't there? Can you kind of give us a feel for what phenomena are considered?

Like radiation effects when you're in

Halden versus what you would get from the Studsvik and the Oak Ridge test.

MS. BALES: Yes, I have a slide coming up that provides some information on the hot cell setup, which is actually very similar between the SCIP, Oak Ridge and NRC's program.

So, when I get to that slide I'll be sure to come back to that point because it's important that some of the features of the test should be well understood as we look at their results.

MEMBER REMPE: That's fine, whenever it's appropriate is great. Thank you.

MS. BALES: I will come back to it. I wanted to say a few words about our peer review group because a peer review is not always part of --

(Telephonic interference.)

I don't know if I just got feedback but it sounded like someone was asking a question.

CHAIR BALLINGER: I would remind people to keep their computer muted. Thank you.

MEMBER REMPE: So, peer review is not a necessary part of a research information letter but when we look at the data resources and their recency of the data, I want to explain that the nuclear fuel community has not yet developed consensus around FFRD

phenomenon.

Significant research is still ongoing and there's active work trying to develop a mechanistic understanding of FFRD.

So, as you wrote the RIL, we recognized that the empirical limits that we were proposing are not consensus-based, mechanistic, or physics-based models, but rather they represent the interpretation of available data at this time from a safety authority perspective.

Considering this, we wanted to pursue a review and solicit perspective outside of NRC. So, we specifically select reviewers with extensive familiarity with FFRD research at national labs, international labs, at national regulatory bodies, as well as EPRI.

The peer reviewers were asked to identify relevant research results that we might have missed to identify alternative interpretation of the research results presented in the RIL and identify gaps and inadequacies of the basis that we proposed.

Ultimately, I want to make it clear that the Staff was responsible for the positions taken in the RIL and we were not subject to the peer review in the sense that they could counter what we were saying.

At the end of the day, there were some instances where the Staff took a conservative position based on our perspective, but we took the comments that we received from the peer review very seriously.

And as a whole, the peer review process significantly strengthened the document.

The peer reviewers provided very thoughtful and detailed comments, they made us go and sharpen our pencils in a number of areas, and in one highlight I want to put in is in the RIL you'll see a definition in the terms section now.

And I think that really came out of the peer review where many of the reviewers wanted us to be more definitive about this new terminology that we were introducing in the RIL.

In the RIL, there's an appendix which we will keep when it's finally published that summarizes the peer review comments as well as the resolution. So, it's written at a high level but that is included in the publication to provide some transparency for the peer review process.

So, as we move into the meat of the presentation, I'm actually going to speak about the outcome of the RIL before I speak to the basis for each of the thresholds in the RIL.

It's critical to communicate at a high level how the RIL supports targeted safety evaluations so I'm going to do that first. And Joy, this is the slide that I mentioned. I'm going to say a few words about the experimental methods used in all of the hot cell testing programs.

I don't have a similar slide for Halden but I'll speak to it a little bit as I walk through the slides.

The RIL actually provides a short orientation to test procedures in each of the programs that are discussed because some details of these tests are important to understand before examining the results.

The majority of the test programs that we cite were conducted in a hot cell and subjected to a time temperature profile similar to the one in the lower right-hand corner of the slide.

Test segments were placed in accordance and heated in a clamshell furnace with four heating elements. Again, this is characteristic of the hot cell programs. In the Halden reactor, individual rods were placed in a closed loop.

There were heaters, electrical heaters in that loop but the whole entire loop was placed in the

core and the fuel rods were operated at low power prior to the transient, so that means that the fuel was producing decay heat during the LOCA transient.

So, in the case of the hot cell tests, all of the heat that was experienced by the rod is from external heaters and the thermal couple on the cladding really set the furnace profile to target a specific cladding temperature transient.

CHAIR BALLINGER: Michelle, this is Ron.

I have discovered painfully that knowing the temperature gradient around the cladding is important for these tests and when you use a quadalyptic furnace, which is what this looks like, and you ramp it up very quickly, are people sure -- I'm assuming this is a SCIP thing.

Are they sure the temperature around the cladding is uniform? Because in past times, when people have done oxidation experiments they've discovered that for this type of furnace, you get kind of a scalloped oxide thickness around.

And you can take an average but it's not really representative of what you're saying. The helical texture that's in the zircaloid tubing combined with if there's an uneven temperature around the circumference can complicate things.

MS. BALES: So, I can speak to the SCIP program. Before launching their irradiated testing program, they did a lot of benchmarking of the equipment, and that included some measurements of the circumferential temperature profile.

They also looked at oxide measurements after significant transients to look at whether there was any scalloping or non-uniformity. So, the equipment was qualified to produce sufficiently consistent and uniform circumferential temperatures.

I guess there was a possibility that individual tests that were done long after that calibration was performed might have some unique effects.

In some cases, some of the rods experience bending after rupture, for example, in which case once the rod goes off center, you can't confirm the uniformity of the heating.

But I think that would be a unique situation that we can look at to explain anomalies. But generally, the equipment was looked at for that and confirmed to not have any significant deviations that would affect the results.

CHAIR BALLINGER: Because that usually translates into an uncertainty bar on the temperature

versus time because the average sometimes does not reflect the dispersion. Anyway, okay, thank you.

MS. BALES: I will say that in this phenomenon, cladding temperature is not the most critical part of the test.

That is certainly important for predicting whether rupture occurs and the moment of rupture, but as we go into the phenomenon that we're looking at of relocation and dispersal, any non-uniformity of the heating is probably going to be in the noise relative to the things we're trying to measure.

Once you get above 760 which is the base transformation, all the entropy goes away anyway I suppose.

MS. BALES: The other things I wanted to point out about the hot cell test are that the test segments are about 30 to 50 centimeters. This includes the Halden test and Powell was also similar in length.

And the hot cell test but also the Halden test were re-pressurized. They were segments cut from commercially irradiated rods, repressurized through a pressure line to various conditions dependent on the test design.

So, as I said, I don't have a picture of

the setup in the Halden reactor in this slide deck but the RIL very briefly mentions this and we can speak about it maybe separately if there's a lot of questions about it.

There's been some work done to look at the temperature profile across the cladding and across the pellet in comparing hot cell tests and Halden tests.

And while obviously the hot cell testing started the rod cold and there's a big difference between what the rod temperature profile looks like before the test.

There is some analysis that is showing the temperature profile after about 20 seconds in the transient is very similar between hot cell tests and irradiated tests.

And particularly when you look just at the temperature profile and it's ability to introduce thermal gradients.

So, even if the absolutely temperature is a little bit different, the fact that it's flat means that the thermal stresses that would be induced across the pellet should be pretty similar even for the hot cell test and in-cell test.

As we get into further, that is part of are understanding of the mechanism, that the

temperature profile across the pellet would impact or could impact fragmentation.

So, I don't know if that was as much as you wanted know or if you have any other questions about the test setups. There's a little bit of discussion about this in the RIL but are there other things that I should mention or that you'd like to address before I go on?

MEMBER REMPE: Not at this time. Again, it was something that puzzled me as I reviewed the RIL and I'll ponder it a bit more if I have more questions. But thank you.

MS. BALES: The test that I'm referring to, they produce images of fragmented fuel, sometimes fragments that are quite small in size. Dispersal was observed in many of these tests.

Looking at the result separately, it can seem that something alarming is happening at some unknown point and it may at first seem intractable. However, as documented in the RIL, a large body of research is available to understand when this happens.

There is also repeatable and conforming basis for clear and empirical limits. The RIL provides the basis for when FFID does not occur and allows for a well focused analysis of a relatively

small region of the core vulnerable to FFRD.

So, that brings me to the main outcomes of the RIL. The Staff examined available research in order to address five elements of FFRD. First, a threshold for when fine fragmentation begins.

Next, a threshold for when we can expect fuel axial relocation. We also sought to quantify a model for predicting the amount of dispersal that you might expect as a function of burnup.

The RIL also documents the phenomenon of transient fission gas release distinct from the steady state fission gas release that is already well modeled. And finally, quantifying packing fractions of axially relocated fuel in a balloon region.

So, putting these elements together, the RIL forms the basis for targeted analysis of only select rods that are of concern for FFRD. This is a fundamental outcome of the RIL and therefore, I will describe this outcome first and return to the basis for each element after that.

To communicate how the RIL supports targeted analysis, I will use an oversimplified schematic to depict the rod population of an LWR core.

The schematic represents each assembly at a given time in mind by its average burnup on the X

axis and operating power on the Y axis.

Burnup is a key parameter in FFRD phenomena as I will explain. An operating power prior to the start of a LOCA is a key determinant for whether a rod will balloon and rupture, which is another key parameter in FFRD phenomenon.

The RIL provides a basis to conclude that only rods over 55 are susceptible to fine fragmentation. The RIL also provides a basis to conclude that only rods with strains greater than three percent are susceptible to axial fuel relocation.

Therefore, only high burnup rods with an operating power prior to the transient that is high enough to result in ballooning presented concerns for relocation.

Since fine fragmentation and axial relocation are precursors to fuel dispersal, only fuel rods within this box are a concern for dispersal. In this schematic that I'm showing here, there's only a few rods that end up in this dispersal box.

However, the number of rods in this box is highly dependent on core design, fuel design, and plant characteristics. This box could be considered just one of many factors that would influence core

design.

As you saw in the animation, there's other core design maps that might have relatively lower heat generation rates or have differences in how second cycle and third cycle fuel rods are operated and may have no overlap between the core loading map the region of concern for FFRD.

MEMBER PETTI: This is Dave, I had a question.

I understand this, it just seems the way the rule is written, it mentions 55 as the burnup but that's just sort of a necessary but not necessarily sufficient metric to characterize if you've got an issue.

And that doesn't come through as strongly as what you just talked about here verbally with us. When they read 55, people are going to go 62 is the limit and now you're saying it's 55.

You're not really saying that, you're saying that's just the first conditions is these other things that could impact.

MS. BALES: It's an excellent point and I think what we need to focus on is the RIL clearly states that fine fragmentation, and I'm going to show some results to demonstrate this, has been seen as

early as 55.

Fine fragmentation in and of itself is not obviously presented as a safety concern. If that fuel disperses, that's when you start to need analysis to confirm safety. In order to disperse, there has to be ballooning and rupture.

So, a high burnup rod above 55 that doesn't balloon and doesn't rupture, you won't have relocation or dispersal. And it's really the dispersal that should be the focus of the safety evaluations and relocation.

But I think your point is right that in the RIL we tried to explain that fine fragmentation and relocation are precursors to dispersal.

But perhaps it's not as clean, as I'm walking through it now, that the 55 for fine fragmentation only is not by itself the issue.

MR. SCHULTZ: This is Steve Schultz. Can you hear me?

MS. BALES: Yes.

MR. SCHULTZ: You also mentioned the strain number that was identified in the RIL associated with the small-sized fragmentation. What you seem to be showing here are fuel rods that are at power levels in the core.

And I presume what you showed in terms of the data set that's included at that strain level is for the assumed LOCA strain, in other words during the transient. Is that correct?

MS. BALES: Correct, you mean as opposed to operating?

MR. SCHULTZ: Yes.

MS. BALES: Yes, the strain that we're speaking about that is a precursor to relocation is a strain that occurs during the transient.

MR. SCHULTZ: And that's of course in terms of what you're showing here like the burnup limit value? That's affected by the assumptions and the evaluation of the LOCA transient and the dynamics of the fuel performance in the LOCA.

MS. BALES: Yes, I think the schematic is really an illustration to describe the zones at a very high level. But I think when we get into the technical basis we can speak a little bit more cleanly about what is precisely changing between relocation and dispersal.

But one of the things that I was trying to communicate with this, you see this box, any fuel rods above 55 are potentially rods that can finally fragment.

But when we look at defining the box for relocation, the horizontal line is my attempt to communicate that only rods that are hot enough to undergo ballooning would experience relocation.

So, on the left there's an image that shows the strain limit which I haven't presented yet but we'll get to in a second.

But the fact that the box has a horizontal line to only include rods with high enough power to strain under a LOCA is to communicate that this relocation box is less than the population of rods above 55 and subject to fine fragmentation.

And without seeing the boxes overlap, if you just watch the figure, the dispersal box is slightly higher, the idea that the difference between relocation and dispersal.

There are some rods that are predicted to balloon but not rupture. The dispersal box is intended to only include rods which are predicted to rupture.

MR. SCHULTZ: Thank you.

CHAIR BALLINGER: This is Ron again. I keep wondering whether we need to be a little bit careful in that the observed behavior is what it is, it's observed.

But a calculation for the LOCA calculation is at least Appendix K or is a stylized calculation where there's a lot of conservatism built in.

And so do we need to be careful that the stylized calculation, if that's what it is, doesn't get us burst or greater than 3 percent strain when that's due to the conservatism in the calculation that's built in.

MS. BALES: I think that's an excellent point and I want to explain that the meat of the RIL, well, the entirety of the RIL is focused on when this phenomenon has been observed in testing, and it's trying to establish empirical limits to define when FFRD will occur.

Everything that I'm presenting now is really just in service of communicating that we're not talking about the entire core, that we're not even talking about all high burnup rods.

But the schematic is a complete oversimplification not only of a core loading map, but also to what you're saying, where that horizontal line cuts off is going to be extremely complicated to calculate.

It's not easy to draw that lower line of the box, that is dependent on the calculation method,

the conservatisms used. And so the RIL doesn't attempt to define a ballooning model, for example, or attempt to draw that bottom leg of the box.

I'm using it in its presentation because I want to communicate that the RIL is linked to analysis but as we go into the technical basis, and we'll spend more time over there, that's really the meat of the RIL.

What has research shown in terms of the onset of these phenomena?

CHAIR BALLINGER: I'm sure we'll further discuss this.

MS. BALES: So, there's just two more points that are addressed in the RIL that I wanted to walk through the schematic to illustrate.

Again, it's just a schematic and it only serves to explain the implications of the RIL, it's just an illustration.

Trained fission gas release is another thing that's addressed during steady state operation, diffusion-based fission gas release is expected and it's very well modeled by fuel performance codes.

However, transient testing has shown that significant additional gas release can occur during the transient, changing the rod internal pressure.

The rod internal pressure is critical for actively predicting whether rods burst when subject to LOCA conditions.

And therefore, accounting for transient fission gas release is critical for defining the dispersal box. So, I think this further emphasizes your point, whether the models are accounting for transient fission gas release affects replacement of this box.

Whether the models are accounting for other factors in a conservative or best-estimate way will affect the positioning of this box.

The final element the RIL addresses is packing fraction and so this is particularly important for rods where they're above the burnup limit so we expect fine fragmentation.

They experience some ballooning and the fine fragmentation can fall into the ballooned region.

Accurately accounting for that phenomenon and having a density of relocation or packing fraction is important for accurately predicting whether the rod bursts because temperature is a critical element in those predictions.

Also, even if the rod is not predicted to burst, it's important that some accounting for

relocation and packing fraction values are used in a calculation of peak cladding temperature because that is a key metric in LOCA evaluation.

So, in summary, with that said on the slides, I wanted to communicate that the RIL forms the basis for targeted FFRD analysis. Only rods with the following characteristics are a concern for FFRD.

Fine fragmentation, we have not seen it below 55, for axial relocation we haven't seen cladding with less than 3 percent strain. Fuel dispersal requires axial relocation and therefore can be limited to rods that are above 55 and strained more than 3 percent.

But dispersal itself can't happen unless there's rupture so also, the calculation of the rupture event is critical to determining fuel dispersal.

CHAIR BALLINGER: This is Ron, I keep beating a dead horse but in this slide, the only thing that's actually calculatable with any precision is the burnup. Everything else is a calculation based on a fuel performance model, which may or may not be accurate.

MS. BALES: I think it's important to emphasize that the RIL doesn't prescribe how to

analyze FFRD. The RIL simply defines when to analyze it.

That means that vendors and their topical reports are to define the models and the basis for those models that need to be used in order to evaluate these limits.

Having said that, I want to explain that in some ways the means of analysis are not a dramatic departure from the existing analysis. For example, as you already mentioned, the burnup of each rod is already tracked.

Evaluating whether a rod is above or below that threshold is straightforward.

The empirical limits depend on ballooning and burst and although there are variability in how accurately that can be predicted, performance codes do already have models for ballooning and the prediction of rupture.

