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NUCLEAR REGULATORY COMMISSION

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ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

(ACRS)

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MATERIALS, METALLURGY AND REACTOR FUELS SUBCOMMITTEE

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WEDNESDAY

DECEMBER 4, 2013

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ROCKVILLE, MARYLAND

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The Subcommittee met at the Nuclear Regulatory Commission, Two White Flint North, Room T2B1, 11545 Rockville Pike, at 8:30 a.m., J. Sam Armijo, Chairman, presiding.

COMMITTEE MEMBERS:

J. SAM ARMIJO, Chairman
RONALD G. BALLINGER, Member
SANJOY BANERJEE, Member
DENNIS C. BLEY, Member
DANA A. POWERS, Member
HAROLD B. RAY, Member
JOY REMPE, Member
PETER C. RICCARDELLA, Member
STEPHEN P. SCHULTZ, Member
GORDON R. SKILLMAN, Member
JOHN W. STETKAR, Member

ACRS CONSULTANT:

WILLIAM J. SHACK

DESIGNATED FEDERAL OFFICIALS:

ZENA ABDULLAHI
CHRISTOPHER L. BROWN

ALSO PRESENT:

EDWIN M. HACKETT, Executive Director, ACRS
JOHN ALVIS, ANATECH/SI
TARYN BURSA, NRR
GORDON CLEFTON, NEI

PAUL CLIFFORD, NRR
BOB CLOSE, CENG
BERT DUNN, AREVA
TOM EICHENBERG, TVA
MICHELLE FLANAGAN, RES
LISA GERKEN, AREVA
KATHY HALVEY GIBSON, RES
TARA INVERSO, NRR
RICHARD LEE, RES
MARVIN LEWIS*
KURSHAD MUFTUDGLU, GE Hitachi Nuclear Energy
IAN PORTER, RES
PATRICK A.C. RAYNAUD, RES
HAROLD SCOTT, RES
KEN YUEH, EPRI

*Present via telephone

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

P R O C E E D I N G S

(8:33 a.m.)

CHAIRMAN ARMIJO: Good morning. The meeting will now come to order. This is a meeting of the Materials, Metallurgy and Reactor Fuel Subcommittee of the Advisory Committee on Reactor Safeguards.

I'm Sam Armijo, Chairman of the subcommittee. Members in attendance today will be Dr. Banerjee. He's moving hotels, so he'll be a little bit late.

(Off the record comments)

CHAIRMAN ARMIJO: Anyway, he will get here. We have Dick Skillman, Dennis Bley, Dana Powers, Steve Schultz, Ron Ballinger, Harold Ray and Joy Rempe. We also have former chairman of the ACRS, Dr. Bill Shack, who is helping us as a consultant. Bill, thanks for joining us. Zena Abdullahi is the designated Federal official for the meeting.

In today's meeting, staff from NRC research and representatives of industry will brief us on their work on the issue of fuel fragmentation, dispersal and following LOCA events or during LOCA events.

This is an ongoing technical issue that

the research staff has been investigating to determine how best to treat this phenomenon in the regulatory arena.

The in-pile and out-of-pile LOCA testing indicates irradiated fuel log rod segments that experience cladding, ballooning and rupture, are likely to exhibit some degree of fuel pellet fragmentation and, in certain instances, dispersal into the coolant.

In NUREG 2121, the RES staff studied the phenomenon and has addressed the influence of burnup. Subsequent to the NUREG, the research staff has also sponsored experimental work.

In addition, the industry has also investigated the phenomenon and developed positions on the potential for fuel dispersal considering issues such as plant type design, operation and fuel core response.

During the November 21st, 2013, fuel performance meeting, we heard of GE Hitachi's assessment of the problem. Today, EPRI and AREVA will inform us of their assessments and conclusions. The meeting is informational and is intended to update the subcommittee on the status of the ongoing investigation.

As the meeting is being transcribed, I request that participants use the microphones located throughout the room when addressing the subcommittee. Participants should first identify themselves and speak with sufficient clarity and volume so that they can be readily heard.

We will now proceed with the meeting. And I call on Kathy Gibson, Division Director of the Division of Systems Analysis in NRC research to begin the presentation. Kathy.

MS. GIBSON: Good morning. Let me first mention that we're here to talk about research aspects of this issue. But we have Paul Clifford here, and Tara Inverso is back in the audience from NRR that are here to answer any programmatic or regulatory questions you might have on this issue.

But our main presenters are Dr. Patrick Raynaud and Michelle Flanagan. They'll talk about the new insights in analysis of the phenomenon of fuel fragmentation, relocation and dispersal under LOCA conditions.

I want to go a little bit through the history of where we've been, and where we are and where we're going to kind of set the stage for the details that Michelle and Patrick will go over.

The work that they'll present is driven a research plan that we developed in 2011 to investigate this phenomenon.

We put together this research plan as a result of unexpected results that emerged from tests in our LOCA program in Studsvik. The Studsvik tests produced observations of significant fuel dispersal characterized by fine fuel fragments, almost looks like sand.

The fuel lines tested at Studsvik had a right average burnup near 70 gigawatt-days per metric ton of uranium. Halden tests used a very high burnup around 90 gigawatt-days.

Citings had already shown significant fuel dispersal, but the Studsvik tests were closer to the U.S. burnup limits and therefore garnered greater attention.

The first aspect of the research plan, as you mentioned, was a literature search to review all of the historical data available from the LOCA testing, the literature searches documented in NUREG-2121 which is the ACRS reviewed earlier this year.

And we just recently received your review of that, and we appreciate it. I understand that it's a little different from the NUREG that you typically

review. It looked like you struggled a little bit with reviewing it. But we appreciate the review nonetheless.

The second aspect of the research plan was a collective reassessment of experimental results of LOCA tests from Halden and Studsvik. This work will be presented by Michelle Flanagan.

Michelle spent two months at Halden Experimental Laboratory facilities reviewing supplemental post-test examinations discussing results and observations from Halden staff and working next to investigators observing the latest LOCA test segments. She also worked with Studsvik Laboratory to perform target examinations focused on emerging theories of the cause of the fuel fragmentation.

She will present a number of key observations resulting from a reassessment of experimental results. She is using observations to support a proposal for the mechanisms and conditions controlling fuel fragmentation, relocation and dispersal behavior.

The observations and proposal of the controlling mechanisms will be used to discuss a regulatory evaluation strategy of fuel fragmentation, relocation and dispersal behavior.

The regulatory evaluation strategy involves thresholds of the onset of fine fuel fragmentation in terms of fuel burnup and local cladding strength.

The third aspect of the research plan used these thresholds to predict the quantity of fuel dispersal that could occur under LOCA conditions.

Patrick will present this work. He spent over six months developing a strategy which partnered NRC's thermal hydraulic code, TRACE, an NRC steady-state and transient fuel performance codes, FRAPCON and FRAPTRAN, to generate highly detailed core-wide predictions of fuel rod ruptures.

He will present the predictions for fuel dispersal for three different variants of a PWR large break LOCA scenario as well as scoping work with the BWR.

His predictions of dispersed fuel were made for several combinations of the proposed fuel burnup and local cladding strength thresholds and therefore provide some preliminary insight into the sensitivity of fuel dispersal to not only plant type and local scenario but also to the proposed driving forces for fuel fragmentation, relocation and dispersal behavior.

So with that introduction, I will turn the floor over to Michelle and Patrick.

MS. FLANAGAN: Thank you, Kathy. So as Kathy said, my presentation today is going to be on experimental observations that we've collected for fuel fragmentation, relocation and dispersal under LOCA conditions.

I'll give a brief background of the experimental work and then highlight a couple of key observations that we focused on as we were reviewing the information and use those observations to support a proposal for the mechanisms that are causing fuel fragmentation, relocation and dispersal under LOCA conditions and then finish with a couple of conclusions.

So for background, the first observation of fuel dispersal was over ten years ago in the Halden reactor program. This phenomenon was first observed, but it was so unexpected that most of the explanations and discussions were really focused on what was non-typical about those experiments and kind of trying to look at what had happened and why it wasn't normal.

Over the next couple of years, we saw these results again so they were repeatable. But still the data was very limited. Then in the most

recent history, around 2010, 2012, we saw that our results at Studsvik repeated significant fuel dispersal.

It started to become something that couldn't be ignored and became a subject of international meetings, and discussions and research program plans that were aimed at resolving them.

However, despite the number of observations that we had by 2012, there still wasn't a unified description of why this was happening or really the ability to identify trends.

And you saw this a little bit in NUREG-2121. There was a lot of information and there was a lot of scatter in that data, the experimental conditions as well as the observations. So it was really hard to put together a theory at that point.

So as Kathy mentioned, we developed a research plan to identify what was needed to learn more and resolve what was going on in these tests.

And so we collaborated with the Halden Reactor Project and Studsvik to review some of the examinations that they had performed on their past rods which, for whatever reason, weren't presented in the enlarged Halden program. You know, there were supplemental images or discussions that we had with

the staff to find out other observations that they had had personally.

And then at Studsvik we ordered a couple service examinations that were based on what we suspected might be going on. So we asked them to look at this specific area, because we thought it could have some insight.

And once we did that work, we came up with five key observations. And I'm going to go into all of these in detail and describe why each of them is significant. So for now I'll just read them.

The first is that extensive fragmentation was not present before the testing. The second was that the extent of relocation and fragmentation was correlated with the local strain of the cladding and the proximity to the rupture location. The third was that there was a significant change quite rapidly somewhere between 60 and 70, some high and very high burnup tests.

We also noticed that pressure transducers in the plenum region, which is where the pressure is measured, sometimes showed slow depressurization which indicates that there are some gas flow restrictions between this plenum region, where the pressure is measured, and the rupture region, where the pressure

is released.

And then finally, for high burnup tests, most of the fine fragments that we collected seem to originate from the periphery of the pellet, and I'll explain how we return to this. Whereas for very high burnup rods, the fine fragments that were collected appear to originate from all radii.

MEMBER POWERS: Michelle, let me ask a question.

MS. FLANAGAN: Oh, already, yes.

MEMBER POWERS: If we go back to your conclusions --

MS. FLANAGAN: Yes.

MEMBER POWERS: You say the extent of relocation and fragmentation is correlated with the local strain in proximity to the rupture location. Is that the local strain in the fuel?

MS. FLANAGAN: Sorry, in the cladding.

MEMBER POWERS: In the cladding.

MS. FLANAGAN: Yes.

MEMBER POWERS: And then you indicate that there is a, you measure a slow depressurization. How is that unexpected? You've got a clad fuel bonding every time you get to these burnups. And so you would expect the flow in the gap region is going to be very

restrained.

MS. FLANAGAN: Well, that's true. We did sometimes see a very rapid depressurization though. Because they're short segments. And so in some cases, especially where the fuel was heavily fragmented along the entire length, we saw a lot of depressurization.

MEMBER POWERS: How do you know that informing the short segment you didn't damage the fuel clad bonding?

MS. FLANAGAN: Just in the cutting of the segment?

MEMBER POWERS: Yes, in making up the segment?

MS. FLANAGAN: I guess there weren't any examinations to confirm that there was still a bond after the cutting. But when I show the images of some of the slow depressurization, I think we'll see that there are cases where there's still a significant restriction between the plenum and the rupture.

And one of the reasons that this is significant is because, as I mentioned, when the tests first were conducted that showed significant fragmentation, one of the theories for why this was happening was that the plenum volume was proportionately larger than in a normal fuel rod and

that that was actually providing a driving force for dispersal.

And in that case, this observation is significant. It suggests that, and this is what I'll get into later, but it suggests that this phenomenon can happen with local forces and not necessarily from the plenum region. And in particular because these tests had a plenum region that was larger than --

MEMBER POWERS: It wouldn't me surprise me if something 14 feet away is going to drive the --

MS. FLANAGAN: Right. But in a one foot rod where --

CHAIRMAN ARMIJO: It'd make a difference, yes.

MS. FLANAGAN: -- these tests are conducted, it might make a difference. And so, oh, I think I'll answer more of your question as I get into those slides --

CHAIRMAN ARMIJO: Michelle --

MS. FLANAGAN: -- and maybe generate new questions.

CHAIRMAN ARMIJO: Okay. I just have a quick question. You said slow depressurization. Can you give me a time scale, you know, between the time of the rupture and the depressurization? Are we

talking about seconds?

MS. FLANAGAN: Yes.

CHAIRMAN ARMIJO: And just --

MS. FLANAGAN: About 60 seconds in some cases to get to full sort of equilibrium --

CHAIRMAN ARMIJO: And this is from a significant rupture in the --

MS. FLANAGAN: Yes.

CHAIRMAN ARMIJO: Okay. The second question, were some of the segments that you tested actually from a segmented fuel rod that had never been refabricated or they were, you know, just your base irradiation somewhere in a power reactor and then unscrewed and then tested?

MS. FLANAGAN: Oh, no.

CHAIRMAN ARMIJO: You didn't have any of those types of --

MS. FLANAGAN: You mean that when it was irradiated that it was already a segment that --

CHAIRMAN ARMIJO: Yes. It's already a full length, you know, partial length segment and rod. You know, a lot of --

MS. FLANAGAN: As far as I know that is not the case. They are all segments of a full length rod that were --

CHAIRMAN ARMIJO: The Germans' Kraftwerk Union used to have something like 20 inch what they call rodlets, that they routinely would donate to the Halden program for various tests.

MS. FLANAGAN: Yes.

CHAIRMAN ARMIJO: And GE, we also did the same thing with longer segments, about a meter long. And the reason we did that is because we were very worried that you change the results of the test by the refabrication process, including the issue of breaking up fuel clad bonding and things like that. But you're not sure?

MS. FLANAGAN: As far as I know, they were all segments that were cut from a full length rod.

MEMBER POWERS: Okay.

MEMBER SCHULTZ: Michelle, before you start into the observations that I see in the next slides, what is the general population of tests and rods that you examined while you were at Halden?

MS. FLANAGAN: You mean the burnup range?

MEMBER SCHULTZ: No. Well, the number of rods, the burnup range and the number of tests?

MS. FLANAGAN: Halden has run 13 of the LOCA tests. And the burnups range from, I think 45 is the lowest until 90 gigawatt-days per ton. And they

span BWRs, PWRs and VVER fuel, which has a central hole. So I'll explain why that might be important sometime later.

MEMBER SCHULTZ: Yes.

MS. FLANAGAN: And in one of my backup slides I have some other parameters that characterize these rods. But does that answer --

MEMBER SCHULTZ: These are test rods or they're test programs with several rods?

MS. FLANAGAN: These are test rods. They're all in generally the same series of Halden tests. The Studsvik rods are also, there were six Halden, sorry, six Studsvik tests. And two separate rods were tested in Studsvik.

So one rod was segmented into four pieces and then tested. And then the other one was a lower burnup run, 55 rod average. And that was tested in two segments.

MEMBER SCHULTZ: Thank you.

MS. FLANAGAN: So the first observation is extensive fragmentation is not present before the test, suggesting that it occurs during the LOCA transient.

It might seem obvious, but it was something that we wanted to confirm. We wanted to

make sure that when we looked at the pre-test images, we didn't see that these rods had extensive fragmentation before the test or that there wasn't anything unusual.

And so here's two examples of pre-test conditions and post-test images which show a significant difference. And also the pre-test conditions look generally like we would expect at end of life. So there isn't anything unusual about the fragmentation pattern of these particular rods.

And this was the case in all of the rods. We have pre-test images of about half of them. But some of them are proprietary. So these are the ones that have been published by Halden.

A second observation, I think I have two or three slides on this. The extent of fragmentation appears to be related to local strain. So in this case, this is a high burnup rod which had an asymmetric strain profile.

And we see that where the strain was very large, and these lines indicate ten percent strain and five percent strain. In the ten percent strain region we have extensive fragmentation across the entire pellet cross section. The rupture location is also indicated with a black dot here.

So near rupture and where the strain is very large we see extensive fragmentation and very fine fragments. But on the same rod, in the top region of the rod where the strain was low, about five percent, we see a more intact pellet.

This rod still experienced fragmentation during the transient, and we do believe that this occurred during the transient and not present before the test. But we see much less fragmentation than we see in these images.

I'm not sure if you can, if you blow these images up you can see that all of this gray area is actually very fine hairline fractures throughout the whole pellet.

MEMBER BALLINGER: The power history for these, excuse me, the temperature transient for the highly fragmented section and the temperature transient for the one at the top, are they the same?

MS. FLANAGAN: Similar. In the Halden test, because they are in-pile and they're heated, they've come to power. The temperature profile across the length of the fuel is actually pretty good. I have a backup slide that discusses it.

But keep that in mind when we look at the Studsvik test. There the temperature profile is very

focused in the center, and it's much hotter in the center than in the periphery region. But certainly in the periphery region on the bottom and top, I don't know if I can show --

MEMBER BALLINGER: I'm more interested in the temperature transient versus time in the various places. Anyway, okay.

MS. FLANAGAN: Okay. So across the axial length it's pretty consistent in the Halden test. And it would be that way throughout the whole test. But I don't actually have a backup slide on that. I have some information with it.

CHAIRMAN ARMIJO: Well, there would be a thermal shock to a hot ceramic when you open it up, release the gas, steam, water, whatever it is, gets back in there. And the rods aren't instrumented, so you really don't know what the temperature might be unless you do model.

MS. FLANAGAN: On the Halden tests they have thermocouples, they have thermocouples on the top and bottom on most segments, not in the center region but on the top and bottom. They have the thermocouple on the cladding. And then they also have thermocouples in the --

CHAIRMAN ARMIJO: In the fuel?

MS. FLANAGAN: No, sorry, on the cladding. It's on the cladding there by the --

CHAIRMAN ARMIJO: Okay. That will tell us.

MS. FLANAGAN: Okay. Another aspect of this fragmentation in the relationship with strains can be shown in the series here. When we saw a large strain along the entire axial length, we observed fragmentation along the entire axial length.

When we observed a strain profile that was very narrow and only large in one segment, we observed fragmentation only in that segment. And when the strain profile was asymmetric, we also saw a fragmentation pattern that was asymmetric.

So this was part of the observations that suggested that this fragmentation is correlated to the local strain in some way.

CHAIRMAN ARMIJO: Thank you.

So what I just showed here is the Halden test. And here is an observation from Studsvik which says something very similar. This was one of the higher burnup rods at around 70 gigawatt-days per ton. And during the test we saw significant fuel dispersal. And it was very fine fragments.

This graph just depicts the distribution

of the fine fragments. And you can see that many of them were smaller than 125 microns. So we had almost sand-like fragments from the central region here. However, there was still fuel left in the segment after the test.

And if you either, this Studsvik program not only did a local simulation, but after the local simulation we actually shook the rods to see if any residual fuel would fall out. So the fuel that's left in these rods really is stuck. It's not coming out. It was shaken, and it did not come out.

So the segments that remained fuel were analyzed most recently. So this is one of the exams that we added after we started to think about theories. And we observed a region near the fuel relocation boundary to see what the fuel looked like in that region and then an observation lower in this fuel segment.

And the image lower in the fuel segment looks relatively intact. There's some hairline fractures and there are maybe some fractures beyond that which we would expect at end of life.

But in comparison to the sand-like fragmentation, there's certainly a difference between what was going on in the center region and what was

going on in the end sections.

However, as I mentioned earlier, the Studsvik test had a much deeper temperature gradient along the axial length. So not only was the strain lower in these extremities, but the temperature was also lower. So it's hard to differentiate in the strain and temperature.

MEMBER SKILLMAN: Michelle, let me ask this question. In this discussion, what is your definition of LOCA?

MS. FLANAGAN: In Studsvik we ran pretty much a large break LOCA-like scenario where a rampup of about five degrees per second up until 1,200 degrees C. And in each of the Studsvik tests there was a different hold time at 1,200.

In the Halden tests, however, some of the rods only went to 850. They were attempting to have more realistic transients.

MEMBER SKILLMAN: So this is an electrically heated dry pin?

MS. FLANAGAN: In the Studsvik test there was a clamshell furnace providing radiant heating external to the rods. So it was really heating up the cladding.

DR. RAYNAUD: That's in the steam.

MS. FLANAGAN: Sorry?

DR. RAYNAUD: It was in steam.

MS. FLANAGAN: In steam, yes.

MEMBER SKILLMAN: In steam.

MS. FLANAGAN: In the Halden test, they actually bring the rods to power. And so there is some nuclear heating internal to the fuel as well as booster heaters to reach very high temperatures.

MEMBER SKILLMAN: Okay. Just the flip side, there is no forced cooling associated with this test. In other words, this is either radiant or internal heating for the pellet and the clad. And so what we're really seeing is the relationship of the expansion and contraction of the pellet versus the cladding.

MS. FLANAGAN: Yes. Well, I'm not sure.

MEMBER SKILLMAN: When I think LOCA, I think cladding strain based on cooling water that shrinks the clad against what could be a swelled pellet leading to cladding failure.

MS. FLANAGAN: Well --

MEMBER SKILLMAN: And I think what you're saying is, no, we didn't flood this cavity and chill the cladding. What we had was a heated clad and pellet either based on radiant heating or some nuclear

heating and in a steam environment. But it didn't have forced cooling water on it.

MS. FLANAGAN: There was a quench process initiated in the Studsvik test. But all of that occurs after the rupture has already occurred. And so even in a real scenario, we would see the same phenomena where you have the steam environment, heatup, rupture and then cooling.

MEMBER SKILLMAN: Oh, I see. This is what Dr. Ballinger was asking about. What's the rate of cooling, what's the cooling rate at that 20 centimeters? And that's what I'm really going after here. You got off the bottom of that pin is what we're seeing the consequence of local fueling against that very hot pin and clad.

MS. FLANAGAN: I agree with you, but the phenomenon that you're describing is taking place after a lot of this has already evolved. So I don't have it in here, but I can send a picture of the LOCA transient and the temperature at transient that shows the cooling rate after the rupture and a lot of the fragmentation has occurred.

CHAIRMAN ARMIJO: Michelle, if you could just very quickly tell us how the in-reactor experiment was performed, you know, starting with the

rod to power, somebody does something and all of a sudden you have a LOCA.

MS. FLANAGAN: Okay. I will, to the best of my knowledge, describe what Halden does. So they have the rod heated at some relatively low power but at certain kilowatts per foot. I don't remember what it was.

And then at one point when they're running the test they evacuate the coolant. They're in capsules, so they remove the coolant from that capsule. And that starts the nuclear heatup.

If they're running a very high temperature test, at one point, usually after rupture I think, there are rods which, I'm sorry, not rods but heating elements which provide supplemental heat to actually achieve 1,200 degrees C. And then after the planned temperature transient they flood the capsule.

MEMBER BALLINGER: So that's Halden, right?

MS. FLANAGAN: Right.

MEMBER BALLINGER: And Studsvik it's an externally heated.

MS. FLANAGAN: Correct. But the same general process happens where they --

MEMBER BALLINGER: Huge difference in the

heat flow and the gradients in temperature between the two --

CHAIRMAN ARMIJO: Yes.

MEMBER BALLINGER: -- between the two.

CHAIRMAN ARMIJO: Yeah, sure.

MEMBER BALLINGER: Especially if it's very fast. So in one case, if you heat it from the outside and it's internally pressurized, the cladding strain is driven by the heat flux into the thread.

And the fuel doesn't see the temperature gradient that would be from nuclear heating from the outside, from the inside out. It only takes, I think, if I recall, Steve, you're the fuel performance quota expert here, at least in the past, it takes only maybe 20 degrees Centigrade gradient across the pellet to crack it.

So if you have a very steep temperature gradient one way or the other, and I'm not sure which one is worse, probably the inside out, it's all elastic cracking if you stay below 1,100 C, right?

MEMBER POWERS: What exactly is elastic cracking?

(Laughter)

MEMBER BALLINGER: When the fuel pellet, the UO2 doesn't become, there's a sort of boundary at

about 1,100 C where the fuel behaves elastically below that temperature.

(Simultaneous speaking.)

MEMBER POWERS: It's what?

(Simultaneous speaking.)

CHAIRMAN ARMIJO: No, ductility isn't the right word. But it certainly --

MEMBER POWERS: Yes, it is.

(Simultaneous speaking.)

MEMBER BALLINGER: There's something called a bridging annulus, all right, where there's a region where you get no restructuring, but it's still elastic. Above 1,100 C you start getting lots of diffusion and migration. And above about 1,600 or 1,700 C you get another region. And then you get the holes in the fuel.

MEMBER SCHULTZ: Yes. But the point is, with regard to the point that Dick has brought up and what you're chasing also, Ron, is what is the nuclear heating. What is the coolant transient? So what are both those transients happening in the fuel and outside the fuel and how well does this match to what is a predicted LOCA --

MS. FLANAGAN: Yes.

MEMBER SCHULTZ: -- and experimental and

analytical results associated with that.

MEMBER SKILLMAN: And stimulation from what pelum's doing and what the clad is doing which is growing or shrinking and which grips which first.