Some fuel performance codes even already model axial fuel relocation. So, I said all of that to say the RIL does not define how to analyze FFRD, which models are acceptable, which models are even recommended to match the experiments in the test.

It just simply leaves it at here's where these phenomena had been observed and this is where

these phenomena should be analyzed, but the analysis should largely map onto existing tools.

Whether they are assessment or ready for use in this analysis is something that would be addressed separately.

Now that I've given you a high-level overview of what the outcome of the RIL is and what the RIL makes possible, I'm going to step through each of the empirical thresholds in turn and describe the technical basis for each of the limits.

First the empirical threshold at which fuel pellets become susceptible to fine fragmentation. To define the threshold at which fuel pellets become susceptible to fine fragmentation, we examine results from 26 tests in which fuel fragment size was carefully measured.

Fuel fragments were processed through a series of sieves and the mass fraction of fragments below 1 millimeter and 2 millimeters are shown in the plot on the left. We see the mass fraction of fine fragments increases with burnup, with some variability between tests.

We have detailed fragment size results at a burnup of about 43, showing no fragments smaller than 2 millimeters, and then again at 6 days per ton,

showing fragments start to be observed at these fine size levels.

Unfortunately, we don't have any result of fragment size distribution between these levels using that sieve fine resolution picture.

But we do have optical microscopy from testing at Argonne National Lab for an average of 55-second burnup before and after LOCA testing that indicates fragments on the order of 1 to 2 millimeters were observed after testing.

The A&L results are the ones that anchor our position with the onset of fine fragmentation occurs at 55 gigawatts per ton.

CHAIR BALLINGER: This is Ron again. I look at this and I look at, let's say, the lower figure at 66. There are two data-points which look to be almost exactly the same burnup but the variability is plus or minus 30 percent.

So, is that a good number to think about in terms of uncertainty?

MS. BALES: That's a complicated question because you're previewing one of my concluding remarks, which is we have used burnup as the Y axis in the RIL. And most likely, the mechanism that is at play that controls fine fragmentation has more

variables than just burnup.

And so in this we're just simply plotting everything as a function of burnup so in some ways that is true that 30 percent could be an uncertainty factor on the burnup threshold, but I think it's probably more accurate to say that burnup is somewhat of an incomplete parameter in the onset of fine fragmentation.

And as we look to the future, a true mechanistic understanding will probably put burnup amongst other factors that control the onset of fine fragmentation.

Once we have those delineated, some of this data might be more easy to explain.

CHAIR BALLINGER: I wonder whether or not the flow conditions, vibration and such, might also be a significant factor that is unpredictable?

MS. BALES: I think in a real LOCA that could be the case.

Most of these tests, except for the red Halden tests, and all of the other data-points would, I expect, have been subject to the same forces and conditions because they were all conducted in the same test setup where you have flowing steam in accordance with the furnace heating.

So, I wouldn't expect a lot of variability between tests when it comes to the applied forces.

CHAIR BALLINGER: But the Halden results say zero?

MS. BALES: For some of these burnups, yes, that is true.

CHAIR BALLINGER: High burnup fuel, zero.

MS. BALES: I'm trying to bring your attention to the one that is at 64.

CHAIR BALLINGER: I see that one but I also see three non-bursts, but let's take the burst ones. At least 2 at 73 or so, or thereabouts?

MS. BALES: There is certainly a lot of variability in the fragmentation behavior and in particular, some notable low fragmentation observations in the Halden test.

So, I think this gets to the fact that we don't have a fully mechanistic understanding.

This is really just empirical threshold that is based only on what we have looked at right now which is the effective burnup.

CHAIR BALLINGER: Thanks.

MR. SCHULTZ: The other question I had on that slide was -- this is Steve Schultz -- each of these data-points are representative of results

regarding fragmentation that are from a test where the fuel rod has been exposed to a particular tailored time, steam, temperature, pressure, condition presumed to be appropriate for LOCA of a type.

In other words, rods and reactors, if they're exposed to a LOCA, are going to behave differently depending on their power history and what their power level and burnup is at the time of the event.

I presume there's a lot of variability in the conditions to which these rods have been exposed in the testing.

MS. BALES: Yes, there is variability in the conditions of the tests. The time temperature transient is a little bit different amongst these tests. The rod internal pressure was different between some of the tests.

In fact, in the SCIP-III program that was one of the parameters that was being investigated, the effect of rod internal pressure. So, that was deliberately varied and so some of these tests have different internal conditions.

In addition, I thought what you were mentioning there is their operating history could also be different and so getting to some of these burnups,

some of these rods are coming from lead test assembly campaigns.

Some are even reinserted rods so they were experiencing a very unique power history during operation. So, there's a lot going on between the tests that with layers of resolution may explain some of the scatter.

But at this point, when we looked at what we could say with this level of knowledge, we plotted it all against burnup and generally see an increasing trend although there's a lot of variability.

Again, you're previewing some of my comments at the end to wrap up but I think that some of the future research will look at how those different parameters affect fragmentation and could lead to a reduction in the conservatism that's depicted by this burnup threshold.

MR. SCHULTZ: You're speaking to my point, I appreciate that. I'll wait for your conclusions later too. Thank you.

CHAIR BALLINGER: Do we know what the temperature profile history of this pellet was prior to the test?

MS. BALES: Are you referring to the optical microscopy that is shown?

CHAIR BALLINGER: Yes.

MS. BALES: I don't have that handy with me. The testing at Argonne was on commercially irradiated rods and if it was at 55 I wouldn't have expected it to be an LTA rod. I can look that up but I don't have it handy with me.

I will say that amongst the tests that are shown in the plot on the left, there was a lot of variability in the operating history during commercial irradiation. So, that represents quite a big span of normal and possibly some extreme operating histories.

CHAIR BALLINGER: It's hard to tell from looking at a computer screen of a micrograph of a micrograph, but generally it's not just relocation that occurs, it's restructuring that occurs sometimes.

And I'm looking at this circle at about 30 percent in or 40 percent in and wondering whether or not that's generally an indication of something of some restructuring that may have occurred.

And that also delineates the area on the right where you get a lot of finds in radiuses greater than that little ring. So, again, it's fodder for 10 or 20-page theses.

MS. BALES: It certainly is, and I'll just say that I think what you're pointing to is the

slightly darker circle.

It's a little hard because this is a map of many different images so the quality to discern a dark zone, for example, is a little hard in this particular image.

The SCIP program has done some really great characterization of pretty transient conditions as well as post-transient conditions.

And I'll just say that this phenomena where we see some more fragmented region in a circle and less fragmented in the center and even on the periphery relative to that mostly fragmented in this ring has been seen additional places.

This is not the only time that pattern was observed.

So, the SCIP reports that are cited in the RIL are still proprietary to the SCIP members but there's quite a bit of information that has been documented to look at before and after and what patterns, porosity, fragment size, and such to see if there's a link to what the final fragmentation results were that were observed.

And NRC's program at Studsvic, we actually looked at a collection of fine fragments that were collected in the sieves after the LOCA test, and we

did isotopic analysis to try to determine where they had come from with respect to the pellet radius.

And so we saw that the fine fragments that were collected originated not just from the pellet periphery but even some of the interior portions of the rod were origins for those fine fragments.

So, that is all to say there has been work to understand where relative to the pellet radius fine fragmentation is occurring, and there's quite a bit of variability.

Okay, as I suggested earlier when we were talking about the 55 limit, fragmentation by itself doesn't present a safety concern. However, if fine fragments can relocate axially within a rod, there can be safety implications.

On the issue of fuel relocation, tests repeatedly showed that even when fuel was significantly fragmented, not all fuel was able to relocate axially.

In the image on the left, we see measurements of one of the NRC's tests at Studsvic. During this test, there was significant fuel dispersal and we're actually going to show a video of this test a little bit later, and I'll say a little bit more about what was observed.

But for this point, I want to say that after the LOCA tests a wire probe was inserted into the test segment through a rupture opening and could travel quite far, as indicated by the green span that you see in the lower portion of the graph.

After shaking the rodlet, which again I'm going to show in a video in a little bit, additional fuel was collected and the wire probe could travel even further as indicated by the pink span.

These measurements suggest a zone of empty cladding but after all testing was completed, a gamma scan was performed and revealed a slightly larger span empty of fuel.

So, perhaps more importantly, the gamma scan revealed a section of the rodlet where fuel remained and appears in tact.

Pellet interfaces can be discerned in the lower portion of the rod down here, so this span is about a pellet length and so we see a pellet interface and relatively in tact fuel judging by the gamma scan alone.

Similar examinations were performed in additional rodlets and these measurements formed the basis for saying that fuel relocation is limited to regions of the fuel rod experiencing greater than 3

percent strain.

So, one of the reasons that we care about fuel relocation is that it's a precursor to dispersal.

Before I speak to the measurements made of fuel dispersal, I want to provide details of the testing so that we can understand how dispersal measurements were made, especially in the SCIP-III program.

The video that I'm going to show will at first be a closeup just below the furnace in the test train. At this location we can see the court's tube and a rodlet is above the frame.

At the moment of burst we will see fuel fragments fall into the field of view below the rodlet. The LOCA test is happening and then the burst occurred and then the black dust that you see is fuel material that fell out of the rupture opening and to the bottom of the court's tube.

The scan is just showing to illustrate what the rest of the test train looked like and then this is in slow motion. So, after LOCA testing, the fuel material that you see in the bottom of the test train was collected and weighed.

And we have 19 measurements showing the mass of fuel collected at this point in the

experiment. After the LOCA tests, the rodlets were shaken and this video reveals what that looked like.

I show this because in the RIL we ready to mobile fuel and dispersed fuel. In the first video the mass of fuel that was collected just after the test that was found at the bottom of the test train, that's what we talk about as the dispersed fuel.

And when we talk about all mobile fuel, we're talking about any fuel material that was able to be shaken out of the rod. And when comparing dispersed fuel to mobile fuel, we see that it all comes down to the burst opening size.

The figure on the left highlights two particular tests but the size breakdown of all mobile fuel is quite similar. So, in these bar graphs, the height represents the mass of fuel collected.

Blue was fuel that was collected after the LOCA tests and the orange was additional fuel that was collected during the shaking.

And you can see that the top graph and the bottom bar graphs have similar situations where we have a lot of particles that are between 2 and 4 millimeters, and above 4 millimeters in this case, and then relatively smaller amounts of fine fragments in each of the size bins.

However, on the right of this figure I've drawn a representation where the size of the two burst openings is scaled, and so in the upper region the burst opening was much, much larger than that of the lower one.

And that is most likely an explanation for why we saw such a difference in the dispersed mass versus what was mobile in total. But if burst opening is a key parameter we face a problem because burst opening size varied between tests.

And there was not an obvious burnup trend so when we are correlating in the RIL when we're correlating this phenomenon with burnup, we can't necessarily rule out large rupture openings in either low or high burnup fuel.

And so for that reason, the dispersal model that we propose in Element 3 of the RIL was not based on the dispersal observed during the LOCA test that I showed in the first video.

The model actually assumes all mobile fuel could disperse and, therefore, it's tied to the limits established for fine fragmentation and relocation. The model proposed in the RIL is for a finely fragmented fuel, all fuel above 55, that can relocate.

In other words, strain greater than 50

percent, all of that fuel could disperse.

Using this model to examine how well it would predict all mobile fuel in seven LOCA experiments in SCIP-III, we see that it is sometimes conservative and sometimes not.

But we're interested in core wide assessment and, therefore, considering these predictions at a core-wide level we expect the results to be conservative.

And other models were examined to some extent and that's the documentation that you'll find in Appendix A where we looked at different trend lines that were taken from the size graph that was shown earlier in the presentation, where fragmentation size seems to sync with burnup.

But at the end of the evaluation, the Staff concluded that conservatively at this point, because burst opening is stacastic that we want to create a model which was assuming all mobile fuel could disperse.

So, there's two additional elements that we're going to go into some details and for that I'm actually going to turn it over to my colleague, James, who is --

James, I'm assuming you want me to keep

running the slides or do you want me to turn the presentation over to you?

MR. CORSON: You can keep driving the slides. Hello, everyone, I'm James Corson and I work in the same branch of the Office of Research as Michelle.

So, I'm going to be talking about the fourth element of the RIL and that's transient fission gas release, which could impact ballooning and burst behavior of rods under LOCA conditions.

As Michelle said, the modeling of fission gas release during normal operations is pretty well understood but during transients, there aren't really a lot of good models to represent this behavior.

So, you can see on the data there seems to be an increasing trend where transient fission gas release becomes more prominent at higher burnup but there's more going on here, there's other factors than just burnup.

The fuel temperature plays an important role. Some tests have shown that you need a threshold of about 600 degrees Centigrade before you get any transient fission gas release.

Stresses in the fuel also play a role so

the cladding mechanical constraint or the internal pressure, those can also influence transient fission gas release, which is why you see quite a bit of scatter on this graph here.

Since releasing more fission gas is going to increase the rod internal pressure, that can impact ballooning and bursts, it's something that needs to be accounted for when trying to predict whether or not your rod is building to burst.

And as we discussed that, whether you rupture that determines whether or not you can get dispersal.

So, right now there are some models that have been proposed for a transient fission gas release but they need a lot more validation at this point before they're ready for use.

Next slide, the fifth and final element is related to the packing fraction of the relocated fuel in the balloon region. This is something that's been studies quite extensively over the years, even for lower burnup fuel.

But for this higher burnup fuel with fine fragmentation you can get a higher packing fraction and that's just related to the fact that if you have a poly-dispersed size distribution, you can get a

higher theoretically packing fraction.

And so SCIP data shows packing fractions ranging from about 70 to 85 percent for fuel that's susceptible to fine fragmentation. And then for the lower burnup fuel they looked at, the one test had a lower packing fraction, which is more consistent with previous measurements.

So, again, it's important to account for this because it can affect the LOCA heat transfer behavior and thus impact whether or not you balloon and burst. Next slide.

That's it for the five elements the RIL addressed. To wrap up we're going to talk about a few other matters we addressed. Next slide.

So, all of this, the RIL really focuses on, again, what rods are susceptible to ballooning and burst, fine fragmentation, relocation, dispersal. It doesn't really talk about how this would be applied on a core-wide basis or what the implications of dispersal would be.

Instead it just points back to previous publications in this area to discuss the potential safety concerns.

And the ones that were listed and discussed in this previous publications are energetic

fuel coolant interactions, re-criticality of dispersed fragments, core coolability and long-term decay heat removal, and potential radiological and source term impacts.

The latter topic is being addressed as part of an update to Regulatory Guide 1.183. Next slide. Lastly, the RIL talks about some of the limitations of the empirical database.

Michelle has hinted at some of these things already but I just want to make clear that all these tests were performed on standard uranium dioxide fuel pellets in zirconium alloy cladding.

So, they weren't performed on any doped fuel or coated cladding and so the limits aren't really applicable to those fuel and cladding types.

Additional research may demonstrate that the limits in the RIL may apply to these new fuel types so that they're bounding but more work needs to be done in this area.

I should note that doped fuel has different fission gas release behavior so that can impact fine fragmentation relocation and dispersal.

And on the other hand, coated claddings at least in unfueled samples have been shown to have less strain and smaller burst openings during burst

testing. So, if you have a smaller burst opening that could significantly limit the amount of fuel dispersal.

So, coated cladding could potentially have some beneficial impacts but, again, more research is needed to verify those findings. Next slide.

Again, as Michelle said, these are simplistic limits. They were only derived as a function of burnup but in reality, there's more going on than just the burnup.

There's the power of the rod right at the start of the LOCA or right before the tests were conducted. Those sorts of things impact things like porosity or stresses within the fuel, it impacts grain growth and subgrain formation.

And all these things are heavily influenced by the operating history so as Michelle said, that could potentially explain some of the scatter that was in the plots shown earlier.

But we need more research to allow for a more mechanistic treatment. Right now, all we really have is burnup and we have some preliminary indications that there's something else going on but we need more research to verify that.

And then finally, these limits anticipate

that we can accuracy predict the cladding stream along the rod. Historically, that hasn't been a real focus of ballooning models.

Rather, they focused on the burst temperature and burst time or the maximum burst strain at the burst location. They haven't necessarily focused on the actual extent of the balloon region.