MEMBER BALLINGER: Well, for external heating you're decoupling the cladding from the fuel almost instantaneous for the first part of the transient at least. And for internal heating, you're --

CHAIRMAN ARMIJO: The other way around, yes.

MEMBER BALLINGER: -- coupling the fuel to the cladding.

MEMBER SKILLMAN: And the effective cooling is also going to increase that coupling perhaps to the point of failure.

MEMBER BALLINGER: Yes. So for external heating, a lot of times you'll see ballooning. For internal heating, you don't necessarily see ballooning as quickly.

MS. FLANAGAN: One of the slides --

MEMBER BALLINGER: That's when internal pressure started, yes. Excuse me.

MS. FLANAGAN: I think that one of the slides I have coming up will show some of the strain

profiles in the two test programs. So we'll see there are some differences.

But one of our original questions when we started to look into this was whether we could really compare and group together the observations of Halden and Studsvik. Were they similar enough that we could take it as a data set?

And I think there're still some questions about how comparable they are when you're looking at really fine parameter observations, so the strain, temperature and --

MEMBER BALLINGER: If you take a UO2 pellet and put it in an induction heater and ramp it just sitting there, no cladding, no nothing, if you ramp it fast enough you'll explode that pellet, literally, just because of the thermal fracturing of the pellet.

MS. FLANAGAN: Well, what I can say is that the cladding temperature profile in the Studsvik and Halden test is similar. The fuel temperature profile could be different based on the different heating methods.

CHAIRMAN ARMIJO: And it will be. It will be very different.

MS. FLANAGAN: And yet, we see similar

observations generally. The burnup where we start to see fine fragmentation is similar in both programs. The apparent impact of strain is similar in both programs.

So there's more work to be done to say that they can be compared as one set. But I think that they're not showing dramatically different conclusions, in one case getting fine fragmentation, in another case none. So I'll talk a little bit more about that with the other observations.

CHAIRMAN ARMIJO: Okay.

MS. FLANAGAN: So another aspect of the relationship between fragmentation and strain, actually fragmentation, and relocation and strain, is that we see a threshold for relocation.

If the strain is low enough, we see the fuel isn't able to relocate axially, right? And so in this slide, I'm comparing an observation from Studsvik and an observation from Halden. I think I have this highlighted.

And in Studsvik we see that where the strain goes below three to five percent is where there's fuel remaining in the rods even after the shaking.

This Halden test was scanned when it was

horizontal. So the image, that area on the right, was actually on the top of the --

MALE PARTICIPANT: Vertical.

MS. FLANAGAN: -- vertical, sorry. And so we see a couple of pellets that were not mobile at the very top. And then below that we see a void where the fuel has slumped down into the ballooned and ruptured region. So again, we see a threshold of strains, or we're attributing it to strains, in the Halden test.

CHAIRMAN ARMIJO: So let's see. Those pellets at the 350 millimeters and above, that was all the fuel that was there?

MS. FLANAGAN: In this particular test, yes.

CHAIRMAN ARMIJO: Yes. Which means that the only thing that was holding them up there was clad bonding or either interference. So the fuel doesn't actually, is that typical that the fuel doesn't relocate unless you have some other, you know, it doesn't actually collapse?

MS. FLANAGAN: Well, that's what I'm saying, is that when the strain is low it is typical, that if the strain is low enough we don't see these fuel pellets relocating axially. And it seems to be a function of how extensive that low strain region is.

I have another slide, it might be next, which would show the number of these neutron radiography scans. I think it's on, it's Observation Number 4.

So the third observation is that we saw significant change in fragmentation size between high and very high burnup tests. And, as I said before, we see a similar size distribution change in the Halden and Studsvik tests.

So in both Halden and Studsvik we have an observation below 60 gigawatt-days per ton. But we see chunks of pellets, either macroscopic, maybe on the order of what you would expect end of life chunks of a pellet.

And then above 70, we start to see a much finer fragmentation size, almost like sand. And we see it in both Halden and Studsvik. So somewhere between about 50 and 70 we see a rather abrupt change in the fragmentation size.

MEMBER SCHULTZ: And we would say that these tests, the conduct of these tests, there's some differences between Studsvik and Halden. But otherwise, you would say that the conditions associated with the testing, the hydraulic as well as the thermal conditions that the rods were subjected

to, are similar. They're not the same, but they're similar.

Therefore we can conclude that we're seeing, the result is in fact a function of burnup, not something associated with differences in testing.

MS. FLANAGAN: Based on the proposal that I'll talk about later, I think that the things that are important to this fragmentation are the same in both tests. So if the proposal is true, that's really driven by what I pictured them by. Then the two tests are producing similar test conditions.

But that's only if the proposal is true, and it's not being driven by something which is very different in the two test proposals. So that's what we think.

CHAIRMAN ARMIJO: So you suggest the pellet properties are the key thing that's driving everything.

MS. FLANAGAN: Yes. And I think what we're concluding is that there're some pellets which, at some burnup, become vulnerable to this fragmentation. But it might be more complicated than just burnup. It's some other, how the structure of the pellet develops with burnup.

So it might not be burnup as much as a

porosity factor or a restructuring of the grains, at what level that happens. So burnup is a sort of general indicator of things that are happening as the pellet --

MEMBER POWERS: Was there a significant difference in the linear heat rate to achieve these levels of burnup?

MS. FLANAGAN: For the test or for the operation?

MEMBER POWERS: For the operation.

MS. FLANAGAN: That is something that is only being looked at more closely now. And I think that Ken will talk a little bit about that. There are some differences between the segments and their operation history. And it could have an influence on the --

MEMBER POWERS: Well, it's not could. It definitely does have an influence on the microstructure.

MS. FLANAGAN: Right.

MEMBER POWERS: And the distribution of the gas bubbles and things like that.

MS. FLANAGAN: I don't have anything about that in my presentation. But I think you'll hear something along those lines from Ken.

So to quantify this difference in fragmentation size, at Studsvik we performed sieve analysis on all of the fragments that were collected from both the high and very high burnup tests.

And so all of the images that are in red are the distribution of the fragment size in the very high burnup tests. And the blue bars represent the high burnup tests.

And so in the very high burnup tests we see an even distribution almost on all the size groups for fragmentation size. And we see a lot of fragment size in the 125 micrometer and then in the different groupings.

In contrast, for the high burnup rods around 55 or 60 gigawatt-days per ton, we see almost exclusively large fragments, larger than four millimeters. There are some in the smaller groups, but mostly you have large fragments.

Okay. So now I'm going to talk about this pressure change issue or observation and why I think it's important.

In the Halden tests, most of the depressurization was almost instantaneous. The graph on the left hand side shows Test Number 4, the TRACE Test Number 4, which is a representation of most of

the transients.

As soon as rupture occurred, the depressurization that was measured in the plenum was almost instantaneous. However, three Halden tests showed a more slow depressurization. And this slow depressurization was similar to what we saw in all of the subject tests.

We tried to figure out why this was occurring and what indicators we had from the other PIE exam that would explain it. And so in this image, on the left hand side, we have neutron radiography of the rods that we looked at.

The red ones that had a slow depressurization, in fact, are highlighted in blue. I don't know if you can see that very well, actually. But it's also written at the top of the table.

And I also have indicated where the rupture occurred along the axial length. So that's by the green arrow that you see on these images.

So in all cases where we had a fast depressurization, we observed either extensive fragmentation along the axial lengths or rods which were EVER rods that had a central hole which would allow for a totally different gas limitation.

And then in two cases, the rods weren't

EVER fuel, but they were instrumented in the top region for a central thermocouple. And so they actually had holes drilled in the top couple of pellets.

CHAIRMAN ARMIJO: Which ones were those?

MS. FLANAGAN: Number 10 and 12.

CHAIRMAN ARMIJO: Where would I find that number, Michelle?

MS. FLANAGAN: At the very top of this table.

(Simultaneous speaking.)

CHAIRMAN ARMIJO: Yes, ten and 12.

MEMBER REMPE: The hole where the thermocouple is by ten --

DR. RAYNAUD: Right here, you can see the hole.

CHAIRMAN ARMIJO: Yes, that's where they had --

DR. RAYNAUD: And where they had this one, you can see the hole in these two and half pellets or so.

MS. FLANAGAN: Yes. And Number 11, I'm almost positive that's the VVER rod. And Number 7 is the one where we saw extensive fragmentation along the whole length.

I also have the strain profiles of a number of Halden tests shown here. And we do see that when we have a slow depressurization there's often a very small strain at the very top.

CHAIRMAN ARMIJO: Maybe I heard you wrong. Let's take that red one with its enormous amount of strength. Was that a fast depressurization?

MS. FLANAGAN: That was a slow depressurization. But controlled --

CHAIRMAN ARMIJO: You have a lot of strain, but --

MS. FLANAGAN: It had a lot of strain in the lower half of the segment. But the very top where the pressure transistor is located we have a small strain.

CHAIRMAN ARMIJO: Ah, okay.

DR. RAYNAUD: Those fuel rods right here. And you can see that there're a few very intact pellets up here. So the strain was very small. They stayed there, they did not move axially.

CHAIRMAN ARMIJO: And it somehow slowed down the depressurization.

DR. RAYNAUD: Like a plug at the top of the rod.

MS. FLANAGAN: Yes. I don't think it

takes many fuel pellets intact in a low strain to really slow down this depressurization.

CHAIRMAN ARMIJO: Yes, it's a gap.

MS. FLANAGAN: But the reason that this observation was so important, at least in my mind, was that it showed the plenum region wasn't contributing a significant impact to the behavior that we saw in the fragmentation and possibly dispersal.

And that's important because these are segmented rods. They're shorter than you'd find in a reactor. And, as I mentioned before, the ratio of plenum volume to the fuel length is much different.

And so if the plenum volume was providing a driving force or really driving this phenomenon, then these tests aren't very representative of the phenomena that we're going to in a reactor. So we need to understand that if we're going to apply this to the other cases.

CHAIRMAN ARMIJO: Yes.

MS. FLANAGAN: So as I get into the proposal, this is where the observation that drove the proposal theory that this fragmentation is controlled by local forces that are occurring right around the rupture, and that all of the driving forces are actually located within a pellet and near where the

rupture and declining temperature is occurring.

And the fifth observation has to do with the fine fragments. As subjects, we took the fine fragments that were collected in both the very high and high burnup tests and performed chemical analysis to look at the plutonium and uranium ratio.

Because that's an indication of where they were on the pellet radius, because we also did a scan of an intact pellet, and we mapped the plutonium and uranium ratio of the fine fragment to that of the intact pellet to map where these fragments had originated.

And so we found that, for the high burnup rods, the fine fragments were mostly originating from the rim region. However the very high burnup fine fragments showed indications of originating from the entire pellet radii. So we see fine fragmentation possibly being mapped to the entire pellet cross section.

CHAIRMAN ARMIJO: Michelle, you have to explain these various color codes in what we're looking at here. This is a fraction of fragments?

MS. FLANAGAN: Correct.

CHAIRMAN ARMIJO: And the red means these are just two different tests.

MS. FLANAGAN: Yes. I should have listed the burnup on those. The laser ablation results from Test 192 are the very high burnup tests. So --

CHAIRMAN ARMIJO: So these are the very high burnup, okay.

MS. FLANAGAN: -- those are very high burnup. And Test 198 is from a high burnup rod, around 60 gigawatt-days per ton.

CHAIRMAN ARMIJO: The very high was in the like 90, 80, 90 --

MS. FLANAGAN: The very high was around 70 gigawatt-days per ton.

CHAIRMAN ARMIJO: Seventy?

MS. FLANAGAN: Rod average.

CONSULTANT SHACK: But that particular pellet was higher, right, the 90?

MS. FLANAGAN: No. It wasn't 90. It might have been 72. It wasn't a significant amount higher.

CHAIRMAN ARMIJO: Okay.

MEMBER BALLINGER: But the starting temperature and ending temperatures were what between --

MS. FLANAGAN: Between the two tests?

MEMBER BALLINGER: Yes.

MS. FLANAGAN: During the test itself?

MEMBER BALLINGER: Yes.

MS. FLANAGAN: They were the same.

MEMBER BALLINGER: They were the same, so it's just burnup.

MS. FLANAGAN: Right.

CHAIRMAN ARMIJO: You mentioned plutonium, uranium, where'd I --

MS. FLANAGAN: I have it on a backup slide. So this is just the results which processed current results and compared the impact power ratios to the ratios measured on the fine fragments. So I can show you a backup slide that explains how this was concluded, how it was concluded that some of these fragments originated from the 3,000 to 3,050 microns.

CHAIRMAN ARMIJO: Okay. So that was just kind of tracking where they came from by using that as a --

MS. FLANAGAN: Yes. Let me just go to that one.

CHAIRMAN ARMIJO: -- yes, indicator.

MS. FLANAGAN: So basically what I did is took a laser ablation measurement across the intact pellet in one of the extremity regions. And then they sort of grouped the relative ratio into five

categories for both the high and very high burnup tests.

And then they did a line scan across a pot of the fine fragments. So they correlated the results to the ratios that they saw in the intact pellet.

CHAIRMAN ARMIJO: And so then they take these sieved fractions and then see --

MS. FLANAGAN: We were only really interested in the fine fragments in this examination. So we only did this for the very fine fragments, everything that was in the smallest group, less than 125 microns.

CHAIRMAN ARMIJO: Okay.

MS. FLANAGAN: We're trying to really understand why this fine fragmentation was occurring, where it was originating and what was driving the fine fragmentation.

CHAIRMAN ARMIJO: Okay, thank you.

MS. FLANAGAN: Okay. And then in addition to the chemical aspects, we also just looked at images. And we saw that in both cases, for the high and very high burnup rods, we saw very similar features in the fine fragments, a lot of porosity, you know, the things that we expect from what we

traditionally understand as the high burnup structure.

So with those five observations, we developed a proposal to explain why this fine fragmentation was occurring, when we would see it and what conditions are driving it.

CHAIRMAN ARMIJO: Michelle, just a little bit on that previous slide.

MS. FLANAGAN: Yes.

CHAIRMAN ARMIJO: In the lower left hand picture, what is the magnification there? These look like very fine grains in View 2. But I can't tell what the scale is.

MS. FLANAGAN: This is 20 microns.

CHAIRMAN ARMIJO: Twenty?

MS. FLANAGAN: Yes.

CHAIRMAN ARMIJO: Okay.

MS. FLANAGAN: In my effort to make a small file size, I think I overdid it on the projection --

(Simultaneous speaking.)

MEMBER POWERS: They look nine micron grains, I mean, they look okay to me.

CHAIRMAN ARMIJO: Yes. Well, that's what I was struggling with, with what the magnification was. I didn't have an idea that --

MEMBER BANERJEE: Is it the same for the top panel? Is that nine --

MEMBER POWERS: Well, those are ten micron, here it is, lines --

CHAIRMAN ARMIJO: Yes, I missed it.

MEMBER POWERS: -- and some of them may look like --

DR. RAYNAUD: These two are of the same magnification?

MEMBER POWERS: Yes.

DR. RAYNAUD: And these two are the same, but they're different in the --

(Simultaneous speaking.)

MEMBER BANERJEE: I see it's not.

MEMBER POWERS: Grain size looks large on the right, for me the right side, the Test 192. It looks like it has large grain size.

MEMBER BALLINGER: So what's the temperature there that it operated at?

MS. FLANAGAN: The temperature of the operation?

MEMBER BALLINGER: Yes. The temperature that that fuel operated at.

MS. FLANAGAN: I don't have that information. But it was typical. It was, I mean,

these were rods that were used in commercial reactors and then taken out to segment for the examination.

MEMBER BALLINGER: You say there's no temperature history?

MS. FLANAGAN: No.

MEMBER BALLINGER: Oh, the transient.

MS. FLANAGAN: In both cases I think we have -- yes, just the transient information. We have the power history for the --

MEMBER POWERS: The only thing they're going to have is linear heat, right?

MEMBER BALLINGER: Yes. Well, okay, linear heat, right, would sort of give an idea.

MEMBER POWERS: Yes. And presumably you're going to have that.

MEMBER BALLINGER: Yes.

MS. FLANAGAN: Yes, I don't have it in the presentation today. But --

MEMBER BALLINGER: What's the linear heat rate?

MR. YUEH: If I may speak, I know what it is. Four cycles, first two cycles I think it was around 20 kilowatt per meter.

MEMBER BALLINGER: Okay, kilowatts per meter.

MR. YUEH: And then third cycle was maybe five. And the last cycle was just --

CHAIRMAN ARMIJO: Well, not much.

MEMBER BALLINGER: So 25 and 15.

MR. YUEH: Well, the third cycle was like five or six. I don't remember. But the last cycle was 15.

MEMBER BALLINGER: Okay. I've got to do my conversations again.

(Simultaneous speaking.)

MEMBER POWERS: But a good point, it's not exceptional.

CHAIRMAN ARMIJO: No, no. I agree.

MEMBER POWERS: But it is interesting that the fission gas bubbles were pretty healthy.

MEMBER BALLINGER: That's what I was trying to get at.

MEMBER POWERS: But I think that's just because they're working in very high burnup.

MS. FLANAGAN: Okay. So the next group of slides are going to describe the proposal that we are giving based on these observations to explain why we're seeing this phenomenon.

And so the proposal is that fragmentation occurs during the LOCA simulation rather than during

operation and that it's driven by retained fission gas in the fuel pellets.

And so what we understand is that during heatup of the transient now, as the rod temperature increases the fission gas expands and generates large internal forces throughout the pellet which, at the moment of rupture, provide a driving force to cause fragmentation.

We also have seen that results suggest that there's possibly a strain threshold for significant fragmentation and fuel mobility. And so we believe that fuel fragmentation and relocation will be limited to a region around the rupture where the strain exceeds some threshold.

And the observations that we looked at suggest around three to seven percent cladding strain. And so this image just highlights that the phenomena that we're seeing we believe is a localized phenomena that's occurring around the rupture opening but that leaves the extremities of the fuel rod relatively intact and not mobile.

MEMBER BANERJEE: Let me understand the first statement. This is a LOCA. So initially the stored heat is coming out of the fuel, right? So the temperature would be dropping for awhile, right?

MS. FLANAGAN: Yes.

MEMBER BANERJEE: When you get the initiation of LOCA, the initial temperature transient is the stored heat comes out. And, you know, the clad temperature doesn't go up if you get into dry-out.

But the fuel should not be rising in temperature. It should actually be losing the stored heat which gives you your blowdown peak in the transient, right? And then after that, you start to get a slow rise until you get reflood. So I'm not sure what you mean by the rod temperature increases.

MEMBER BALLINGER: Well, also in the LOCA as soon as you lose the nuclear heat, well, the power, the temperature across the pellet flattens out.

MEMBER BANERJEE: Yes, equalizes.

MEMBER BALLINGER: It flattens out. So there's no gradient left anymore in this.

MEMBER BANERJEE: Yes. So it tries to come to equilibrium in that sense. So there is a temperature transient. But it's not necessarily rising. It's flattening, reducing and then stops a slow rise which then gets to reflood. It's a peak and comes down again.

MEMBER BALLINGER: So you're arguing that there's a connection between the planned failure and

the fragmentation itself?

MS. FLANAGAN: The cladding strain and then the rupture, yes.

MEMBER BALLINGER: A long time ago, the PNNL folks ran a whole bunch of tests where they ramped temperature for fuel rods that were looking just at cladding strains to failure, no fuel inside.

But you might take a look at those to see if there's any relationship between the kind of morphology that you see for the cladding failure and those. They just did ballooning tests. They were looking at the issue of flow blockage and things like that.

But they did a lot of tests where they got failures at various temperatures for different, in starting internal pressures. And that's a completely clean experiment or clean from the fuel.

MEMBER POWERS: Yes, but it's useless. Because it has never been exposed to any radiation environment or pick up --

(Simultaneous speaking.)

MEMBER BALLINGER: So some of those Studsvik failures, they look strangely, because the major damage is annealed out.

MEMBER POWERS: No, no, no, no. It's the

oxygen pickup and the hydrogen pickup that make a difference.

MEMBER BALLINGER: Is that right?

MEMBER POWERS: I mean, those tests were very interesting at the time. They're totally useless nowadays.

MEMBER BANERJEE: So going back to that point though, what is happening is the periphery of the fuel pellet is coming up in temperature. Because the temperature profile is flattening across the pellet.

So in some ways, that statement is correct. But it's not the overall pellet. I mean, it's losing energy actually, and the average temperature will be coming down. But the periphery is going up.

So you might need to refine the hypothesis and look at the temperature profiles within the pellet in typical LOCAs. I'm sure people can supply you with those things.

DR. RAYNAUD: If I may say something. I completely agree with you. And that happens very rarely in the transient, what you're describing. But typically the ruptures happen maybe, you know, 20 or 30 seconds.

And once you completely drive out core and you have some significant heatup that's occurred, whereby the cladding is upwards of 800 degrees Celsius or so, and I think by that time, after it has reached equilibrium, then the fuel pellet temperature is beginning to increase again.

MEMBER BANERJEE: Yes. So I don't know the history in my head, but the fuel pellet and the cladding are more or less in equilibrium, because you've got very little heat transfer outside.

So essentially everything is rising together in temperature. And I don't know whether the average temperature of the pellet gets back to what it was when the LOCA started.

Clearly you had a temperature profile when you started. The temperature was very hot. The periphery was cool. Now it's all flat and totaling up together. And one would have to look at these transients and see what's happening. The highest rate of heatup would be from the large break LOCA. So there's a lot of information there.

DR. RAYNAUD: At the time of rupture, and this is ballpark numbers, that the cladding and the pellet are roughly at the same temperature, as you pointed out, the profile was pretty flat, relatively

speaking.

And both are around 800 degrees Celsius. So that would mean that the pellet is cooler than the center line temperature might have been at full power operation. The periphery of the pellet is probably hotter than it was in --

MEMBER BANERJEE: Absolutely. And we agree with that. There is no issue with the periphery being hotter. So all I'm saying is you might want to refine that hypothesis to saying that there's a peripheral region which is hotter, and what you're saying applies there. But the center is cooler. So you would expect the periphery to fragment in some way based on that hypothesis.

CHAIRMAN ARMIJO: And that fragmentation can happen before the rupture or after the rupture. Have you nailed that down, that you're sure when the fragmentation happens?

MS. FLANAGAN: No. I don't think it's clear yet. But Halden just ran a test in the fall which didn't rupture. So they ran the transient up to that point and then terminated the test without rupture. And I believe that that test is going to provide a lot of insight into the rupture event contribution. But until we look at those tests, there

really isn't any information to discern --

CHAIRMAN ARMIJO: Can't really tell in advance?

MS. FLANAGAN: No. I mean, we were looking at these fuel rods after the LOCA test. I mean, we don't have anything in situ. We do know that the thermocouples indicate fuel relocation occurs prior to being measured.

During the LOCA, fuel is able to relocate. And we know that from looking at the thermocouples that are on the cladding going very low in one of the tests that had significant fuel relocation before the rupture. So, I mean --

CHAIRMAN ARMIJO: But you're addressing that in the experiments. Because you're right. You can't tell by reading the tea leaves after all that damage has occurred. You've got to terminate the thing before the clad ruptures. And then you're sure whether you've got a lot of fragmentation in other pellets or not.

MS. FLANAGAN: Yes. I think after we looked at these examinations and really thought about a proposal, we see areas that we really want to focus on, that we really want to understand. And that's certainly one of them that came out.

With the idea that the strain and rupture location might have a contribution, we want to understand how to separate those two and look at a rod that hasn't ruptured.

MEMBER SCHULTZ: Michelle, I missed what you said. Is this a one segment test that has been done at Halden where there was no rupture, one segment?

MS. FLANAGAN: Yes.

MEMBER SCHULTZ: Do you know what the burnup was for that segment?

MS. FLANAGAN: It was around 70 gigawatt-days per ton. It was actually, the last three tests at Halden were all on sister rods. And so one had a very mild rupture. In fact, that was close to not rupture, but it did rupture. So it had a very mild rupture.

Another one was a full rupture, a full plan and volume and a full pressurization. And then the last one was no rupture. So with those three tests, I think we'll be able to compare the fragmentation pattern and actually look at the influence of rod internal pressure and a rupture event.

MEMBER BANERJEE: Is that what you show on

Slide 12 there, the pressure in the rod?

MS. FLANAGAN: Yes. This is the depressurization. But none of these are the last test that didn't rupture. These are earlier tests.

MEMBER BANERJEE: So they started at pretty high pressure.

MS. FLANAGAN: So I described three tests. The first one that was a sister rod was a low rod internal pressure to start. This is trying to not rupture, so they started with a low rod internal pressure and a very small plenum volume. So it was not five year, but it would be lower than these.

And then the second test would have been comparable to these. And then the third test, again, it was a very low rod internal pressure. So they did try to vary that in order to compare.

MEMBER BANERJEE: And you see fragmentation into these fine particles for the high burnup fuel even when you start with a low internal pressure? Do you see that?