So, it may be necessary to make some conservative assumptions to identify the mass of fuel susceptible to relocation and dispersal. And as Michelle said, we treated the burst opening size as stacastic.

And so we based our limits assuming there would be a large burst opening size.

However, there has been some research done by the national labs in the U.S. to look at the influence of different parameters and how they impact burst opening size.

So, it's possible that in the future there may be a more mechanistic model to predict burst opening size. Next slide. Where does that leave us?

As Kim had mentioned in her introduction, we're participating in the next phase of the SCIP program and this actually includes some testing to address the gaps that are in the existing database.

So, it has some tests on doped fuel, some additional tests to characterize transient fission gas release, and more testing in the immediate burnup range between 45 and 60 gigawatt days for MTU, where there was a bit of a gap in some of the figures that we showed.

Separately, at NRC we're working on refining some of our analysis tools to perform coal-wide FFRD analysis.

We perform some preliminary calculations in the lead-up to the SECY in 2015 where we used a combination of scale and parks neutronics tools that traced thermal hydraulic systems analysis code and FRAPCON, fuel performance code, to estimate the total mass of fuel dispersed during the LOCA.

Since then we've used similar workflows for MELLLA+ analysis on BWRs, so we're looking to extend those to more realistic core designs for LOCAs at higher burnup and to use some of the newer modeling features in our FRAPCON code and in improvements in trace and so on.

I'm going to turn it back over to Michelle.

MS. BALES: Thanks, James. This is effectively the conclusion slide and I wanted to end

the presentation by explaining to you that the RIL is a foundation for next steps.

As you would have maybe gathered from some of the questions but also what James just talked about in terms of the limitations, you could consider this an awkward time to write the conclusions of FFRD.

There's a lot that we still don't understand and if when we sit down to write an update or a revision in five years, I bet it will be much more precise and much more satisfying.

But at this time we wanted to establish what we know today, especially as the industry is looking to increase burnup limits and explain what we know from the available research up until this point.

We fully expect research to continue and we would anticipate, for example, industry building from the RIL based on their licensing needs, justifying less conservative limits with more detailed or problem-specific arguments where they're able to do that.

We also expect that research at the national labs or in international collaborative programs can build from the basis that the RIL provides and produce information that is needed to go further, either to refine the limits or make them a

function of more properties than just burnup.

MEMBER PETTI: Michelle, question? What's the timeframe for the additional testing that you're talking about? Is it five years or less?

MS. BALES: The SCIP-IIII program is on Year 2 I believe and that is where we'll get a little bit more information about the midrange burnup as well as some information of doped fuel.

I think there are additional research programs that will continue for much longer than that.

We know about the SCIP-IV program because we are members of that program but I believe there is research well beyond that that could add to this body of information that might come out in the next couple years.

I can only speak to the SCIP-IV program because that's the program we are members of.

CHAIR BALLINGER: Thank you for that presentation.

I'm going to venture into some stream of consciousness talking here I suppose, but we probably should wait until we hear from Members first and then we'll go and ask for comments from the public.

So, other Members, unfortunately we have only four or five of our Members present and this is

a very detailed presentation of a multi-variant problem where without being able to be present at the presentation, it's going to make it pretty difficult for other Members to understand what's been going on with the information.

So, in any case, Members, questions and comments, please?

MEMBER PETTI: Ron, my comment, having read the CAPS paper in JNM and the RIL is there's still a heck of a lot of uncertainty around this. There's questions about prototypicality of the entire experimental database in a lot of ways.

You'd expect the in pile to be the most prototypic but it has some problems, no experiment is perfect. And the only way you get a resolution on this sort of stuff is you do lots of testing and lots of different experimental approaches.

And like an Impressionist painting you step back. If you look real close you get lose. You step back and you may see some better trends.

But there's still a lot that we don't know and it all relies on the mechanical properties of the cladding to find out when it's going to burst, the size it's going to burst.

And we don't know the mechanical

properties, the relations well enough. So, there's models that exist, I understand that but they weren't looking at this issue.

One may need a hell of a lot more precision and better models than what's already there to get a good calculation.

CHAIR BALLINGER: Now I'll start the stream of consciousness discussion.

The problem is defined in the sense that we have a right circular cylinder with dished pellets and we have a more or less bounded power history for Light Water Reactors.

But that's it, that's what constrains it and like you say, it's a multi-variate problem with several variables which are just undefined and maybe unknowable in terms of what the values are.

And it's possible that you could develop a program that would go on for the next 20 years and still not get enough information, it's one of these forever things.

And you wonder whether or not we should come back and look at the consequences of the phenomena to see if the consequences can somehow focus the next or ongoing or future research efforts so that it doesn't become a never-ending problem.

Because there's probably 15 or 20 variables there.

There was an infamous figure that was produced by I think Adrian Roberts, who has since passed away, where he was being facetious and he drew a chart which had the relationships between all the variables and fuel performance.

And I think it was Adrian Roberts.

MEMBER PETTI: I've seen the figure, yes, it was Adrian Roberts I believe.

CHAIR BALLINGER: And you sit back and you laugh at it but it was correct. And so I'll just stop talking and ask for other comments from Members.

MEMBER BLEY: Ron, this is Dennis. Your stream of consciousness is worthwhile. It seems to me at points some real discussion inside the Committee and I think your scheduled for a letter but I think you should be if you're not.

CHAIR BALLINGER: We are scheduled for a letter but I'm not sure this is the right time for a letter.

MEMBER BLEY: Maybe not but it's probably time, given the number of people who were here, to at least have the full Committee meeting and the others know more about this --

I'm not sure if it's time, it could be a good time for a cautionary letter based on what you were just saying. Let's look for places we can bound the consequences and see how much it's worth, how much and when it's worth really going a lot further in this.

And most of the time in the past before COVID-19, this was a typical turnout for the Subcommittee and we had to have a pretty good briefing, a couple hours over the same stuff. I think that would be appropriate here.

Anyway, enough from me.

MEMBER REMPE: This is Joy, I would like to follow up more on the question about the prototypic aspects and non-prototypic aspects of the sources of data and what Dave said I agree with, that there's no perfect test.

And if we could ask the Staff before the full Committee meeting to generate some sort of list of pluses and minuses for each source of data to drive home that point, I think it would be a useful task for them to do.

What do you think?

CHAIR BALLINGER: I think you're correct as far as it goes, but again, I keep coming back to

how prototypic does it need to be? In other words, if we need a very precise description of the problem, then test data that's the -- I've got figure out the right word.

How prototypic the data needs to be is dictated by the level of detail that you need to base decisions upon. Is that not correct?

MEMBER REMPE: I'm with you about we need to bound the problem and I guess I'm doing that as an exercise to drive home the point there's no perfect test and maybe instead of doing more tests that will still not be the perfect test and answer the question, look somewhere else.

That's why I think it would be good to help see why there's some problems with each source of data and I didn't get that enough from the RIL. Okay?

CHAIR BALLINGER: The other wild card in this is I'm aware of at least one vendor, a fuel vendor, that's looking at this and they have had meetings that I've participated in at least as an observer with the Staff.

And so I know that at least one vendor is looking at this and communicating with the Staff. One wonders whether or not the others are not doing the same thing, maybe they are, maybe they aren't.

But that's a perspective which when you deal with consequence is an important thing to listen to.

And this meeting hasn't done that and I wonder whether or not we shouldn't think about having a follow-up meeting, regardless of whether we write a letter or not, where if the vendors have enough information that they can talk about, we get their perspective as well.

What do Members think about that?

MEMBER PETTI: I think it's important to do.

CHAIR BALLINGER: So, again, that's the stream of consciousness thing. Who else do we have here?

(Simultaneous Speaking.)

MEMBER PETTI: Steve has his hand up.

CHAIR BALLINGER: Who?

MEMBER PETTI: Steve Schultz.

CHAIR BALLINGER: Okay.

MR. SCHULTZ: I just wanted to comment on your last note there.

And it also was brought up in James' presentation that there is in fact a lot of work on it, there has been a lot of work going on the, if you

will, forcing function side of things over the last 20 years as new information and new evaluation and new analyses have been done associated with the LOCA event itself.

As you said, Ron, the experimental database associated with LOCA does go back 40, 50 years but there's been a lot of work to look at what is anticipated to be actual conditions in LOCA analysis for the units as well as for the fuel.

In addition to that, and again James mentioned it, new fuel types are going to have different performance than those that had been tested here.

And as I look at the research papers that are associated with the testing, the researchers have tried extremely hard to differentiate between the cladding materials and the fuel materials that they have in fact tested.

But it's very difficult to do, and the technology in fuel design and cladding design has really changed in the last 10 or 15 years and there have been important changes that have improved at least steady state fuel performance.

And most of those do in fact affect the transient fuel performance as well. So, just in

summary, there is a lot that could be done and if a letter were to be written at this point, it certainly could focus on what we've discussed today.

That's the connection between the experimental evaluations and the conclusions that can be drawn from it. But there's three or four other areas that need to be explored including the overall consequence evaluation.

CHAIR BALLINGER: Greg, what do you think? You come from the operational side and so this has a significant implication for the operational side.

MEMBER HALNON: Hold on, I've got something going on. I'm sorry, Ron, I had a personal issue. So, I'm coming up to speed on this, obviously it's not in my expertise to look at the research and whatnot, but there are some questions that enter my mind.

And you all do a lot of research and modeling and prototypical modeling and whatnot. It seems that there's a lot of data out there in the industry that could be ascertained from actual configurations of fuel once it's been removed.

And I'm not sure if it's even physically possible to slice and dice a fuel rod as a high burnup and take a look at it.

Maybe there is and maybe there isn't but it just seems like the empirical data could be brought in to the equations to confirm where we're going, that would be good.

But overall, what I took away from this is that at the very minimum, we as a Committee should encourage prompt continuation of this research and get to a conclusion where we can all stand back and say, yes, that's a good limit.

And so the fuel fabricators and the designers going forward, especially for the fuels coming out like ATF, they really have to be --

My learned opinion is probably not as useful as some of the you guys who get into more often but that's where my head came away from.

CHAIR BALLINGER: I keep coming back, as David has, to the multi-variability of the problem. I was once on a Committee where we were analyzing and doing stress analysis for a complex shape of a device.

And I was mystified by the results and I pulled the finite element guy aside and I said, hey, what are the real stresses here? He looked at me with a straight face and said what do you want them to be?

And that looks to me like this is so multi-variate, if we're not careful we'll end up

getting what we want them to be. And that could turn out to be not a good thing.

So, okay, if we haven't heard from anybody else --

MEMBER BROWN: Ron? I've just waited since I'm obviously not a fuel person and I enjoy the graph and data-points. When I look at a research effort such as this, I try to look and see what it's going to be used for, the end result.

And I guess Slide 31 or 32, 33 talked about what's next, but all to me all it said was justifying less conservative limits with more detailed product-specific arguments.

And I guess I would have looked at this data to say does this allow me to extract more power from a particular fuel design or can I get longer life from that fuel design based on a better understanding of these characteristics?

But I didn't see that. Maybe I missed it in the discussion, but it seems to me that if this is going to be done, it ought to have something other than just information value, other than the few statements here about less conservative limits.

I wasn't sure how that was going to be used. So, that was what I took away from the

discussions.

CHAIR BALLINGER: That's a good comment because that's another reason to want to understand what the industry perspective is on this, and that we haven't heard.

And so I keep thinking whatever we write, that's definitely a recommendation at least from my point of view. I'd be curious to know what other members think about that?

MEMBER PETTI: I'm quickly skimming that long paper from CAPS again and the thing that strikes me -- I guess there's proposed testing in TREAT -- is what you really have to do now --

Okay, we've done everything that's been done to date, how do you do a better experiment?

Because it looks like the Halden stuff was done at lower linear power rates than typical but they were done at higher temperatures in terms of the temperature which you get to than a lot of the cores.

And so how do you do something when you kind of look at things a little more systematically and start with stuff that you think is going to be good but then things that are going to end up being not good, and try to find that boundary.

Is there something that can be done taking

everything you've learned to date to design the next generation of experiments, if you will? Because it's hard to tell reading the paper how different was SCIP from Oak Ridge.

If they're all very similar, then it's just more data with slightly different run-ups and the like. But there's a lot of stuff in the CAPS paper that says that you could change the conditions a little to be more prototypic and get answers that are more prototypic.

CHAIR BALLINGER: Coming back to the consequences issue, let's say everything that we've learned today happens, let's say that in doing a LOCA you do get ballooning, which we know would happen, you do get dispersal, you do get relocation and all the same.

How does that affect the answer? If it has a great effect on the answer, and given all the uncertainties, we have to factor that in, what are the temperatures and all that stuff?

If it has a very strength effect, that points you in one direction but if in effect, the consequences are within the uncertainty of the analysis, then it may be a nice thing to know that happens but the consequences are such that you don't

need to have more detail.

Or maybe you need one specific set of experiments to fill out something, to bracket something, but those are two very different paths and they're all dictated by what the consequences are likely to be should it actually happen.

MEMBER PETTI: I don't disagree, Ron, I just worry that as you propagate down the calculational train here and you try to do more and more, the uncertainty bounds tend to grow and in some ways I worry that the phenomena that you try to model get even more complex or uncertain.

I'd certainly be interested to know what the impact is. If it seems to always be not a big deal but that may be hard in the end. But I think it's worth hearing from industry on that for sure.

MEMBER HALNON: This is Greg. What is the burnup that we see in the three cycle fuel now? Isn't it much less than 55?

CHAIR BALLINGER: We're over that.

MEMBER HALNON: I didn't have a feel for it.

CHAIR BALLINGER: Peak rods are well above 65. Am I right there? Who should know? Michelle should know.

MS. BALES: Currently burnup lead average is limited to 62, so there are some rods that are above 55.

MEMBER HALNON: And that has been increased, I assume, over the years just based on better core designs and longer cycles.

So, the impact is obviously just going to be in that realm, the life that cycles or the amount of capacity factors that you're able to get, or all of the above.

So, certainly the impact is going to be from a physical perspective there, and in the fuel design, I'm not real good on that so I don't know in the fuel fabrication if there's going to be additional margins that have to be put in there or not.

MEMBER PETTI: I think some of these things can be done in parallel. It sounds like these two experiments are going to go forward, they're going to try to be more prototypic since the TREAT guys are co-authors of the CAPS paper.

And then hearing from industry, they'll be a nexus somewhere here whenever all this stuff gets completed. It will be worth another look.

CHAIR BALLINGER: That's a very good segue and I'm assuming that public comments will come from

members of the industry.

So, if there aren't any other comments right now from Members, I guess the public line is actually open so can we ask for comments from members of the public? I'm not sure how we do this in terms of who controls what.

But I guess if you want to make a public comment, just do star 6 and start talking.

MR. SONTOS: Ron, can you hear me?

CHAIR BALLINGER: I can hear somebody but I don't know who it is.

MR. SONTOS: This is Al Santos. Can I go ahead?

CHAIR BALLINGER: You certainly can.

MR. SONTOS: Al Santos, NEI. I want to thank the Staff for turning around this report so quickly. We've only had about a week to review it but the industry has a lot of detailed technical comments on the report.

So, the industry requests an opportunity and specific time to provide the detailed technical expert comments.

Even if we considered a revision to the RIL or to present at a follow-up ACRS Subcommittee or full Subcommittee, full Committee meeting regarding

the RIL.

So, those are the first points we wanted to make. The second one is that similar to what I hear, it seems like there's a lot of discussion on this.

The RIL as written today is a very considered treatment of the data, even choosing to apply additional conservatisms when presented with evidence that a test may have already been unrealistically conservative.

The industry continues to ask the NRC to incorporate the research that has been summarized here in a way that provides reasonable assurance of adequate protection of public health and safety.

And lastly, we just want to reiterate that the report, interpretive test data, and conservatisms are in a manner that should be construed as subjective.

And industry technical experts request an opportunity to provide a comment and feedback to be incorporated in the report or for the ACRS Committee. We just wanted to have some high-level talking points here to provide fuel.

CHAIR BALLINGER: Because of our protocols, our rules, we can only have comments, but

I have a question for Michelle, she might know the answer to this hopefully.

If we were to treat this RIL as if it were a Reg Guide or a NUREG, it sounds to me like the industry might offer public comments which may in the end result in a modification of the document.

Is that one way to look at this? Somebody is doing something here. So, would the Staff consider effectively putting it out for public comments -- I don't know how they treat RILs -- and take those comments into consideration.

It sounds to me like the RIL was issued in a very expeditious way but there are some comments that may be important.

MS. BALES: It's a good question and I think that in order to answer it I'm going to explain -- and Kim alluded to this in her introductory remarks, but maybe we can go back to the line of thought that she was raising.

From the nature of documents the NRC issues, a research information letter is designed to be a communication between the Office of Research Staff to NRR Staff.

And we wanted to do that very quickly in a timely manner because we know that NRR Staff is

receiving applications to extend burnup limits right now and we wanted to put information in the hands of those NRR reviewers so they could understand in a concise way what information was available on FFRD.

So, that was our motivation for the schedule that we kept and our target audience is NRR reviewers. As Kim mentioned in her introductory remarks, in the past RILs have been the start of other regulatory documents.

So, they could be the basis for a later guidance document or information that's contained in a RIL could integrate into the standard review plan. Any of those steps, which are so premature at this stage, necessitate a public engagement.

So, if those steps were to be taken, it would naturally happen that the industry and members of the public would be able to engage because those are clearly requirements of those types of documents.

So, a RIL typically would not have a public comment period. I think I'm only aware of one instance where there's been a public comment period for RILs.

So, I just say that to explain what the RIL is relative to other regulatory tools and to explain that it would not surprise me if a year from

now we were talking about something that was built on the RIL that does have public comment.

Now, that does not mean that we don't want to continue to engage with stakeholders, I think that's a critical part of NRC's principles of good regulation is to continue to have transparency and engage with our stakeholders.

So, I don't want to preclude that in any way and I think that when it comes to the research information letter, to the extent that we understood the importance of going external, that's why we proposed the peer review process, because we wanted to get outside perspective.

We wanted to ensure that we weren't operating in a vacuum with such a strict safety authority perspective that we were missing something. And so we sought outside peer review, recognizing the potential for us to be too narrowly focused.

So, I'll just stop there and say I think this is the start of additional documents and I see Joe Donahue in NRR has his hand raised. I think he would probably be more appropriate to finish my thought.

MR. DONOGHUE: Chairman Ballinger, is that okay with you?

CHAIR BALLINGER: Sure.

MR. DONOGHUE: I'm the Division Director in the Division of Safety Systems in NRR. I think Michelle put it very eloquently and very well. I'll just add we have been interacting as you know with individual vendors.

We've also been interacting with stakeholders in general on high burnup. We've held two public workshops on the topic and I think Michelle already explained the background and the motivation for the RIL being reduced.

As far as getting public comments, she let it out very well. This is a step in a direction that is going to include public comment in some form. What I don't want to do today is go out in front of my staff who has to evaluate --

As Michelle said, our Staff gets the RIL, we have to decide what's next specifically. Is it just an update to this SECY paper that she mentioned from 2015 or is it more than that?

Could it be a guidance document as you've all alluded to? Not exactly sure yet. So, I think that there's fast-paced activities in high burnup and accident-tolerant fuel.

I don't want to ask Research to go through

a public comment period on this because that's going to delay our ability at NRR to take the information and start taking next steps. That's just my own feeling.

It's up to you and the Committee on how much you want to hear. The last thing I'll say is the vendors are all preparing -- you've heard about some of them, but in some ways they're considering -- in one case we have a similar interim increased burnup from one vendor.

But topical report reviews are anticipated here and I think you will have the opportunity, the ACRS will have the opportunity, of course, to interact on all of those reviews.

CHAIR BALLINGER: Thank you. If I've spoken out of turn in terms of procedure, I apologize. But I wonder whether or not it would not be timely to have a Subcommittee meeting on this particular topic?

Not the RIL but high burnup fuel and the issues related to high burnup fuel, where we could have both the NRC Staff as well as the vendors and other stakeholders be able to speak.

And it sounds to me like there have been a few public meetings that are sort of on this topic in the recent path. What do Members think about that?

MR. DONOGHUE: That would be helpful for me because clearly an industry perspective and a vendor perspective would round out the holes in my head about this.

CHAIR BALLINGER: Joy, Dennis, Steve?

MEMBER BLEY: I liked the idea when you first brought it up a while ago, I think that would be a useful thing.

CHAIR BALLINGER: I'm trying to get a little bit of my thoughts together and what to say at the full Committee meeting, what a document would look like should we produce one or whether or not we should just recommend that we --

Thank you very much, we understand the issues that have been presented to us, the uncertainties are such that we think we should have further discussions at a subsequent meeting, whenever that should occur.

MEMBER BLEY: The only thing I'd toss in, and you hinted at it, is if we decide to do what you just suggested, our staff and the NRC Staff should get together and we ought to make sure we're not procedurally getting in the way of anything associated with the RIL.

I think bringing the general information

back to the Committee is probably very helpful.

CHAIR BALLINGER: The RIL is what it is. It's issued so there's no question of the Committee, at least I don't think so, saying don't do this. That's just not the way it works.

So, our normal letter comments would be different in this case.

MEMBER HALNON: Ron, it just seems premature at this point in that we would be getting into some internal processes that we might influence in the direction that is not necessarily fully informed.

CHAIR BALLINGER: We could simply treat this meeting as an information briefing, which is exactly what it is and make comments assuming it was an information briefing, with suggestions that we've all bantered about.

That may be one way to look at it and that would seem like -- oh, Michelle has got her hand up.

MS. BALES: I didn't want to interrupt but I wanted to clarify the RIL isn't issued yet. It was in concurrence and it was made publicly available in draft form in order to facilitate this meeting.

But technically, it is not issued so I wanted to just clarify that.

CHAIR BALLINGER: Thanks, I don't know how often the Committee has looked at or had meetings on a RIL but I don't think it's been very frequent. Al has his hand up or maybe it's been up for a while and he didn't put it down.

MR. SONTOS: I just wanted to say that to Michelle's point, there has been a past present of RIL being commented on by technical experts from the industry. So, putting that out there, that's all.

I just wanted to let that be known.

CHAIR BALLINGER: Thank you.

MEMBER BLEY: Here's a question, can we as a Committee look at RILs? I was trying to search my memory.

There have been a number of cases where we've looked at your section of the SRP or a reg guide or a NUREG that also had associated with it a RIL and came under our review as part of the other documents.

So, we've seen them before coming before the Committee, I don't think just by themselves but I'm not positive of that.

CHAIR BALLINGER: You've been here a lot longer than I have so you would know. Okay, I'm going to have to try to put thoughts together and I'll solicit --

Now there's a flashing blue circle around Dave. What does that mean?

MEMBER PETTI: I don't know, I just got unmuted to ask you are we going to recommend that we write a letter or not?

CHAIR BALLINGER: I'm casting about for suggestions, I'll send an email out to everybody was well because my memory is not as good as me writing something down. And people are taking notes.

But yes, I'm casting about for recommendations of whether we should write a letter of some kind and what it should say.

MEMBER PETTI: I'm struggling with a letter that would help the draft RIL be, quote, better, that's one thing.

The letter could be much broader and talk about the issue in broader terms but it wouldn't necessarily affect the subsequent steps of the RIL.

Same thing, we need to get industry's perspective. Some of the things we've heard, I don't know that they affect the next step. So, I'm with you, I'm struggling as well. I'm trying to figure out exactly what we'd say.

MEMBER REMPE: Could we ask Michelle or maybe Kim what would a letter from ACRS do? We didn't

ask you at the beginning of this meeting, which I sometimes do. What does the Staff anticipate from ACRS and how does it affect your schedule?

What would you do with a letter if there were some recommendations or comments in it? Is it too late, this thing is going out the door and you'd consider it as you go forward?

What didn't does it make in your opinion?

MS. WEBBER: Go ahead, Michelle, I'll add in if I need to.

MS. BALES: I was just going to explain that in our office instructions for RILs, in the section on peer review, it acknowledges the ACRS Committee is a body that can serve as peer review.

So, in one element we can just think about the benefit of the ACRS writing a letter that examines the RIL from a peer review standpoint and makes comments about your technical review.

And I think with respect to the timing of it, the RIL is done from the Staff's perspective, it is complete with concurrence but we're very conscious of not issuing it until the ACRS meetings were complete.

Because we anticipated the possibility that ACRS members would have important comments that

we needed to consider. So, I think in one respect a letter that serves to expand the sense of peer review is certainly one element.

I'll just say for myself, and I'm just reacting to the things in real time so I haven't thought about this too much.

Nut some of the ACRS Members were commenting on pulling back to see where does this information fall relative to a broader either research need, or where these phenomena fall relative to looking at upstream LOCA possibility events or downstream consequences.

I think that's another area that I thought the ACRS comments were very important to put the RIL in perspective.

So, even just in this meeting I think that we've gathered that but it could be that putting that into a letter helps to just place the RIL in the context of a bigger picture.

MEMBER REMPE: Michelle, I'm a little slow and so I heard you say at one point from the Staff's perspective the RIL is done.

But then I heard you say, which I am more sympathetic and encouraging of, is that you considered us a technical peer review, you've heard things but it

was from individual members that you had thought you didn't want to issue the RIL until the full Committee had written a letter because there might be some changes.

Is the latter statements that I've summarized where you're at, that, yes, there is the opportunity that our letter might make you hold off in the final publication and you might consider some of our comments?

MS. BALES: Yes, sorry, when I said the letter was done from a Staff's perspective, what I mean is there are no action items that we have on our list that we are still waiting to incorporate, or no additional data that we're waiting for.

The only input that we have not received that we know we want to receive are these ACRS meetings. So, what I mean from the saying that the Staff is done, there's nothing else that we know to do that we haven't yet done except for these ACRS meetings.

So, the latter is true.

MEMBER REMPE: Thank you, that helps. Kim, did you want to add anything else?

MS. WEBBER: No, actually, Michelle did a fantastic job explaining it much better than I could

because she's very familiar with the RIL process.

MEMBER REMPE: Ron, I would like to have a presentation. I'm just one Member but I'd like to see a presentation at full Committee and I think it would be a worthwhile letter for us to put together at this time.

Because we do have this opportunity and the Staff has said they're waiting to hear our comments.

CHAIR BALLINGER: We've assumed that would be the case and that's why we scheduled the full Committee meeting. So, we're slotted into have this take place so I think for sure, the only questions that I have are the tone and content and scope of the letter.

I think I've got a few ideas and I'll be soliciting within the next five minutes written comments from Members that are in attendance so that I can strike while the iron is hot, or Zana and I can strike while the iron is hot.

So, that would be the path forward, unless people have other suggestions. Dennis, the blue circle is flashing around you now. I don't know what it means.

MEMBER BLEY: I had my mic on for a while

then I turned it off.

CHAIR BALLINGER: Kim, your hand is up.

MS. WEBBER: I was just thinking about Michelle's response and the value of your review and ideas around the RIL.

I just wanted to add that I fully agree with Michelle that having your perspectives on the RIL in a letter would be very valuable to us.

I know it takes more time, there's a presentation writing the letter, but it would be of value to us and so I think we're looking forward to that.

CHAIR BALLINGER: Thank you, again. So, now it comes to the full Committee. I don't have it exactly in front of me so I don't know how much time, Zana might know, we have slotted. Is it an hour or two?

MS. ABDULLAHI: Let me look, I'll get it to you in a few minutes.

MEMBER BLEY: Ron, whatever it is, I would suggest that we try to make sure it's at least two hours between now and then, because I don't think an hour would be long enough to --

(Simultaneous Speaking.)

-- the other Members. I think you need a

couple hours.

CHAIR BALLINGER: We started at 1:00 p.m. and it's 3:00 p.m. and we've had --

MEMBER REMPE: This is Joy and I'm just going to interrupt you. Right now you're scheduled for Wednesday morning at 8:30 a.m. to 10:00 a.m. for the presentation.

But Matt often puts in an hour right after so he's got, really, from 8:30 a.m. to 11:00 a.m. for the combined time to have the presentation and read him the letter. That's something you might be able to negotiate with him.

That's where it's at right now.

CHAIR BALLINGER: My guess is that if we allowed that time for presentation and questions as opposed to reading in a letter and then read the letter later on, that might free up some time.

Because my guess is that by that time we'll also get requests for members of the public to make comments. So, I think if we go two and a half hours -- did I do the math right?

MEMBER REMPE: Yes, you did and by the way, I'd also note that from 1:00 p.m. to 2:30 p.m. was the research review and we got done with that so we do have some flexibility with the schedule in

December.

I'm just pointing out some things and what Matt prepared, I'm not the chair.

CHAIR BALLINGER: That's good. I don't see anybody's hands or anything up, I guess we've got to notify Matt that we shortened up the meeting once again. So, if there aren't any other comments, I think we are finished.

On that basis, the meeting is adjourned.

MEMBER REMPE: Thanks everyone for the presentation and discussion.

(Whereupon, the above-entitled matter went off the record at 3:08 p.m.)

Research Information Letter 2021-13: Interpretation of Research on Fuel Fragmentation, Relocation, and Dispersal at High Burnup

Briefing of the Metallurgy & Reactor Fuels Subcommittee
of the Advisory Committee for Reactor Safeguards
November 17, 2021

This presentation will address…

FFRD history at NRC

The programs cited in the RIL and the peer reviewers used

The outcome of the RIL

The basis for empirical thresholds included in the RIL

Other Matters

This presentation will address…

FFRD history at NRC

The programs cited in the RIL and the peer reviewers used

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The basis for empirical thresholds included in the RIL

Other Matters

FFRD history at NRC

- RIL 2008-01, "Technical Basis for Revision of Embrittlement Criteria in 10 CFR 50.46"

- NUREG-2121, "Fuel Fragmentation, Relocation, and Dispersal During the Loss-of-Coolant Accident"

- SECY-15-0148, "Evaluation of Fuel Fragmentation, Relocation and Dispersal under Loss-of-Coolant Accident (LOCA) Conditions Relative to the Draft Final Rule on Emergency Core Cooling System Performance during a LOCA (50.46c)"

- RIL 2021-13, "Interpretation of Research on Fuel Fragmentation, Relocation, and Dispersal at High Burnup"

This presentation will address…

FFRD history at NRC

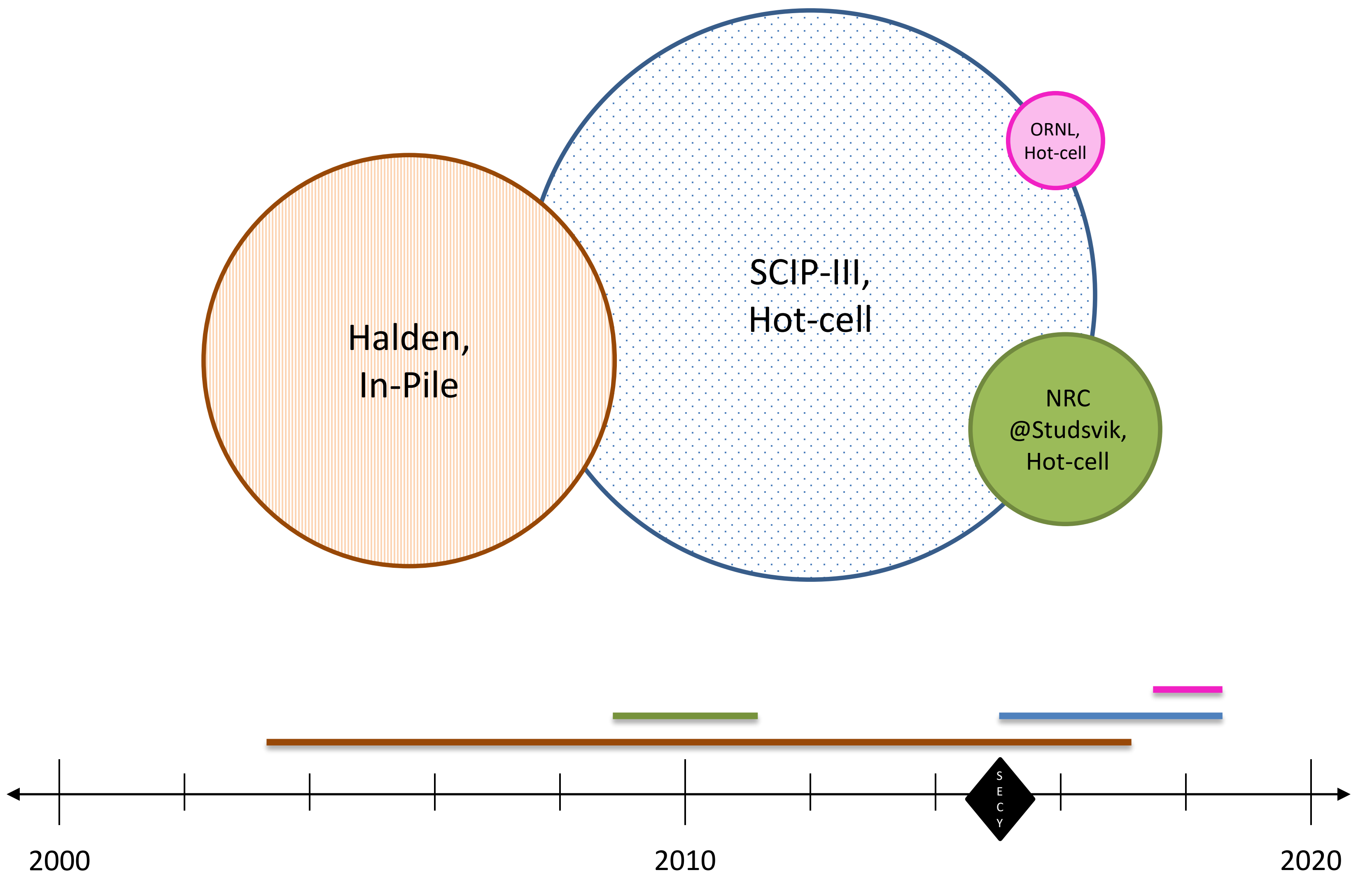
The programs cited in the RIL and the peer reviewers used