MS. FLANAGAN: The only test that had a very low rod internal pressure are the one that was just run which hasn't been examined yet and then another one which was 70 gigawatt-days per ton. And it showed less fragmentation than the Studsvik test at

the same burnup.

But it was also BWR, it had a different rod internal pressure. So we see that there might be less fragmentation. But it's not clear, with the number of things that are different, what accounts for that or how to account for that.

(Off microphone discussion)

MEMBER SCHULTZ: So they tried to emulate the power and the hydraulic response. And they buried the internal pressure for this last test.

MS. FLANAGAN: Well, yes. And they can shut off the test at earlier points. And so once it started to balloon, they terminated the external heating. So they know how the rod will -- as I said, they have like booster heaters to get the rod up to the higher temperatures.

MEMBER SCHULTZ: Right.

MS. FLANAGAN: So they can control the temperature to some extent with those. And so they terminated the test and reflooded a little earlier.

CHAIRMAN ARMIJO: But when the terminated the test, did it look there was incipient ballooning or actual ballooning but not rupture?

MS. FLANAGAN: The only information that we have so far is a gamma scan that was conducted

afterwards that looks like there was ballooning. But it's not very precise.

So it takes awhile for Halden to actually examine the rods, because they transfer them to another facility. And they have to cool off. So we don't know yet how extensive the ballooning was on the one that didn't rupture.

DR. RAYNAUD: But the whole goal of the test was to have a balloon without the burst in order to see if there would be some fragmentation relocation within the rod without the rupture events.

And so based on the pressure, live pressure readings during the test, you know, you could see that the pressure started decreasing fairly rapidly. And that means that the rod was ballooning, because it's a closed system.

And, you know, it's very tricky. That's why they did not succeed the first time in the rod rupture. Because it's very tricky to know exactly when to cut if off to balloon enough but not too much so that you rupture.

MEMBER BALLINGER: And these cladding temperatures are about 800 C?

MS. FLANAGAN: In these tests where they terminated it around rupture, yes. In some cases they

went beyond in other tests.

MEMBER BALLINGER: Okay.

CHAIRMAN ARMIJO: But it's the right experiment, you know. Because then you're sure when the fragmentation occurs.

MS. FLANAGAN: Right. Or at least you can look at the effect of rupture and see what contribution it has and then see if it's already occurred, then look more into the phenomena that happens at the time --

CHAIRMAN ARMIJO: Yes.

MEMBER BANERJEE: They can actually see this during this process of depressurization, you know, ballooning. Ballooning will cause depressurization, right?

MS. FLANAGAN: Right. So in the test, because the volume is not very large, they will see a drop in pressure as the rod starts cooling.

MEMBER BANERJEE: Right. But they can actually see what's happening with the pellet during this period?

MS. FLANAGAN: No. They only can do an exam afterwards.

MEMBER BANERJEE: Afterwards, right. So they can only infer when it happens, right?

MS. FLANAGAN: So in this test they'll look at the rod and the fragmentation after everything is done and it's sent off to another lab. And they'll have to decide whether that can be attributed to the transient itself.

MEMBER BALLINGER: So your hypothesis is that the fragmentation is because of the collection of fission gas bubbles. And that would have had to occur pretty much instantaneously. Because below, again, below about 1,100 C you don't get fission gas bubble migration unless it's very high burnup, very, very high.

I don't know how you get bubbles. You just don't get that kind of migration. So if you don't think there's a contribution of just the thermal gradients going on in there also?

MS. FLANAGAN: There could be. But what I'm suggesting is the fission pockets and the porosity are, the fission gas which is trapped in the fuel pellet at high burnup is under very high pressure.

MEMBER BALLINGER: Oh, yes.

MS. FLANAGAN: Higher than actually the rod internal pressure outside. And so you have a lot of pressure pushing on the --

MEMBER BALLINGER: But those are spherical

bubbles which meant that the internal pressure and the external, those are real bubbles. It's balanced by the constraint.

That's what you get a sphere from. So you had to get migration of fission gas or a collection of fission has where you've got that internal pressure balance back and forth.

MS. FLANAGAN: Well, but at the moment of rupture the rod internal pressure goes to zero --

MEMBER BALLINGER: Oh, yes.

MS. FLANAGAN: -- quickly. So that's why I think it has to be --

MEMBER BALLINGER: Oh, I don't doubt that when you get those bubbles the internal pressure is enormous. But I just wonder whether or not the thermal gradient also contributes to the fact that, you know, those stresses all add.

MS. FLANAGAN: Sure. It's very hard to separate the influences of all of the things that are going on at the same time with a rupture event. You have temperature, strain, the rupture event itself. There're so many things simultaneously going on that it's really hard to separate them.

MEMBER BALLINGER: You also have the phase transformation in the Zircaloy which happens at around

762 or 770. So apart from the stabilized layer from the oxidation, you're getting a phase transformation from alpha to beta. And that's where you get plasticity.

MS. FLANAGAN: Yes. We had a lot of things happening simultaneously. I think what we were focusing on at first was are the things that are happening in these tests comparable to in the reactor.

And then if we confirm that they are, then move on and try to separate each of the influences and then develop a proposal to probe further, separate out some of these variables and try to look at their individual contributions.

MEMBER POWERS: When I look at your slides labeled Proposal, I get a little confused when you use the word strain. That's always strain in the clad --

MS. FLANAGAN: Always strain in the cladding.

MEMBER POWERS: -- and then strain in the fuel.

MS. FLANAGAN: Yes.

MEMBER POWERS: All of these high burnup rods have a restructured rim, right?

MS. FLANAGAN: Yes. I mean, there are Halden tests which were a lower burnup around 45 and

50. So those --

MEMBER POWERS: Yes, but I'm not concerned about them. These all have a restructured rim. And so you have, in the rim region itself, you really don't have much accumulation of fission gas at all. And your fission gas is really accumulated in the sub-rim region.

Have you tried to look at the stresses in the fuel pellet itself with some of these fuel fragmentation codes?

MS. FLANAGAN: No. I mean, I don't know, our fuel performance codes don't have models for fragmentation in them.

MEMBER POWERS: Other people have.

MS. FLANAGAN: I know. I've heard you say that. But I'm not familiar with it. Because, I mean, this is a very --

MEMBER POWERS: That's why I keep bringing them up to you. And you need to go chase them down in Idaho. Am I going to have to go get the code for you and hand it to you, Michelle?

(Laughter)

MEMBER BALLINGER: What code might this be?

MEMBER POWERS: There's actually been a

huge amount of work during the last 20 years on modeling strains in the, and fragmentation, in the fuels itself.

The codes look very good to me, because I don't know squat on this subject. So, I mean, it's easy to snow me.

MEMBER BALLINGER: You're impressed.

MEMBER POWERS: I'm easily impressed. And I was kind of hoping Michelle would go pick it up and educate me. Because she's a very good instructor.

MEMBER BALLINGER: All of what happened, catalytic, that happens, the small bubbles, the internal pressure is less than the pressure in the big bubbles. So when you get big bubbles --

MEMBER POWERS: Ron, that can't be. A simple energy balance --

MEMBER BALLINGER: Oh, okay.

MEMBER POWERS: -- would tell you that a small bubble has to balance the surface energy and that you can add --

MEMBER BALLINGER: You have to let me finish.

MEMBER POWERS: No, I probably won't.

(Laughter)

(Simultaneous speaking.)

MEMBER BALLINGER: The big issue is when you're consuming small bubbles to make big bubbles you get a sort of auto-catalytic thing that goes on.

MEMBER POWERS: I know. There's been a lot of catalysis going on here.

MEMBER BANERJEE: So mainly Ostwald ripening in the --

(Simultaneous speaking.)

MEMBER POWERS: And the pressure goes down when you form a big bubble. It's another OR dependence because of the surface energy of the oxide.

(Simultaneous speaking.)

CHAIRMAN ARMIJO: And things are happening pretty fast. So there's not a lot of time for diffusion and, you know, pressure, okay.

MEMBER POWERS: There's a huge amount of time for diffusion here. Because you only have to diffuse a very little distance.

CHAIRMAN ARMIJO: Not very much. Okay, we're going to have a lot of fun with this project.

MEMBER POWERS: Well, the next question, Michelle, is what you're trying to determine, I think, and correct me if I'm wrong, is that do I have a global thing that would influence how we go about analyzing a design basis LOCA for fuel burnups

exceeding the current limit of, let's say 61 gigawatts per ton.

Or do we have a localized thing that's a peculiarity and, no doubt, a pain in the ass? But a LOCA is a pain in the ass anyway, so one more is not going to hurt. That's what your objective is.

MS. FLANAGAN: Well, that became the objective. I think that when we started we didn't know. When we started we thought that perhaps where there was a rupture we had to assume everything above the rupture was vulnerable to coming out. And that's a significant amount of fuel.

And so as we looked further into these observations and looked at, you know, the possibility that it was a localized phenomena and trying to come up with a proposal, so why would we only see this fragmentation in regions of strain and near the rupture.

And that's when we started to have the idea that this could be a localized phenomenon. And that makes a huge difference when you're calculating the amount of fuel that's vulnerable to dispersal. So that became our direction as we looked at the results.

MEMBER POWERS: I understand the observation.

MS. GIBSON: If you want to know how much is there going to be, where does it go and what does it do.

MEMBER POWERS: Well, I mean, it seems to me you articulate three things there. But you can cut it off with how much is there. If it's just this little localized thing, then I don't care what it does or where it goes and what not. If it's a big thing, then I definitely care where it goes, and what it does and what not. I mean, that's what your objective is.

MEMBER SCHULTZ: With regard, go ahead, Dana.

MEMBER POWERS: As opposed to what Patrick was talking about earlier, relocation down into a balloon region which gives you a hot spot and changes, all the stuff that Sanjoy worries about that nobody else understands.

CHAIRMAN ARMIJO: Well, I think we'd better keep moving. Because we still have Patrick coming up. And I think, Michelle, you have just really two more slides.

MEMBER SCHULTZ: I just had a comment on this. You've got a statement, the last statement, is if the local strain is large enough. I understand that you've observed that this is a local phenomena,

not at the end but near the rupture. But given that this is the local cladding strain, to go ahead then and suggest that the local strain is large enough to result in fuel fabrication --

(Simultaneous speaking.)

MEMBER SCHULTZ: -- fragmentation, that kind of turns it around. Suddenly you've drawn a conclusion that it's the cladding strain that results in fuel fragmentation.

MS. FLANAGAN: What I'm suggesting is that there is fuel which is vulnerable to fine fragmentation. And then there are conditions which allow that fine fragmentation to occur.

So I think burnup and fuel properties have to do with what fuel becomes vulnerable to fine fragmentation. And then the strain allows that fine fragmentation to actually evolve and occur.

MEMBER SCHULTZ: All right. So it sounds like you've got another piece, conclusion here to go to next.

MEMBER BANERJEE: So let me understand this again, what you're saying. If it is localized, suppose you get some local ballooning or something. So the pressure goes down.

Are you saying that pressure reduction is

not communicated everywhere, so it's just a local area that is depressurized in fragments? Or what's the hypothesis in terms of the physics?

MS. FLANAGAN: For the moment, I think it has a lot to do with the rupture event itself, the rupture event having a dramatic local depressurization around the rupture opening.

But that's really going to be answered more when we start to look at the latest results of a non-ruptured fuel rod. So, I mean, it's a proposal because it's an evolving understanding.

MEMBER BANERJEE: Well, the pressure reduction is not communicated in some sense.

MS. FLANAGAN: Well, that's what we see with some of the readings of slow depressurization in some of the tests. These are short segments. And even in the short segment we sometimes see slow depressurization in the plenum region where it's measured which indicates that there is some restriction of gas communication in those rods.

So it's not in every test, but in many tests we see that there's some restriction in the gas flow. And in a longer rod, we would expect even more.

MEMBER BANERJEE: Okay. It's a working hypothesis.

MEMBER SKILLMAN: Michelle, I always make the comment, based on what Sam communicated a few minutes ago, clarity of this material would be highly improved if, when you talk about fuel and strain, you make a distinction between pellet and cladding.

MS. FLANAGAN: Yes.

MEMBER SKILLMAN: Because there is an interaction here. And sometimes I think the discussion moves from one to the other very easily. But the distinction between the two is very important in the context of the conclusion that you're communicating. So I would ask if you could clarify pellet versus clad.

MS. FLANAGAN: Yes. That's a very good point.

MEMBER SKILLMAN: Thank you.

MS. FLANAGAN: And I will definitely do that as I go through the rest of the presentation, but also when I document this further.

MEMBER SCHULTZ: That's my concern with that statement. Then the next step will be we will go to the LOCA codes, predict large cladding strain and therefore presume that we have large fuel fragmentation there.

MS. FLANAGAN: That's exactly what we're

doing, actually.

MEMBER SCHULTZ: Yes, that's what I thought.

MEMBER SKILLMAN: And what I'm --

MEMBER SCHULTZ: I don't see the data supporting that yet.

MEMBER SKILLMAN: See, what I'm waiting for is this next shoe to drop. And that is when you talk pellet, strain, fission gas, pellet fracture, interaction with clad, then I'm waiting for coolant flow, clad shrink and the resultant dispersal.

It seems to me we had some history in the industry to understand how that logic of events occurs. So I'm waiting for this next shoe on here's what happens when you hit it with cold water. Because we have some interesting real information that shows what happens.

DR. RAYNAUD: When you hit it with cold water it's usually much longer after all of this has happened.

MEMBER SKILLMAN: Very much longer.

DR. RAYNAUD: So it probably wouldn't have a direct impact on any of these observations.

MEMBER SKILLMAN: But what's already in the clad?

CHAIRMAN ARMIJO: We're speculating an awful lot. What you really need to do is get to the sequence of events that happened in the fuel rod. And that test, that recent test where you try and terminate it, you terminate it before the rupture, it's going to tell you a lot.

It'd have to be a line up, at least a sequence of how this mechanism works. And I think you guys are on the right track in doing it systematically like this. Because there are too many variables. And to try and analyze it real time before you have enough data, is fun but --

MEMBER POWERS: No. I think that the hallmark of this whole area, I mean we did review Patrick's document, is they're being very systematic. And I think that's excellent.

MEMBER BANERJEE: Does the rate of change of temperature matter in this? Because the high burnup fuel from an event like a LOCA would be in relatively low heat spots and things. So it would heat up slower than you would expect. Now, if it doesn't matter how quickly it heats up, of course it's independent of that. But it would be expected to heat up slower.

MS. FLANAGAN: In these tests, all of the

heatup was pretty much induced to a similar value. And what Patrick will present later looks at how hot each rod gets.

And so even though we don't really have a way to input into his models an influence of the heatup rates, we do obviously know whether the rod ruptured or not and know that that would have an influence. And so Patrick will share a little bit about the high burnup rods and what power they are at, what temperatures they reach.

MEMBER BANERJEE: So all you are interested to a first approximation is the temperature they reach, not so much how they reach it, how quickly. Because that quickly will vary some, but not by a huge amount.

MS. FLANAGAN: At this point, we don't have any information with the experimental observations to discern an effect of heatup rates. So we wouldn't be able to use, we wouldn't be able to --

MEMBER BANERJEE: It's probably a second or a variable anyway in this program, yes.

CHAIRMAN ARMIJO: Okay, Michelle, you've got --

MS. FLANAGAN: Okay. So I showed this slide, but I haven't said the first paragraph which

describes just why we think that this could be a localized effect. And we believe the change in fragmentation size that we see somewhere between 50 and 70 has to do with the evolution of localized regions in each pellet.

We know that at high burnup, a large amount of fission gas is retained under very high pressure. And these fission gas pockets and other characteristics of high burnup fuel, including re-structurization and small grains, can make this material, or what we propose is that it makes this material more vulnerable to fine fragmentation.

And so that's where I'm linking, there's a vulnerability in the fuel based on its structure. And then there's an event which allows that vulnerability to cause fragmentation. And so that's what I'm linking to strain.

And so if this is the case, then what we really need to understand the amount of fuel dispersal that we would see is an overlap of burnup, strain profiles, whether the rod ruptured or not. And ideally, we would also look at the rupture opening.

I didn't present this in the slides today, but we do see that some ruptures are very small pinhole cracks. And others have large fishmouth

openings.

Obviously, the fuel fragments must be smaller than the rupture opening in order to disperse. And so if we had a good model for how wide the rupture opening is, we could even refine this further. We don't have good models for how wide a rupture opening is. And so we have to make some bounding assumptions based on rupture and non-rupture.

So I'm not going to talk more about this slide, because it's really set the stage for what Patrick has done. And he has his whole presentation based on this comparison. But that's what we were able to do if this proposal is true and these thresholds are accurate.

CHAIRMAN ARMIJO: Okay.

MS. FLANAGAN: So my conclusion is that we reassessed some PIE results, some LOCA tests that were available from Halden and Studsvik. We conducted a few additional examinations based on some developing theories. And we developed a proposal for the conditions and variables that control fuel fragmentation, relocation and dispersal.

And that proposal was used to define thresholds for the onset of fine fragmentation in terms of fuel burnup and local strain. In this

presentation, I think the results support transition to vulnerable fine fragmentation somewhere between 50 and 70, it's not clear where, and then a strain threshold for fine fragmentation somewhere between three and seven percent.

And these thresholds can be used in analysis to make an assessment of how much fuel dispersal we could see in a large break LOCA or in any LOCA scenario.

MEMBER BANERJEE: That observation of strain is an empirical observation.

MS. FLANAGAN: Yes.

MEMBER BANERJEE: But is the strain not associated with the burnup? Or is it an independent variable in the problem?

MS. FLANAGAN: I think it has more to do with the rod internal pressure and the temperature. But I just want to, because I'll probably go back on this, you know, these same profiles are all from Halden tests and have similar heatup. I mean, maybe some of them have different peak cladding temperatures.

But we see a huge variability in the strain profile between tests. There is probably some explanation for why we see such variability in the

shape of the balloon. But most of our models have really been focused on the maximum strain and targeting to make sure we get that right.

I think very little information was available to look at the actual shape of the balloon, how long it is, whether it's a very localized or lengthy one. So I think there's a lot of stochastic behavior in the strain profile. There's probably some explanations to make it less --

MEMBER BANERJEE: I think you answered my question, Michelle.

MS. FLANAGAN: Okay. Also there's a lot of references. So these are most of them. But there may even be additional ones.

CHAIRMAN ARMIJO: Well, you are going to follow-up and check into that fragmentation codes that Dr. Powers --

MS. FLANAGAN: Yes. I guess --

CHAIRMAN ARMIJO: I think it's great stuff. So it's probably worth --

MEMBER BANERJEE: What is the code? Dana never told us the --

CHAIRMAN ARMIJO: No, he didn't tell us that.

CONSULTANT SHACK: It would help to have a

name.

MS. FLANAGAN: Yes.

(Simultaneous speaking.)

CHAIRMAN ARMIJO: I'll try and find it out for you.

MS. FLANAGAN: And the thing is that we not only need a code that predicts some space on the perimeters, but it also should be on the perimeters that we can actually calculate in our fuel performance codes. And the hydraulic codes have to be able to marry, you know, a dynamic phenomena. So, I mean, our fuel performance codes and some hydraulic codes that model LOCA certainly don't yet have --

CHAIRMAN ARMIJO: Down in that detail.

MS. FLANAGAN: -- at that detail. So it's going to have to be some combination of information anyway. It won't be straight forward.

CHAIRMAN ARMIJO: Okay, okay. Thanks a lot, Michelle.

MEMBER BANERJEE: So let me just ask a question. If you did develop a sort of mechanistic model for this, would it vary to code like FRAPCON? Or what is the next step if you've got some understanding of what's happening?

MS. FLANAGAN: I think it would have to go

into a FRAPTRAN code which actually looks at the temperature of the cladding and the fuel on a radial segment basis. Because it's not just the fuel pellet as a whole but different regions of the fuel pellet. It has to be a dynamic code that looks at the temperature changes that are happening quite rapidly in LOCAs.

MEMBER BANERJEE: So you're interested in the initial transients as well. I mean, you're into the blow down. Everything is flat, right, almost flat? Because your transfer is so low.

MS. FLANAGAN: If it ends up that a lot of this phenomena is happening at the rupture, then that modeling, the dynamic response in the rupture moment is going to be really important. And that's going to take a lot of work to look at --

MEMBER BANERJEE: But you have a framework which already does this so that you can take your physical models and phrase them into that? Or do you have to also develop the framework?

MS. FLANAGAN: Well, one thing we have to, I mean, there are models that sort of -- and Patrick can say more about this -- but if it's driven by fission gas pockets then we need to have a pretty detailed description of where the fission gases are

remaining, how that evolves with burnup.

And so there is some framework in the codes already for that. But it may need to be even more detailed and more robust if it's going to be driving a fragmentation from that line. So I think that there will be a lot of work to develop a model for this behavior in our current codes.

MEMBER BANERJEE: But is that your long term objective? And where are we going with this? It's nice to know this phenomena, and that's a first step. But now that we recognize something is happening, we have to first of all assess whether it's important for a LOCA. But I imagine --

MS. FLANAGAN: Right.

MEMBER BANERJEE: If it's not really localized, then we start to be concerned.

MS. FLANAGAN: Yes. I think, like anything, it's going to depend on how significant of an issue it is. Because if it is a lot of resources to develop a code that handles this on smaller scale, and it's not perceived to be a significant driver for safety in the LOCA, then the empirical observations and the empirical thresholds, even at the bounding set, may be as far as we go.

We certainly have some bounding

understanding and empirical observations. And so the extent to which we need model it on a localized level is going to be driven by how important the phenomenon is relative to other aspects of the LOCA.

MEMBER BANERJEE: But is anybody else doing anything on this?

CHAIRMAN ARMIJO: You know, just to refresh your memory, the staff was marching forward with a rule making of 50.46(c) to address the issue of cladding embrittlement.

And then this phenomena came up, and the plan originally was to say, well, that's interesting, but let's get this rule out. Then I think you got Commission direction that said, no, why don't you take care of the whole problem all at once.

So the first thing is to find out how important this thing is from a, you know, from a safety case issue. And, you know, if the staff can envelope the thing, even without a detailed understanding of the mechanism, that may be all you need to do. That's up to the staff to decide.

But it is holding up the 50.46(c) rule making which, it supports some of the rule problem which I think is being solved just with time. So it's important, but I think you'll be working on the

mechanism of this thing for many, many years. And somewhere along the line, you've got a regulatory responsibility to say is this really important and does it really change how we treat --

MEMBER BANERJEE: But it's an iterative process.

CHAIRMAN ARMIJO: Sure.

MEMBER BANERJEE: You even put anymore empirical things. We take some observations and, you know, refine them as time goes on.

CHAIRMAN ARMIJO: Yes, right.

DR. RAYNAUD: That's a great segue to what I'm going to say.

CHAIRMAN ARMIJO: Okay, Patrick. I'm sorry that we're running late, Patrick. I'm not going to rush you, okay. But somewhere around 10:30 it would be a good time to, if you can find a good spot, for you to recommend that we stop there so you're not interrupted with that.

DR. RAYNAUD: Well, what I'm going to talk about here is I just found out we don't have mechanistic, you know, physical retail models to predict how much fragmentation, relocation and dispersal we have.

But with the experimental thresholds and

hypotheses that Michelle just talked about, with the codes that we currently have, that exist, mainly FRAPCON, TRACE and FRAPTRAN, FRAPCON and FRAPTRAN are the steady-state and transient fuel performance codes. They kind of work together. And TRACE is the systems' thermal hydraulic code.

And I'll describe how we kind of link those three codes to lower -- the quantities such as how much cladding frame we have in the whole core, what the local burnups are and such things, and then compare them with the experimental thresholds that Michelle just talked about to get some estimates of how much fuel might be dispersed into the core.

Michelle told you how this issue of fuel dispersal kind of sets up over the last ten or 12 years or so. NUREG 2121 kind of summarized what the literature had, that was a couple of years ago. And the big question ultimately, as Sam pointed out, as Dr. Amijo, sorry, is that --

CHAIRMAN ARMIJO: It's okay, Sam's fine.

DR. RAYNAUD: -- a need to get to how safety significant this is. And so here I'm going to present the analytical work that follows Michelle's experimental work to predict how many fuel rods rupture and how much fuel might be dispersed from

those fuel rods.

And the next step which is not presented here would be to do some kind of consequence analysis to determine what the safety impacts are of that dispersed fuel.

And this is exactly what this summarizes. It's experimental research that defines what thresholds need to be achieved in order to have some fuel dispersal. Then we take that and we predict how many fuel rods rupture, the local conditions in those fuel rods, and compare those calculations, those results, to the thresholds that came from experimental work and then determine how much fuel is dispersed. And the last of it would be consequence analysis.