The outcome of the RIL

The basis for empirical thresholds included in the RIL

Other Matters

Data Sources for RIL



Peer Review Group

- Ad hoc, issue-focused group. Reviewers selected with extensive familiarity of FFRD research
  - *Nathan Capps, ORNL* – Author of two significant publications on FFRD, extensive experience modeling aspects of FFRD and collaborator in ORNL FFRD experimental program
  - *Tatiana Taurines, IRSN* – Extensive experience modeling aspects of FFRD and leader in SCIP program review group discussions
  - *Fabiola Cappia, INL* – Collaborator in FFRD publications, lead for INL PIE campaigns of HBU fuel, extensive work examining evolution of fuel microstructure with burnup
  - *Ken Yueh, EPRI* – Designed and led FFRD research campaigns at Studsvik for EPRI and NSUF at ORNL/INL, leader in SCIP program review group discussions
  - *Daniel Jädernäs, Studsvik* – Collaborator in SCIP experimental design and expert in SCIP results

Peer Review Outcome

- Peer Reviewers provided thoughtful and detailed comments
- Reviewers pointed to a number of places where our positions could be stronger. The edits result in a RIL that is more solid.
- Reviewers suggested a “definitions and terms” section.
- We have a 5 page “Summary of Peer Review Comments and Resolution” that may accompany the RIL as documentation of the peer review process.

This presentation will address…

FFRD history at NRC

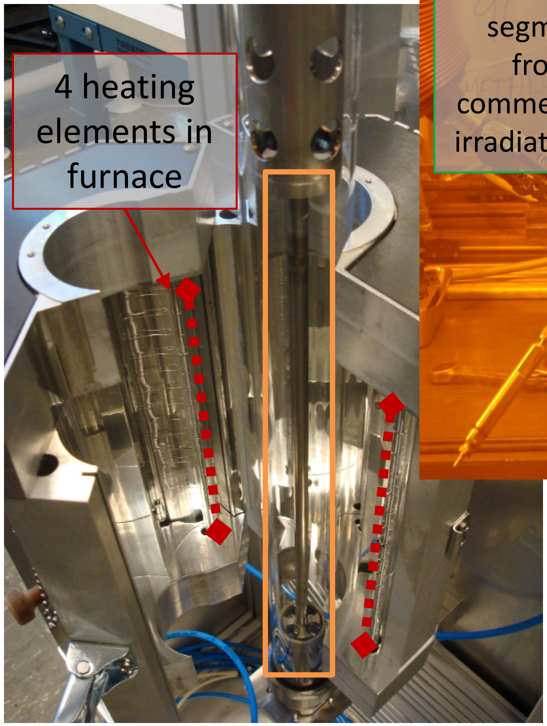
The programs cited in the RIL and the peer reviewers used

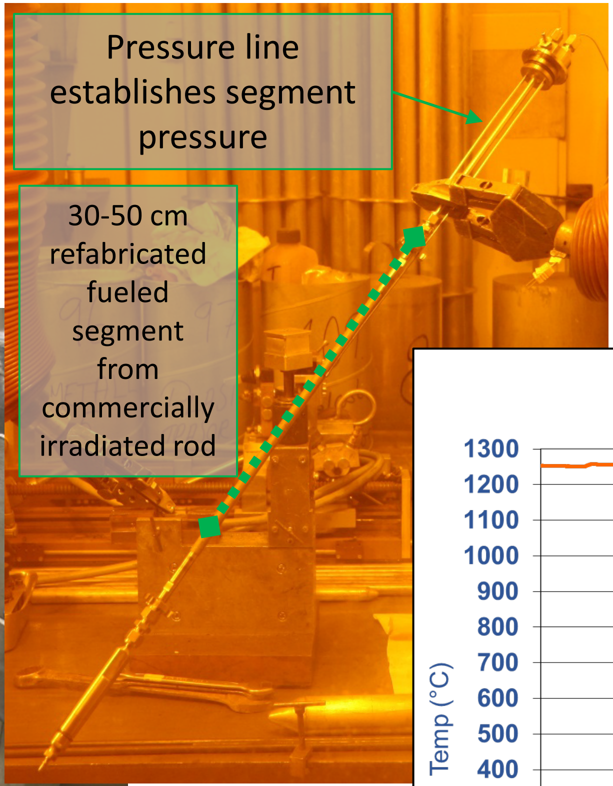
The outcome of the RIL

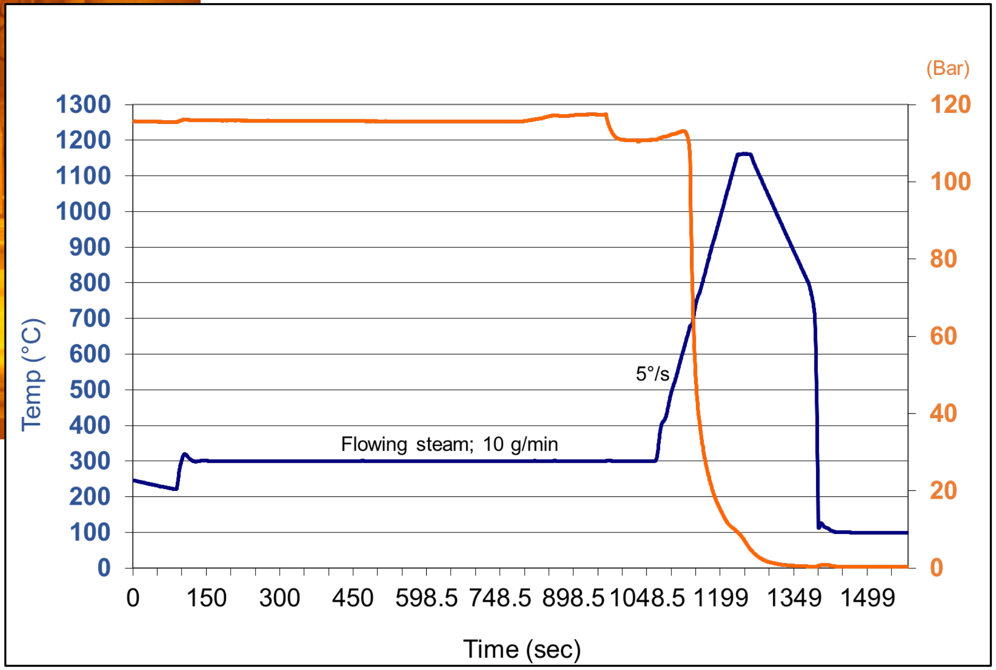
The basis for empirical thresholds included in the RIL

Other Matters

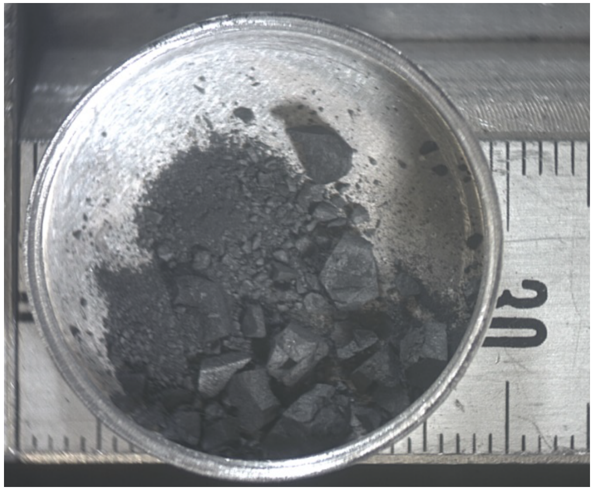
Hot-cell testing to simulate Loss-of Coolant Accident condition

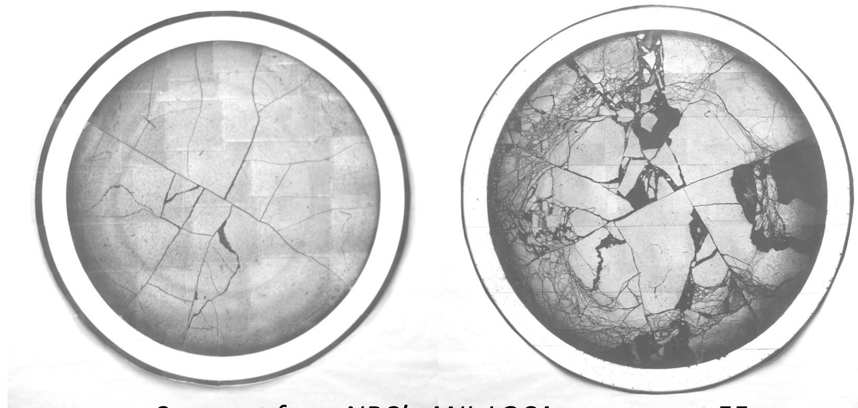




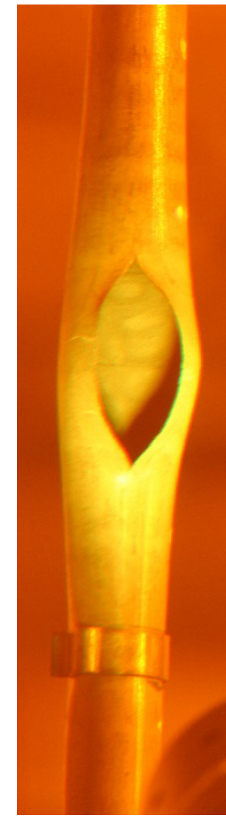


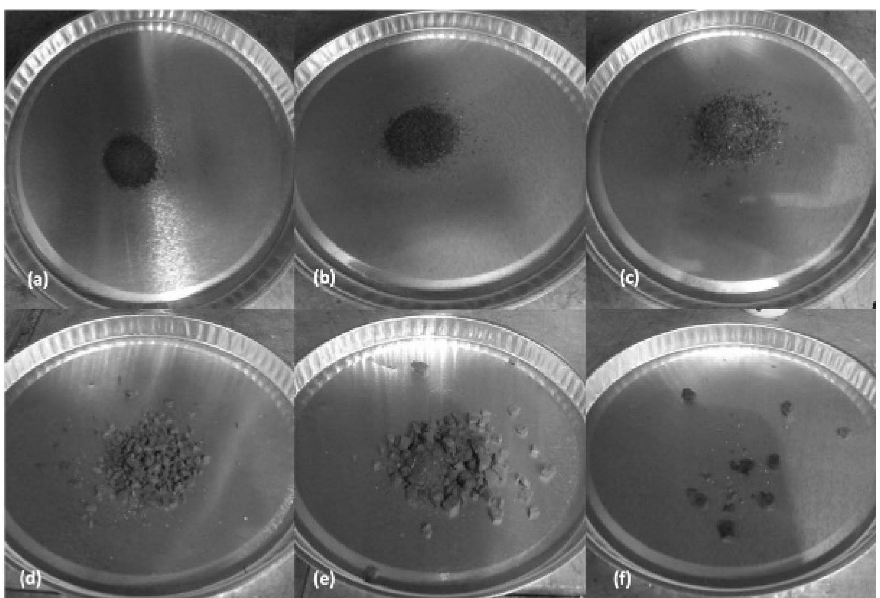
Outcome of the RIL:
Identify when FFRD occurs

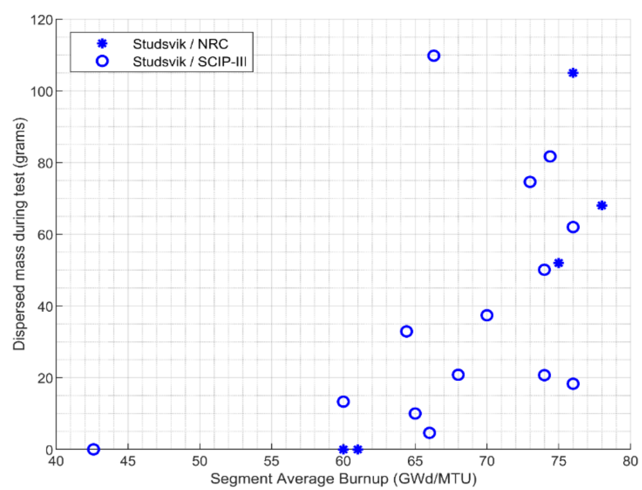




Segment from NRC's ANL LOCA program at 55 GWd/MTU before and after testing





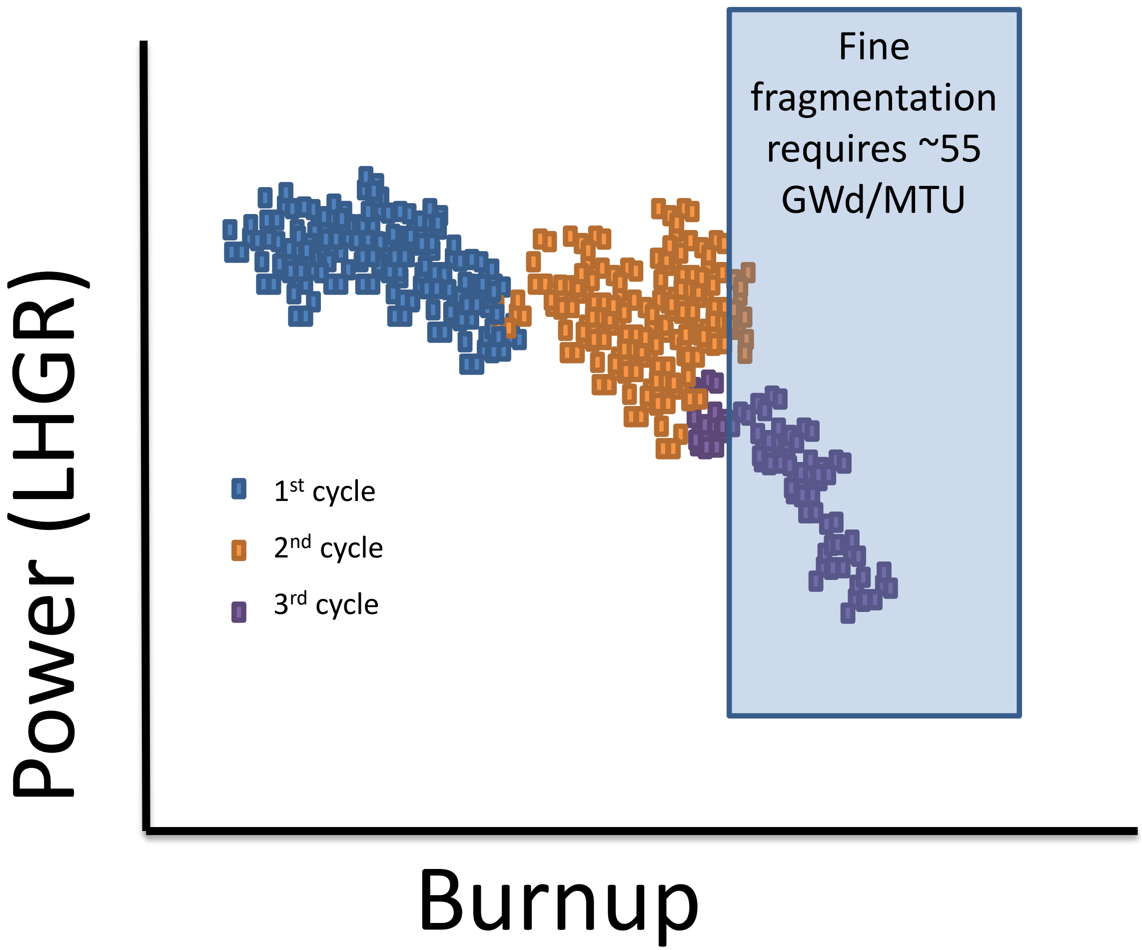


Outcome of the RIL:
Identify when FFRD occurs

Address five elements of the RES staff's interpretation of FFRD research and describe the technical basis for these elements:

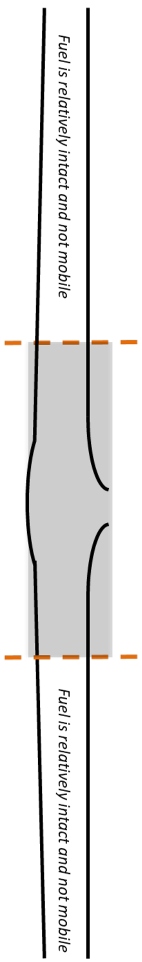
1. Fine fragmentation threshold
2. Fuel relocation threshold
3. Model to quantify dispersal
4. Document *transient* fission gas release
5. Quantify packing fractions in the balloon region

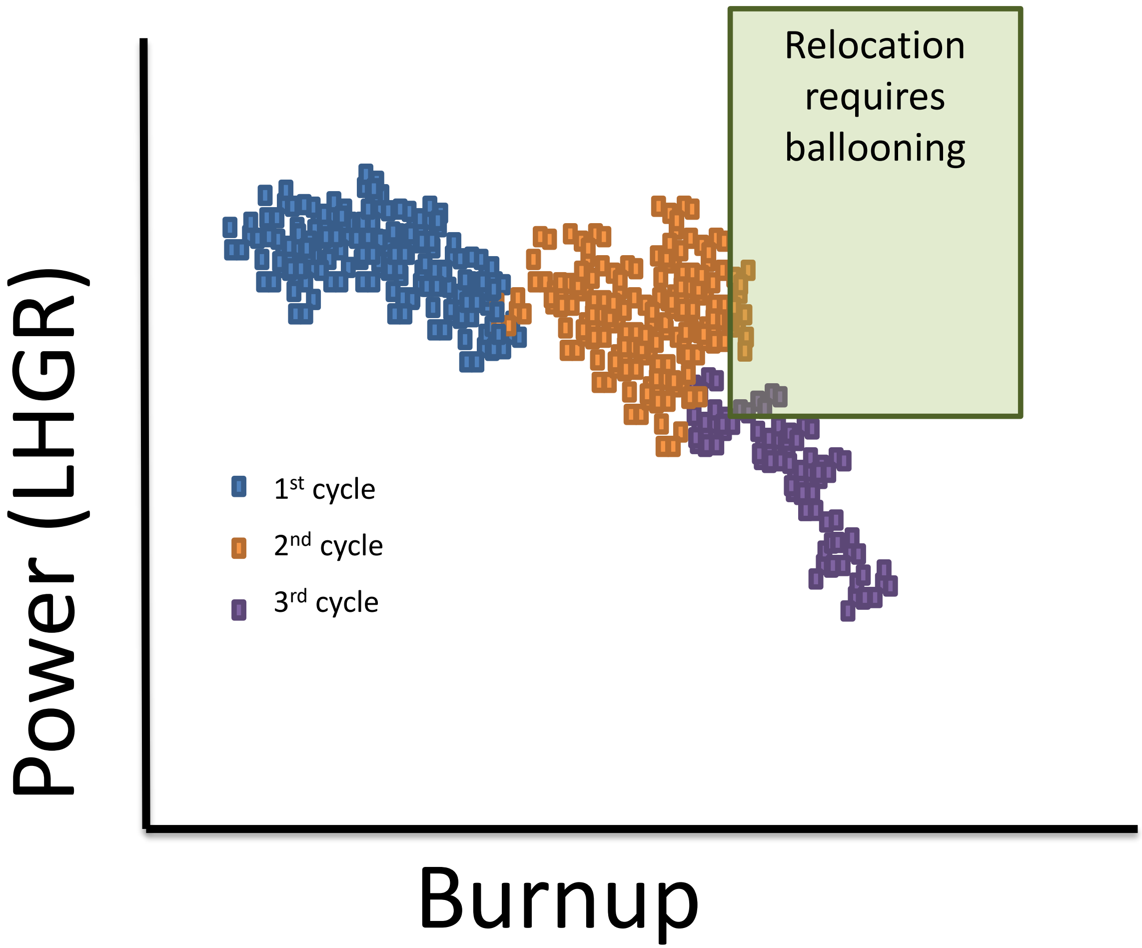
Outcome of the RIL:
Identify which rods are a concern for FFRD



Outcome of the RIL:

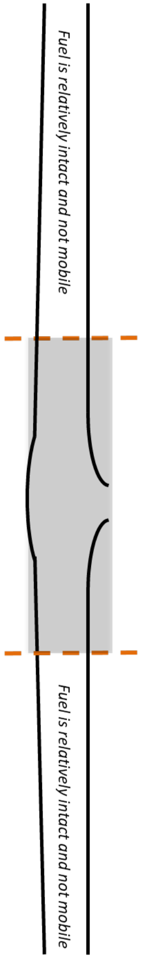
Identify which rods are a concern for FFRD

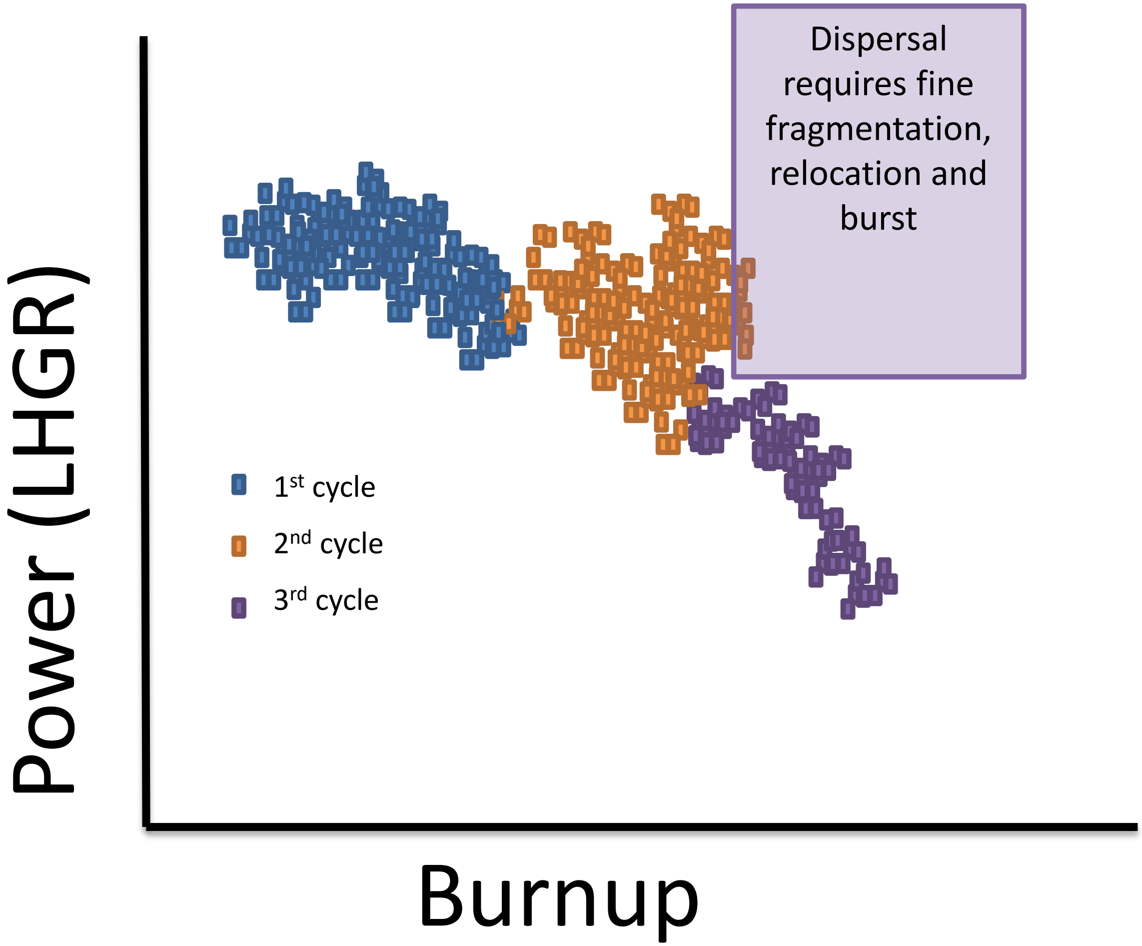




Outcome of the RIL:

Identify which rods are a concern for FFRD



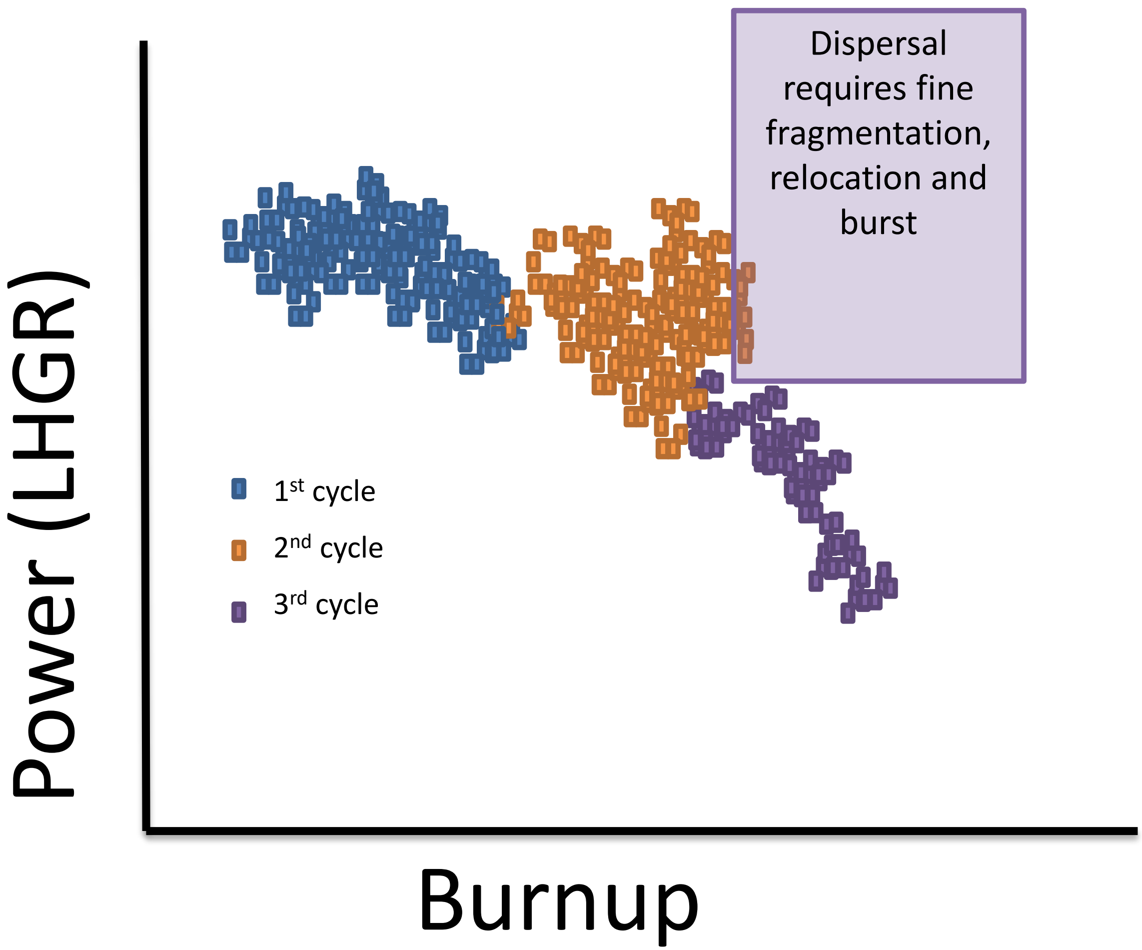


For the **dispersal** zone, some core loadings may result in no region of overlap

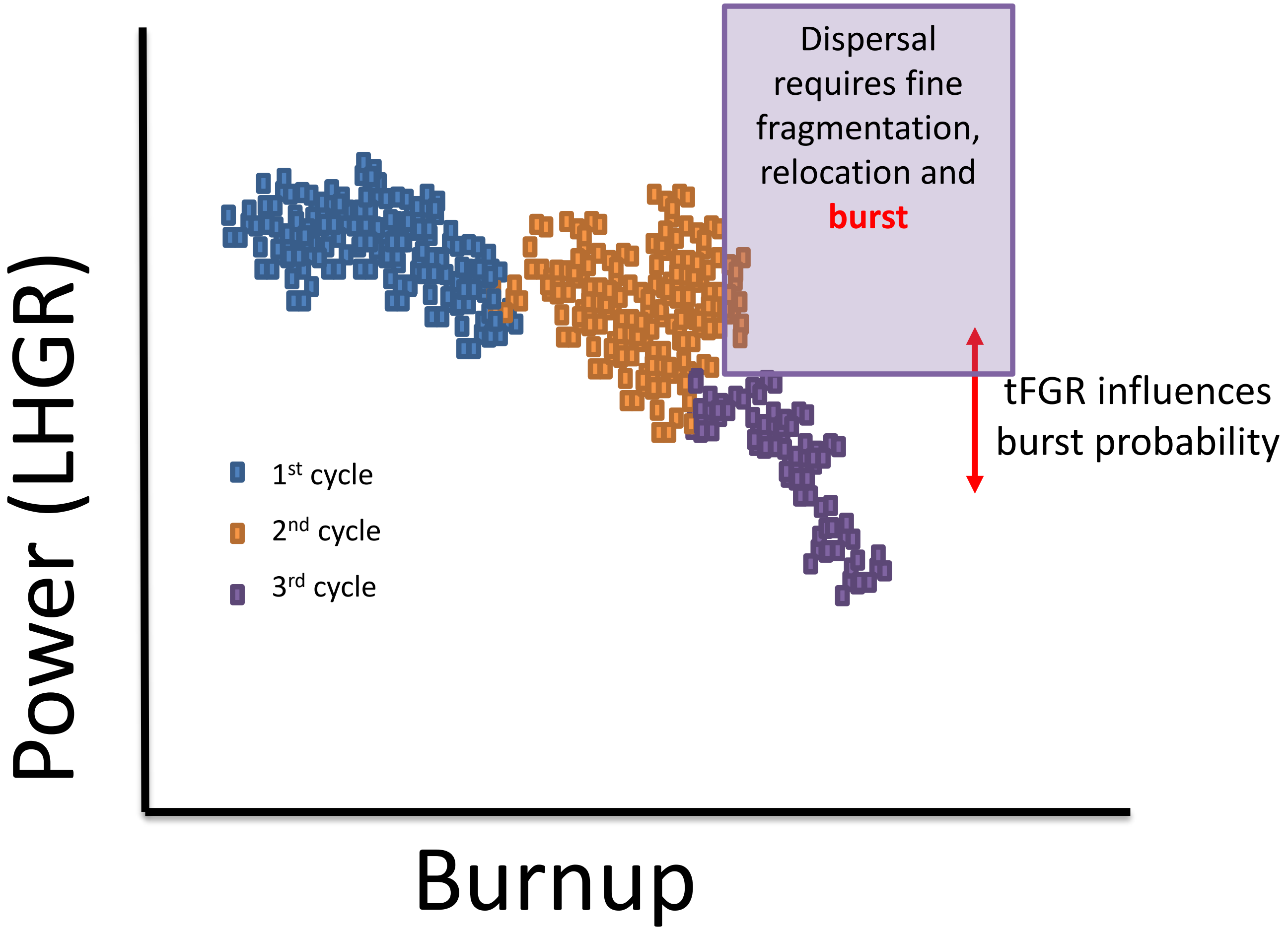
Overlap influenced by:

- ECCS response
- Plant design
- Loading pattern
- Fuel and cladding design

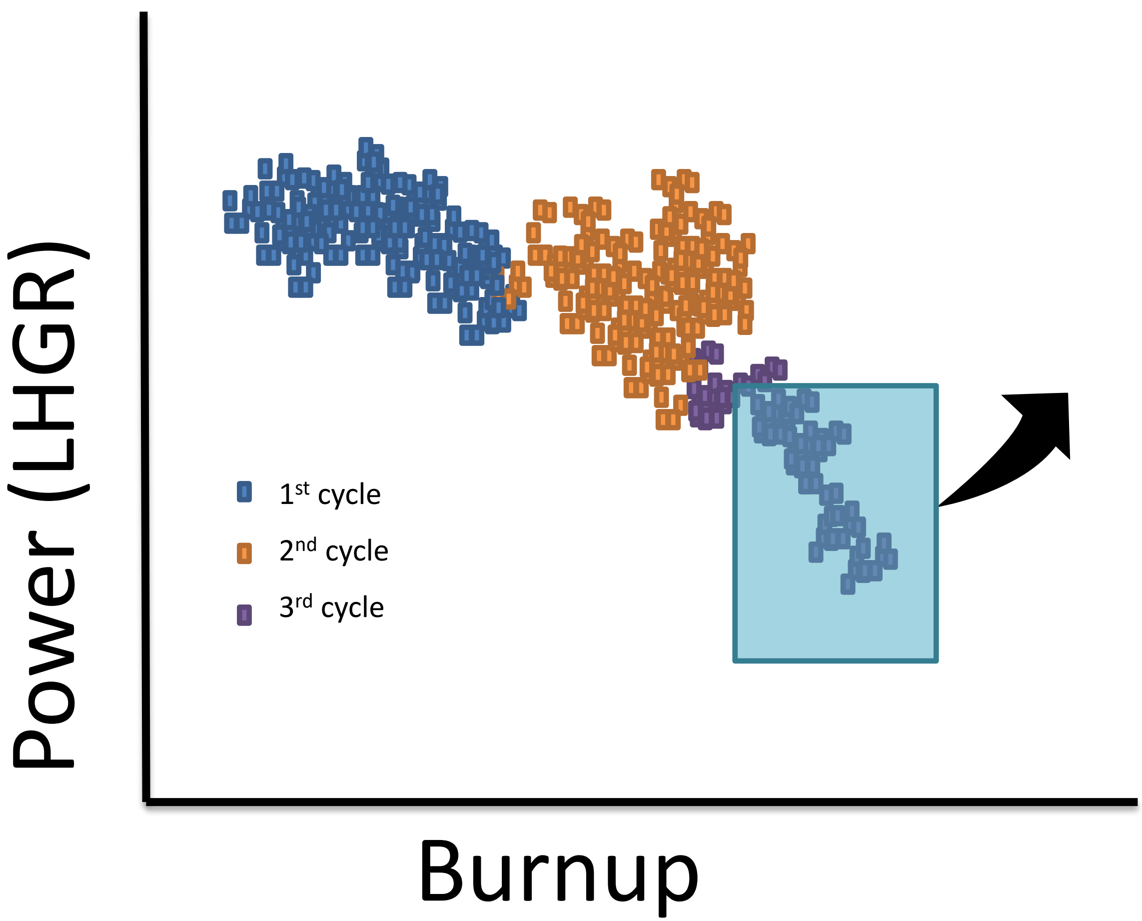
This information is prototypical of PWR. BWR's will have few if any rods susceptible to dispersal due to different operating practices, system pressure, etc.

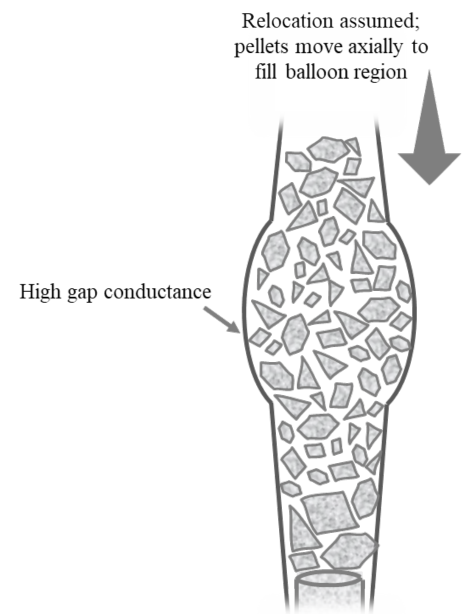


Transient Fission Gas Release - Increasingly important at higher burnup; Important to accurately predict burst



Relocation **packing fraction** - Important to accurately predict burst and peak temperature for non-burst high burnup rods





Assume the balloon region is 70-85% fuel (15-30% void) by volume for calculating rod behavior

The RIL supports targeted FFRD analysis

- Fine fragmentation
  - Not seen below 55
- Fuel axial relocation
  - Not seen in cladding with less than 3% strain
- Fuel dispersal
  - Fine fragmentation and relocation are prerequisites; Therefore, dispersal requires BU>55, strain>3%
  - Doesn't happen unless there's rupture
- Transient Fission Gas Release
  - Increasingly important at higher burnup
- Relocation packing fraction
  - Important for non-burst high burnup rods

This presentation will address…

FFRD history at NRC

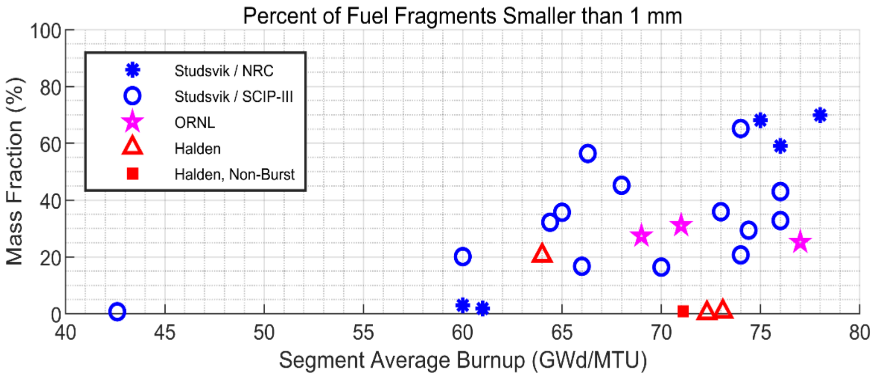
The programs cited in the RIL and the peer reviewers used

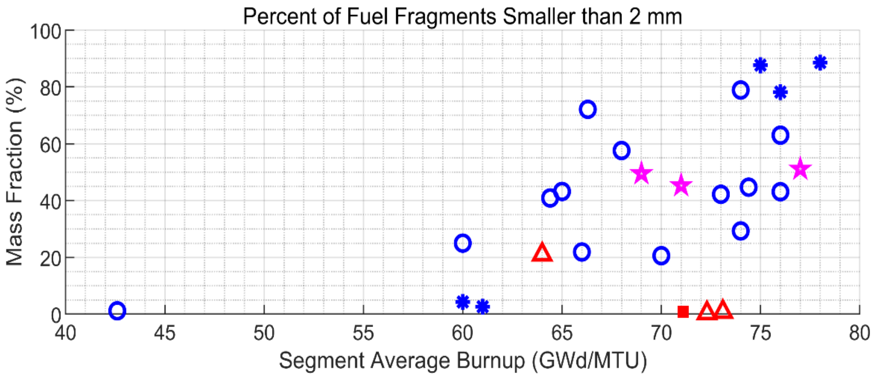
The outcome of the RIL

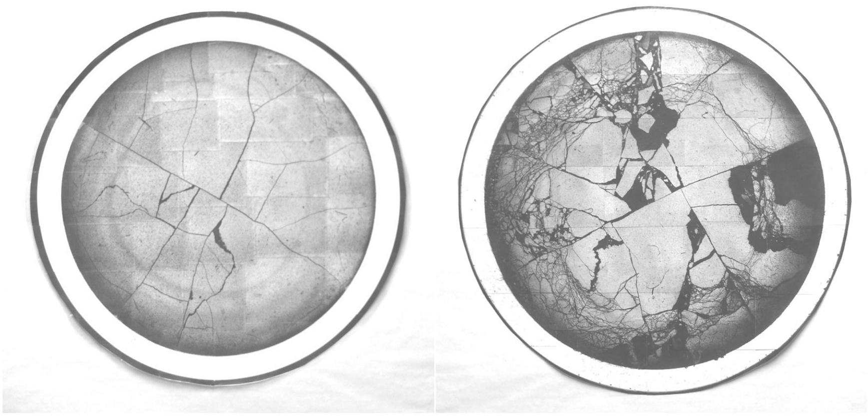
The basis for empirical thresholds included in the RIL

Other Matters

Element 1: Empirical threshold at which fuel pellets become susceptible to fine fragmentation





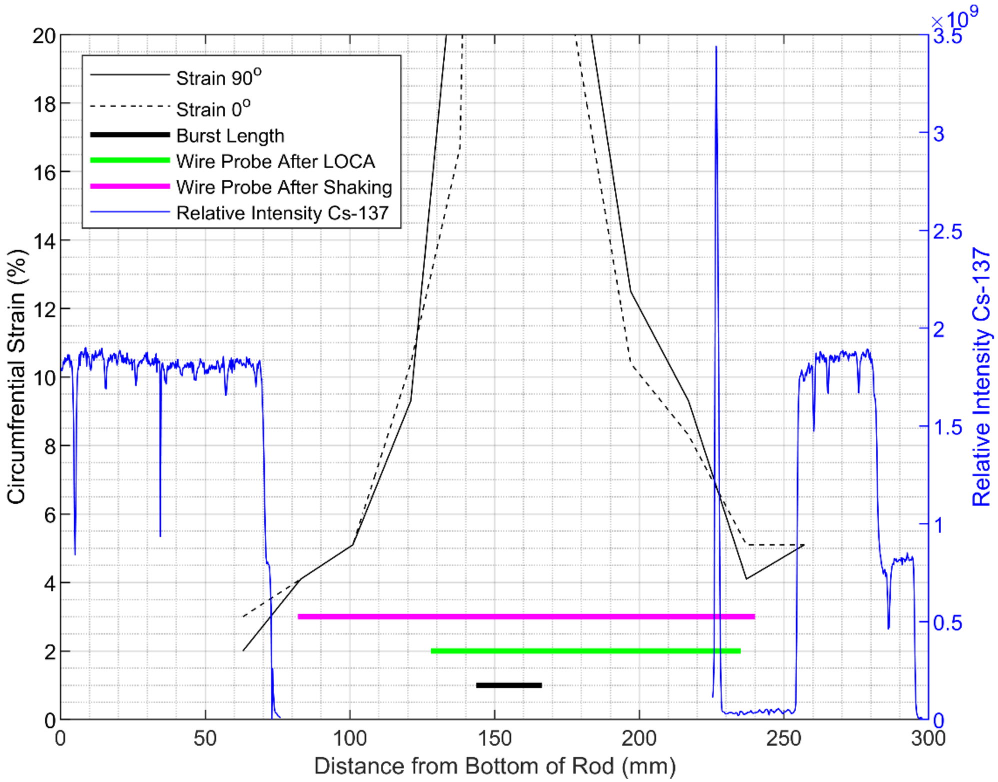


Segment from NRC's ANL LOCA program at 55 GWd/MTU before and after testing

Research supports a pellet-average burnup limit of **55 GWd/MTU** as the **onset of fine fuel fragmentation**

FFRD

Element 2: A local cladding strain threshold below which relocation is limited



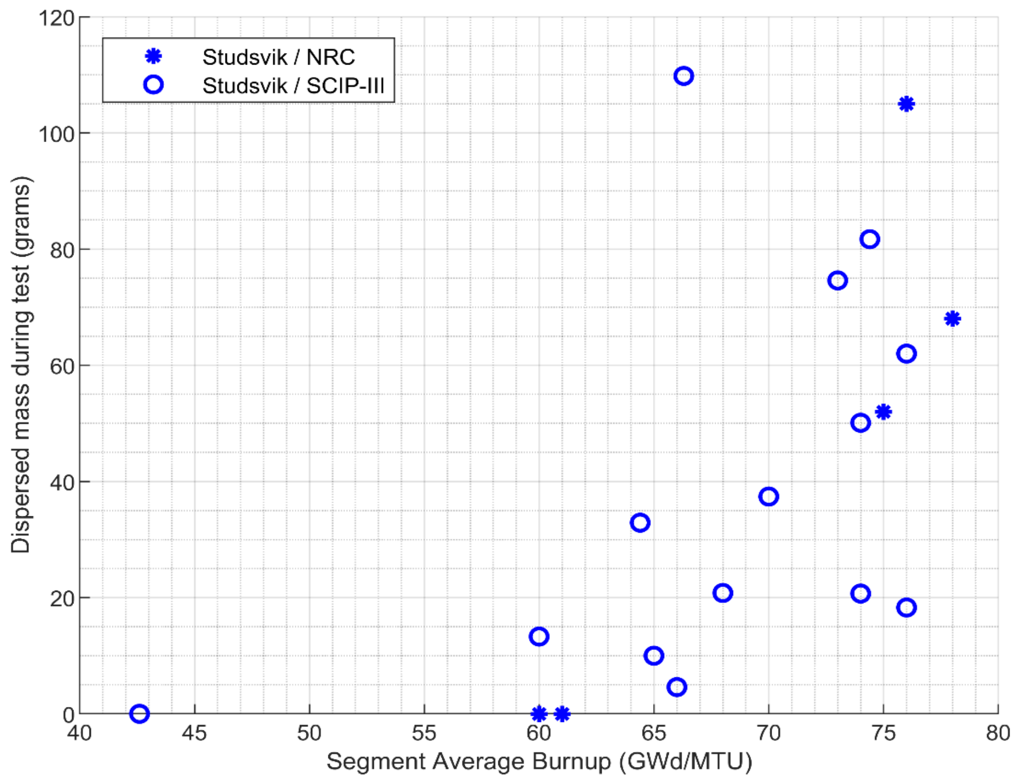
NRC test #	Strain threshold, top (%)	Strain threshold, bottom (%)
189	6.0	3.0
191	6.0	4.0
192	5.0	4.0
193	1.0	4.0
196	3.0	5.0
198	4.5	9.0

Research suggests **fuel relocation is limited** in regions of the fuel rod experiencing **less than 3% cladding strain**.