So we use the codes that we have at our disposal. The first is FRAPCON. That's for steady-state fuel performance. We use FRAPCON to initialize the burnup dependent parameters in TRACE for the fuel rods that are modeled in TRACE and also to initialize FRAPTRAN with all the fuel rod initial conditions. FRAPTRAN is the transient fuel performance code. Then you run a steady-state --

MEMBER BANERJEE: But it's primarily a temperature transient, isn't it? You're not doing all sorts of detailed other calculations in it. You don't

do --

DR. RAYNAUD: Well, FRAPCON models the base irradiation. So there's no transient there. It's a completely steady-state code or value. And you input the power history of the rod over the course of its irradiation.

And it essentially calculates the thermal and mechanical evolution of the rod as well as oxidation, and hydriding and the end state of the FRAPCON. The empirical FRAPCON calculation is essentially the local conditions along the entire axial length of the fuel rod.

For example, you know, what the cladding strain is, how much the fuel has swollen, is the gap closed or open, what the local temperatures are across the radial profile of the rod and the axial length of the rod. And rod --

MEMBER BANERJEE: And what does it do, start up a series of steady-state calculations given some external boundary conditions from TRACE? That's what it does?

DR. RAYNAUD: Well, we actually don't use TRACE.

MEMBER BANERJEE: Until you finish with it?

DR. RAYNAUD: The coolant conditions are assumed to be known and relatively constant when you're at, you know, certain like full power operation, for example.

MEMBER BANERJEE: The steady-state, that's straight forward.

DR. RAYNAUD: Right, exactly. And then the power history is known, you know, from an FSAR or final safety analysis report or some core analysis that we know the power history. Those are the inputs to FRAPCON. You don't need TRACE in the background to run FRAPCON. It can run stand alone.

TRACE then comes in order to model the transients. So TRACE has to start with a steady-state initialization and then from that steady-state in TRACE you run a transient.

And then you have the, well, thermohydraulic response of your entire system. But here we're really interested in what happens at the fuel rod level.

And one of the main things that we take out of this is the predictive cladding surface temperature. And then we use that as a boundary condition in our FRAPTRAN transient fuel performance analysis. We essentially enclose the cladding outside

surface temperature in FRAPTRAN and --

MEMBER BANERJEE: It's not the heat transfer coefficient. It's the temperature.

DR. RAYNAUD: Well, actually the way the code is written, we have to kind of trick it into that. The thermohydraulics in FRAPTRAN have some limitations.

MEMBER BANERJEE: It's just a conduction calculation, right, other than the boundary?

DR. RAYNAUD: Yes, essentially. You know, there's a transient heat transfer of the model. But it is a conduction. But it cannot do, for example, flow reversal or that sort of thing.

So if we just input cooling conditions such as the coolant, you know, flow of pressure, enthalpy, we find that FRAPTRAN is not able to converge. Because that data, you know, the flow is reversed several times during the blowdown and then the reflood. And FRAPTRAN just doesn't know how to deal with those things. So what we find --

MEMBER BANERJEE: But let me ask you, maybe that would be useful to clarify. I mean, if other people know this, I'm happy to move on and learn it later. But all you're doing is you're giving it conditions of pressure. Let's say you transfer

coefficient or clad surface temperature or some --

(Simultaneous speaking.)

MEMBER BANERJEE: Yes. So when you get full reversal, why does it matter to this code?

DR. RAYNAUD: Well, there's two options to input the coolant conditions in FRAPTRAN. The option that you just described works. The option that is more complex, whereby you give it a reflood rate and all sorts of things like that, it doesn't really function for a complicated transient like this. It's a very simplified model.

So I guess the particular point is we enclose the cladding surface temperature in FRAPTRAN by tricking it. Essentially we tell it that the cooling temperature is the cladding surface temperature that is calculated in TRACE. And we impose an artificially large heat transfer coefficient.

MEMBER BANERJEE: Fine.

CHAIRMAN ARMIJO: Patrick, is there enough detail in TRACE or at the pellet level where you know that the temperature's radiant, radial temperature is radiant in the pellet?

DR. RAYNAUD: Not in TRACE.

MEMBER BANERJEE: No. There's a vestigial

calculation.

CHAIRMAN ARMIJO: Where would you know that, you know?

DR. RAYNAUD: FRAPTRAN calculates all that.

CHAIRMAN ARMIJO: FRAPTRAN does?

DR. RAYNAUD: Yes.

MEMBER BANERJEE: But you don't iterate between the two?

DR. RAYNAUD: No. And I think we're moving in that direction. But whether or not --

MEMBER BANERJEE: Yes. That's what I was originally asking you, whether it was coupled. But it's not, really.

DR. RAYNAUD: No, not yet.

MEMBER BANERJEE: Got it. So the gap changes and all done basically in TRACE in a very rudimentary manner. I mean, they can do whatever they feel like. Once they see what's happening in FRAPTRAN they go back, and probably if there's a big change in the gap it's --

DR. RAYNAUD: Actually TRACE does have a model that tells you what the temperature profile is and it tells you the cladding in the gap. It does calculate those things, otherwise it could never

calculate the --

MEMBER BANERJEE: It does that, but --

CHAIRMAN ARMIJO: You're going to have to do something. But is it detailed enough that it says you --

DR. RAYNAUD: It's a thermal --

CHAIRMAN ARMIJO: -- thermal activity in this part of the pellet is degraded, and in this part of the pellet it's not degraded to that level of detail?

DR. RAYNAUD: I believe all those things have been recently input into TRACE. I think --

CHAIRMAN ARMIJO: That's good.

DR. RAYNAUD: -- there's been a lot of recent improvements in the fuel models in TRACE. The biggest limitation of TRACE's fuel performance models is it doesn't dynamically model the ballooning phenomenon. And FRAPTRAN can do that. So that's a big added feature of FRAPTRAN. Because the cladding strain is very important.

MEMBER BANERJEE: Eventually there's no reason why they couldn't be coupled.

DR. RAYNAUD: You're absolutely right. And we have, Ian Porter is a student at University of South Carolina doing a PhD, and he's actually an

extended summer hire here at NRC. He's actually here in the audience. And he's working on that as part of his PhD. So hopefully that works out.

So now what I'm going to describe is one analyses we currently have performed using this scheme, using the three codes FRAPCON, TRACE and FRAPTRAN. We did some PWR analyses and some BWR analyses.

And this is, you know, I would say we're still working on refining these analyses. So all the results I'm going to present today are the first cut that we completed.

MEMBER BANERJEE: Let me ask you another question before we move. There was concern at some point about the fact that, I don't know, FRAPCON or FRAPTRAN, both perhaps, assumed axial symmetry so that if you had eccentric pellets and things that you couldn't do sort of a 3-D calculation. Is that correct?

DR. RAYNAUD: That's still true. It's a 1 1/2D code. So it's axisymmetric. Yes, you're right.

MEMBER BANERJEE: So you just have a radial code in that system.

DR. RAYNAUD: Yes.

MEMBER BANERJEE: And you have a Z code in it, I imagine.

DR. RAYNAUD: We think of it as RZ, but there's no coupling between the axial slices, so basically it's a 1D calculation at each axial node.

MEMBER BANERJEE: Okay. So the actual diffusion is not taken into account very well.

DR. RAYNAUD: For the coolant conditions, you are heating up the coolant as you move up the rod. And there is gas communication in the rod. But in terms of heat transfer, there is no axial heat transfers.

MEMBER BANERJEE: That's fine, okay. But there is also no eccentricity that you're able --

DR. RAYNAUD: Right.

MEMBER BANERJEE: I mean, there was a long discussion about this at some point. I think Paul remembers this. So nothing has been done about that.

DR. RAYNAUD: No. I mean, going from, you know, 1D to 3D is not easy. And, I mean, really --

CHAIRMAN ARMIJO: 3D's stochastic.

DR. RAYNAUD: -- we haven't had a very strong need to do that.

MEMBER BANERJEE: I think there was some assessment somebody showed us which showed it wasn't a

very important effect.

MEMBER SCHULTZ: That was done at the PNLL at one point.

MEMBER BANERJEE: Yes.

DR. RAYNAUD: When you have a statistical poll that can vary gap sizes, or pellet diameter and cladding diameter, you know, that would essentially mean you're changing the distance between the pellet and the cladding. But you are not modeling hot spots as immediately.

MEMBER BANERJEE: Okay.

DR. RAYNAUD: Once you cut down and close the gap those problems are gone.

MEMBER BANERJEE: All right.

DR. RAYNAUD: In the fuel burnups, we chose a four-loop Westinghouse PWR because it's the most common type of PWR in this country, 17 by 17 fuel, ZIRLO cladding.

And we ran it through a double-ended guillotine cold-leg break, large break LOCA. We did this in the middle of the cycle, full power operation. And we analyzed three variations of that scenario.

You know, if all systems are responding as designed, if you have a loss of onsite power and if you have one train of emergency fuel cooling systems

it is unavailable. And what you'll see is that there are some significant differences between the three scenarios.

The next two slides, I think I'll go pretty fast through them, but I'm happy to provide as much detail as you want either here or offline.

MEMBER POWERS: Don't offer that, the --

(Laughter)

DR. RAYNAUD: We have power histories from final safety analysis report, steady-state core. And, you know, there're some assumptions that go in there that the core sort of repeats itself over time.

But we were able to, for each assembly in the core, get some fairly representative power histories. And when you calculate the average core discharge burnup, it's around 50, 51 gigawatt-days per ton. And the fuel is probably pretty representative of what's going on in the industry.

So we have all these different power bins, and we generated power histories from those. That's important because that allows you to model the steady-state irradiation and to know the state of your fuel rod at the beginning of the transient.

The transient was modeled first using TRACE. So as I said, you know, worse large break LOCA

for this type of plant, the initial outrace with the FRAPCON for fuel rod burnup dependent parameters and with the TRACE steady-state for the initial thermohydraulic state of the system.

And here is the core-wide peak cladding temperature plotted as a function of time for these three scenarios. The green line is the ideal system response. When you have a loss of offsite power the overall peak cladding temperature does not really increase. However, you have a delayed crunch at the very end of the transient by about 20 seconds or so.

However, when you have one train of ECCS that's inoperable, then you have about 50 degrees Kelvin of peak cladding temperature increase and a pretty significant later quench, about 60 seconds later. And we talked about this for like the cladding surface temperatures that then go into FRAPTRAN.

The TRACE core and the FRAPCON, the FRAPCON core will not mobilize exactly identically. So we had to do some cross-referencing. All in all, the result is that we need to run about 300-plus FRAPTRAN runs to model every combination of TRACE and FRAPCON conditions to obtain a core-wide picture of what's going on.

And so for each FRAPTRAN run, the

transient fuel performance, we know how many rods correspond to that one rod that we do. There's some averaging that takes place. We don't model the 50-plus thousand watts that are in the core. But it's still a relatively fine degree of nodalization, sub-assembly or on the order of an assembly.

MEMBER BANERJEE: Can you just lead us through what all those colors mean?

DR. RAYNAUD: Yes, absolutely. So this is how the TRACE core was modeled. You had two rings, azimuthal sectors.

MEMBER BANERJEE: You probably want to pull the mic close to you while you talk.

DR. RAYNAUD: Sorry.

(Simultaneous speaking.)

DR. RAYNAUD: So this right here is the radial core power assembly distribution at the middle of cycle. These just show fresh fuel assemblies, once burned fuel assemblies and twice burned fuel assemblies. And basically this just repeats, this is the radial power distribution assembly-wise, for fresh assemblies, once burned and twice burned.

And this is, you can see here that we have like a lot of different colors which means a lot of different groups. For example, this assembly, this

one, this one, and this one form one bin. But, you know, every color marks off on a different bin.

And in TRACE what you see is that it's a coarser nodalization. All these yellow assemblies here, of course, are on the one TRACE bin. But in FRAPCON we have a finer distribution. So basically, you know, I don't know, maybe there's two FRAPCON bins here that correspond to the yellow assemblies.

MEMBER BANERJEE: The TRACE is on top?

DR. RAYNAUD: TRACE is on top, yes. And FRAPCON's at the bottom.

MEMBER BANERJEE: I got it.

DR. RAYNAUD: And basically we subdivided the TRACE bins into more bins in FRAPCON. So we have to kind of reconstruct all that to make sure that we capture every combination that occurs when we run the FRAPTRAN calculations. It's a lot of Excel work, but it functions.

Essentially, what we're trying to do is just to get the transient fuel rod performance, transient fuel rod behavior as calculated by FRAPTRAN. And more specifically, really what we're interested in is the cladding strain and ballooning behavior. Because that's what will result in fuel rod ruptures. And that's what we're trying to get to.

So now I'm going to show some results. Actually, I could stop now, Dr. Armijo, if you want.