FFRD

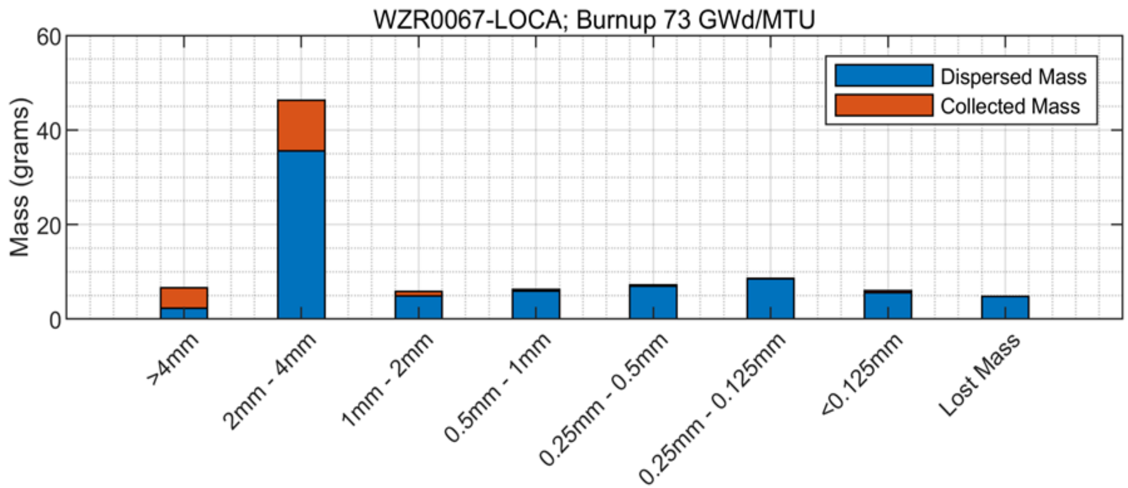
Element 3: A conservative value for the mass of "dispersible" fuel as a function of burnup

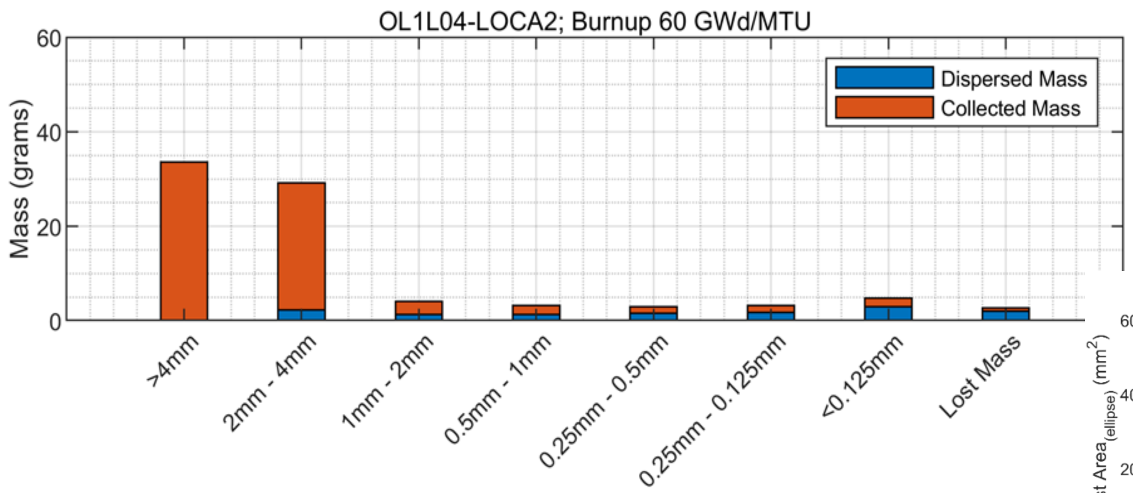
What do dispersal measurements look like?

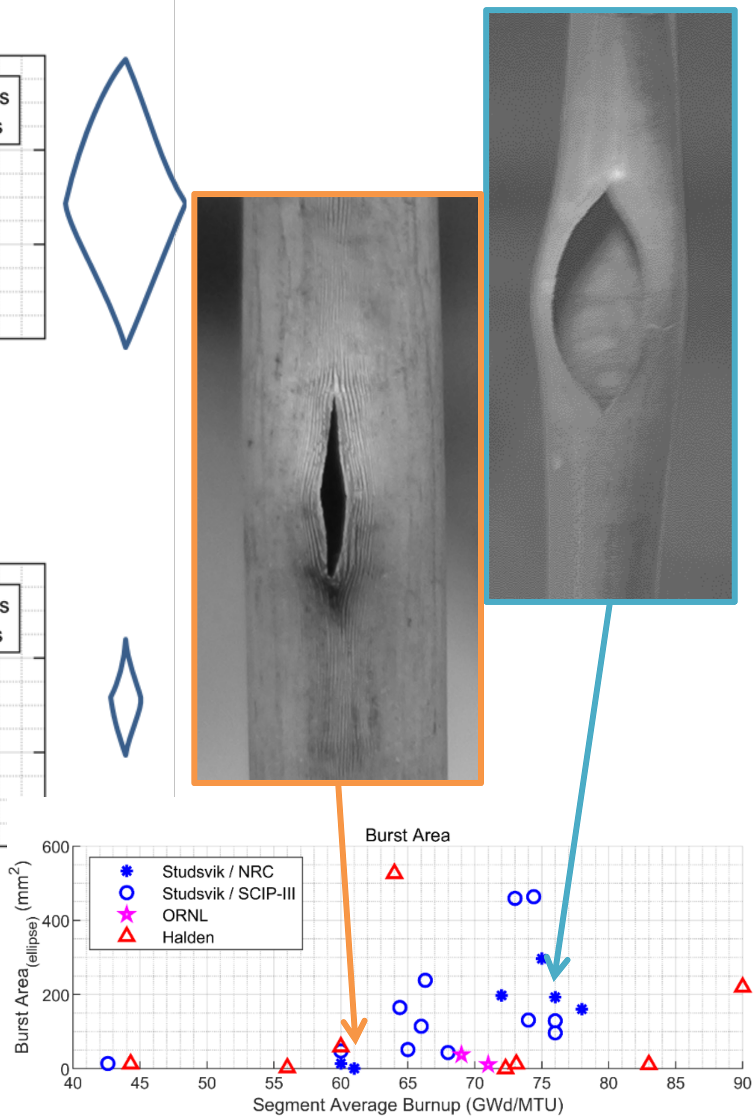


Dispersal "during the test"

Element 3: A conservative value for the mass of “dispersible” fuel as a function of burnup

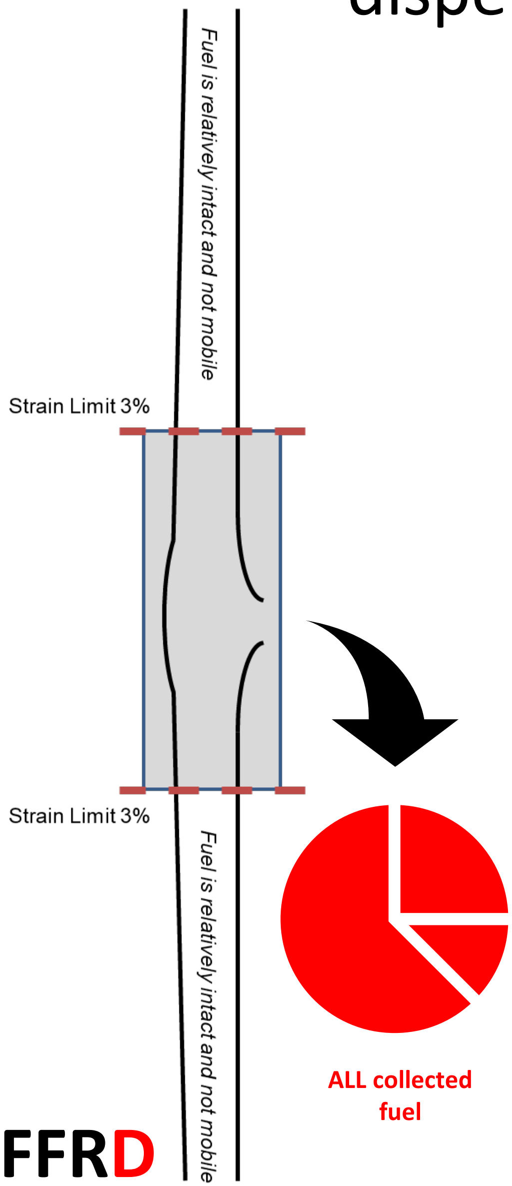






FFRD

Element 3: A conservative value for the mass of "dispersible" fuel as a function of burnup

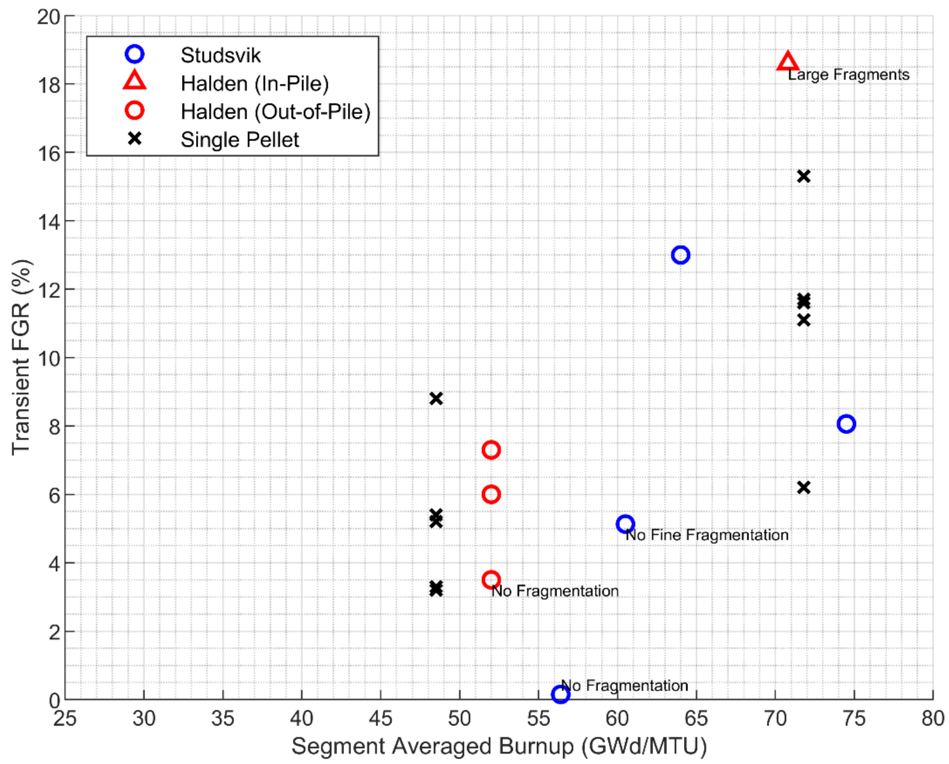


	Difference between dispersal predicted by the model and all mobile fuel observed in the experiment	
SCIP test	Mass (g)	Prediction/Measured
OL1L04-LOCA-2	125	250%
N05-LOCA	-19	76%
VUR1-LOCA-1	15	109%
WZR0067-LOCA	-16	83%
VUL2-LOCA1	-7	94%
VUL2-LOCA3	8	105%
VUL2-LOCA4	5	102%

Recommend a model to predict the mass of fuel dispersal to be all fuel above the **burnup threshold of 55 GWd/MTU** in the length of the rod with **greater than 3% cladding strain** to disperse.

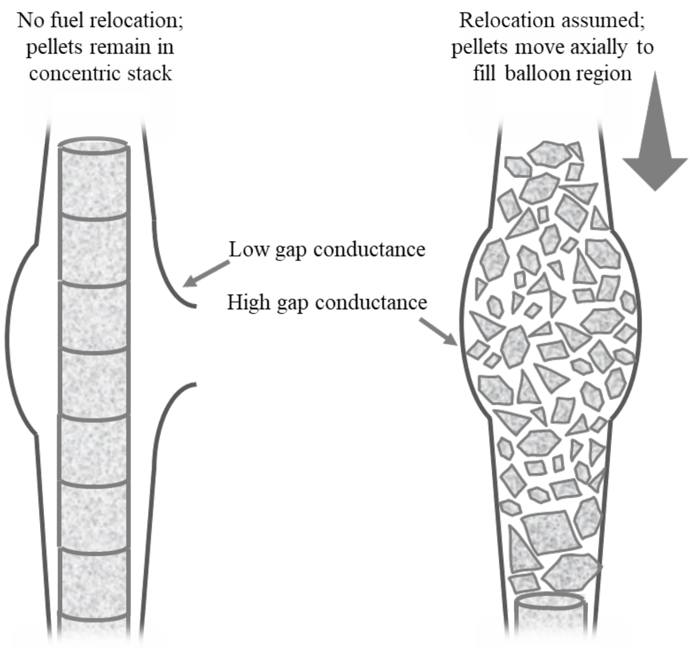
FFRD

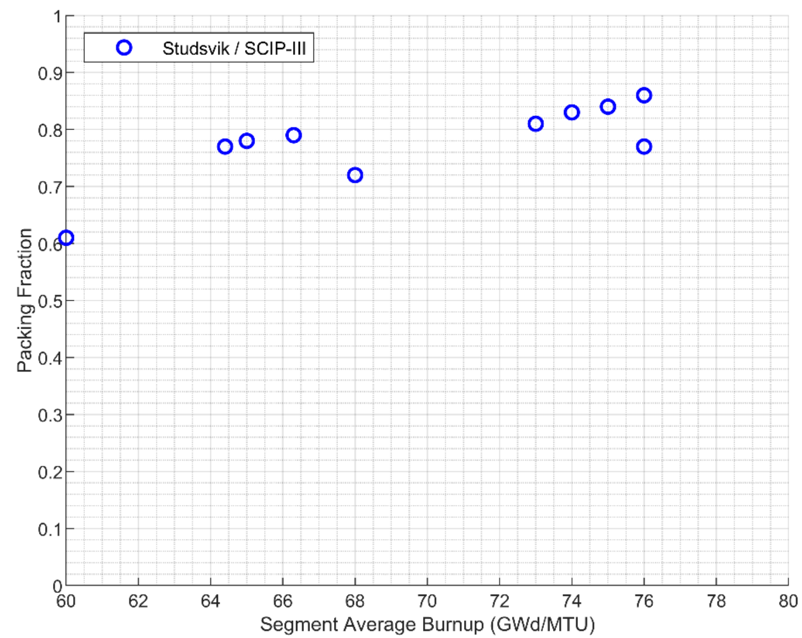
Element 4: Provide evidence of significant tFGR that may impact ballooning and burst behavior of high burnup fuel under LOCA conditions



Data shows increasing transient fission gas release with burnup. However, many other factors besides burnup impact tFGR (e.g., fuel temperature, stresses in fuel). Licensees will need to address tFGR in their LOCA evaluation models. Some models exist for tFGR, but more validation of those models is needed.

Element 5: Establish a value for the packing fraction of relocated but non-dispersed fuel in the balloon region





It is reasonable to use packing fraction values between 70 to 85 percent for fuel susceptible to fine fragmentation. (Fuel at lower burnup would likely have a lower packing fraction).

To determine the impact on ballooning and burst, it is important to examine a range of packing fractions to account for these effects.

This presentation will address…

FFRD history at NRC

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Other Matters

Discussion of Consequences and Consequence Modeling

- Refers to SECY-15-0148 and NUREG-2121
- Reiterates potential safety concerns associated with FFRD:
  - energetic fuel-coolant interactions
  - recriticality of dispersed fragments
  - core coolability and long-term decay heat removal
  - radiological impacts, including control room dose and equipment qualification*

** Being addressed outside of the RIL, as part of an update to Regulatory Guide 1.183, "Alternative Radiological Source Terms for Evaluating Design Basis Accidents at Nuclear Power Reactors."*

Limitations of the Empirical Database

- Limits are not applicable to doped fuel or coated cladding.
  - Additional research could demonstrate that the limits in the RIL apply or are bounding
  - Note doped fuels have different FGR behavior, so it would be important to understand implications on FFRD
  - Note coated claddings have been shown to have less strain and smaller burst openings, which could mean better performance with respect to FFRD

Limitations of the Empirical Database

- Limits are simplistic, derived as a function of burnup only.
  - Burnup is likely a surrogate for more direct variables such as porosity, stresses within the fuel pellet, grain growth and subgrain formation. These features are likely influenced by operating history
  - Additional research to allow for more mechanistic treatment of these variables could allow for refinement of the limits
- Limits anticipate accurate prediction of cladding strain along the axial length of a fuel rod. Burst opening size is presumed to be stochastic and therefore limits assume large opening size.
  - Additional research to validate balloon height, axial strain profile and burst opening could allow for refinement of the limits

What's next?

- Participating in SCIP IV
  - Includes testing of non-standard fuel
  - Additional testing to characterize tFGR
  - Testing in the mid-level burnup range
- Refining analysis tools to improve core-wide FFRD analysis
  - Building from 2015 and MELLLA+ experience
  - Enhancing resolution and realism
  - Utilizing new modeling features

What's next?

- RIL will establish foundation for next steps
  - Industry can build from the RIL based on their licensing needs, justifying less conservative limits with more detailed/product specific arguments
  - Researchers can build programs from the RIL that produce the information needed to go further


Questions?