CHAIRMAN ARMIJO: Yes. This would be a good time. Let's take 15 minutes and reconvene at 10:40. Is that 15 minutes?

(Off microphone discussion)

(Whereupon, the foregoing matter went off the record at 10:25 a.m. and went back on the record at 10:43 a.m.)

CHAIRMAN ARMIJO: Let's come back to order. Sorry for being a little late. Patrick?

DR. RAYNAUD: Okay, you've got it. So the next few slides present the result of the first PWR study that we did. And since then we're in the process of refining it and what not.

So don't take these in absolute numbers as the absolute, perfect result but more as an indication of where we're going, what the methodology is and general trends, you know.

So this slide shows how many, I remind you the large break LOCA where all trains of ECCS are available, the plant functions as designed, everything's perfect. And this plot here shows how many fuel rods have ballooned in each assembly.

Two hundred and sixty-four is the total

number of fuel rods in the assembly. So when you see 264, which is the dark green, it means all the fuel rods in that assembly have ballooned.

On the right hand side it's the number of fuel rods that have ballooned versus the balloon strain. And it's broken down by fresh fuel, once burned and twice burned fuel.

What this shows you is that even if the plant responds as designed you still have a fair amount of ballooning or of rods that balloon in the core.

That said, most of the rods have pretty small ballooning strains. I mean, you know, relatively speaking on the order of five to 15 percent ballooning strains. So you haven't reached rod to rod contact yet. The rod pitch, in this case, was if you reach 38 percent ballooning strain you've hit the next rod.

CHAIRMAN ARMIJO: One of the things that jumps out is the twice burned assemblies.

DR. RAYNAUD: Yes.

CHAIRMAN ARMIJO: There's darn few of them, and they're pretty small.

DR. RAYNAUD: Yes, you're absolutely right. The twice burned is these down here on the

bottom right. And there's only one in the center ring of the core. It's the very center of the core. And that's the only one that has some ballooned rods here. About half of the rods in that assembly are ballooned.

CHAIRMAN ARMIJO: That's the only one that could have high burnup?

DR. RAYNAUD: That's correct.

MEMBER BANERJEE: And that's in high heat flux region.

DR. RAYNAUD: It's in a pretty hot region of the core, yes.

MEMBER SKILLMAN: What's our estimate of the rupture strain?

DR. RAYNAUD: Well, the rupture strain depends on what pressure and temperature you rupture at. So I can't give you a number that would always be the same. But in this case, these rods did not rupture. They only ballooned. We had no predicted ruptures for this particular scenario.

MEMBER SKILLMAN: Okay.

DR. RAYNAUD: But the result has been you have no fuel dispersal of course, because no fuel rods ruptured.

When you do a loss of offsite power, a

very small change, because you delay the quench a little bit. So you're able to balloon for a little bit longer. And you can see when I toggle between the two slides that you've increased your balloon strains a little.

But the overall number of rods that balloon is very similar. And that's largely because over all of the temperatures that you reach for the different assemblies and such are about the same. They're just delayed quench. You stay there for a little bit longer.

The next case is when you have one train of ECCS that is inoperable. And there we do have some ruptures predicted. This shows which rods were predicted to balloon. Basically almost all of the rods that are in the inner ring of the core are predicted to balloon.

And in this case, a large number of them have reached 38 percent strain which means you have rod to rod contact. In our code, when you reach rod to rod contact the ballooning stops. That's the way the code is written. Because we can't really model the detailed, you know, the balloon kind of becomes squarish sometimes. There are some funny things --

This is a limitation that we have. But it

does indicate a lot of ballooning.

MEMBER BALLINGER: Are you assuming uniform strain?

DR. RAYNAUD: Azimuthally using it for ballooning, if that's what you mean, yes.

MEMBER BALLINGER: Yes.

DR. RAYNAUD: Yes. Because we had a 1D code in it. And now this next slide for that same scenario is which rods ruptured. And you can see that there's a fair number. I think when you add it up it's about 10,000 or 20,000 rods. I forget exactly the number.

But we're talking about 20-plus percent of the core that rupture, most of them in the inner ring of the core. And when you look at the number of burst rods versus -- this time it's not the ballooning strain, it's the burst time, the X axis has changed -- you can see that most of the ruptures happened between, you know, 120 to 160 seconds.

And if you go back and look at the temperature histories of the transients, and you have to look at the red line here, that's when you reach the highest temperatures in your transient.

MEMBER BANERJEE: This is for 1ECCS system --

DR. RAYNAUD: Yes, correct.

CHAIRMAN ARMIJO: Your PCT, what's that acronym stand for?

DR. RAYNAUD: The PCT, in this case core-wide PCT, was about 1,050 Kelvin.

(Off microphone discussion)

DR. RAYNAUD: Oh, sorry.

MEMBER BANERJEE: Why is it all one-sided?

DR. RAYNAUD: That's because this is the quadrant that the, this is the cold-leg that broke was in that quadrant.

MEMBER BANERJEE: Oh, okay.

DR. RAYNAUD: So you have --

MEMBER BANERJEE: So you've got some asymmetric --

DR. RAYNAUD: Yes, yes. You do.

MEMBER BANERJEE: Well, I guess TRACE could --

DR. RAYNAUD: TRACE gave us those, you know, coolant conditions, asymmetric, because TRACE has the full core 3D model. And then, you know, when you look at FRAPCON and FRAPTRAN, one bin might be in several quadrants. I mean, there's some averaging that takes place, but you can nonetheless build these kinds of pictures.

MEMBER RICCARDELLA: You said the rupture strain is a function of pressure and temperature. I understand how it's a function of temperature. Why is it a function of pressure?

DR. RAYNAUD: Well, there's a curve, see --

MEMBER BALLINGER: For internal pressure, the initial pressure, right?

MALE PARTICIPANT: Well, there's strain --

DR. RAYNAUD: Especially at the time of the transient. I mean, when you --

MEMBER RICCARDELLA: When the pressures causes the strain. But the strain at which rupture occurs would seem, why would that depend on the pressure?

DR. RAYNAUD: Well, depending on how much pressure you have in the rod, you're going to rupture at a different temperature. And the material parameter, material properties are temperature dependent. So you're going to follow a different stress/strain path essentially to the rupture. And you'll have a different --

MEMBER RICCARDELLA: Different temp strain, I understand that there are temperatures.

MEMBER BALLINGER: Those are all those

useless results that Dana said we had at PNNL.

DR. RAYNAUD: So there's NUREG-0630 shows a curve that is essentially, rupture strain is a function of rupture temperature. And that has sort of a, looks like a, I forget which camel or dromedary, but it has two humps, you know. It's a double hump. And the dip is where the alpha to beta phase transfer information occurs, thank you.

And, you know, then there's another plot. And that's really what the rupture criterion is that shows, it's a line to represent rupture, it's temperature and pressure are the axes. And essentially, if you cross that line, if you're at a given pressure and you hit a certain temperature you'll rupture. If you're at a given temperature and you exceed a certain pressure you'll rupture.

And so the criterion in FRAPTRAN is that pressure versus temperature curve, which has not too much scatter and it's a pretty well defined line, so it's a pretty good criterion to use, because the scatter is small.

And how you get to that point though, that depends on the temperature history of the rod. And you've accumulated different amounts of strains as you balloon.

MEMBER SCHULTZ: So that correlation goes back to what reference?

DR. RAYNAUD: NUREG-0630 was on rods that were actually fueled, if I'm not mistaken. And there was another NUREG/CR after that that added a lot more data points to those curves.

Some of them though had been de-fueled segments, I believe. Actually some of them might have been fresh cladding. I mean, there's a big mixture of data. Some of them are more or less valid, depending on whether you believe that fresh cladding can represent high burnup cladding and that sort of thing.

MEMBER SCHULTZ: That's fine. I'll look it up, thanks.

DR. RAYNAUD: So now how do we look at the results that we generated which is how many rods ruptured and the local conditions at the rupture? And then we compare all of those things to Michelle's thresholds that she obtained experimentally.

So here's some of the conditions. Essentially what Michelle said, the fuel rod needs to rupture for there to be dispersal. You need the fuel fragments to be smaller than the rupture opening. But we can't accurately predict what the rupture opening looks like.

So what we did was an assumption that all the fine fuel fragments that were below a size X that you can pick, we picked one millimeter as our sort of best guess, all the fragments that are smaller than one millimeter in diameter can escape the fuel rod if it's ruptured. And all the fragments that are larger than that will stay in the fuel rod.

Again that's, you know, it's an assumption. And depending on what number you pick, you're going to have very different results.

We also assumed that there's a local pellet average burnup threshold where you transition from a rather coarse particle distribution, that was what Michelle called the high burnup test, around 50, 60 gigawatt-days per ton.

And then past a certain burnup, let's say that's between 50 and 70, let's say 60, then you're transitioning to fine particle distribution which was Michelle's very high burnup rods which essentially almost all the fuel is very finely fragmented.

And then for axial fuel mobility to occur, and that being a condition for the fuel to be dispersed, you need a certain cladding strain that would be between three and seven percent. So let's say five percent.

And when you pick these thresholds, this table shows how much kilograms of fuel are dispersed depending on what thresholds you pick. It's kind of a busy table, but the left-most column right here, this is the burnup number that you pick for your threshold from coarse to fine fuel fragmentation.

Then, you know, once you pick that burnup then you look at what fuel fragment mobility threshold strain you pick for the cladding. Whether you pick three, five or seven percent, you're going to get different numbers.

And then this is the, you know, what particle size do you assume can fall out of the cladding when it's ruptured?

So if you pick that every particle below one millimeter in size can fall out of the cladding if it's ruptured, and that the transition from coarse to fine fuel fragmentation is 60 gigawatt-days per ton and your fuel mobility cladding strain threshold is five percent, you end up with 6.7 kilograms of fuel dispersed for the whole core.

And you can see that, you know, these numbers vary a lot depending on what thresholds you pick. These are best guesses at this point. So that's why I want to highlight that particular number.

That amounts to 35 grams per fuel assembly or 123 grams per fuel assembly if you only considered the assemblies that have ruptured fuel rods.

Again, these predicted masses of fuel that is dispersed vary a lot depending on what burnup threshold you pick. That's really one of the biggest impacts but also what is fine enough to be dispersed.

CHAIRMAN ARMIJO: But even at four millimeter size, you're still talking 60 kilograms. It's not like the end of the world as far as the amount of fuel that gets --

DR. RAYNAUD: A gut feeling would say, yes, you're probably right. But I don't --

CHAIRMAN ARMIJO: Well, you know, that's --

DR. RAYNAUD: -- we would need to run some calculations --

CHAIRMAN ARMIJO: -- preliminary.

DR. RAYNAUD: -- to be sure of that, yes.

MEMBER SKILLMAN: I don't share that point of view. Sixty-four kilograms is enough to take the lid off the reactor building. Avogadro's number is a big number. And that is your carrier of your fission product curve. And so when you see what's in those 6.7 kilograms or 64.9 kilograms, it's exciting. That

is a huge amount of inventory.

DR. RAYNAUD: We're talking fine fuel fragments, right?

MEMBER SKILLMAN: Let's start at the top. One millimeter sounds small. That's 1/25th of an inch. That's 40 mils.

DR. RAYNAUD: Okay.

MEMBER SKILLMAN: You get 6.7 kilograms of that material in your reactor cooling system, I would say your reactor building is off limits. If you have less than that --

MEMBER BANERJEE: No kidding.

(Laughter)

(Simultaneous speaking.)

MEMBER SKILLMAN: -- huge events. As Sam says, it doesn't end the world.

MEMBER RICCARDELLA: But you still have that large break LOCA.

CHAIRMAN ARMIJO: But from a coolability standpoint is what I was thinking, not a --

MEMBER SKILLMAN: Okay. If you go to the radiological side, it's a huge event.

CHAIRMAN ARMIJO: Yes, sure.

MEMBER SKILLMAN: Is it cool, got you, it is.

DR. RAYNAUD: I think that's what I'm more --

MEMBER SKILLMAN: Now, the other thing is what's running? The direct cooling pumps running or not running? Because your driver becomes the mass flow through the core.

DR. RAYNAUD: I mean, there's a lot of implications, you know, with this fine fuel dispersed in the core. And I don't think we have definite answers. But how much of it is entrained in the coolant, how much of it just falls to the bottom and sits at the grid spacer or who knows what? What are the consequences for, you know, for flow if you go into re-circulation mode for example.

MEMBER BANERJEE: Don't go there.

DR. RAYNAUD: You know.

MEMBER BANERJEE: Yes. It can do all sorts of things.

DR. RAYNAUD: We don't know those answers. I mean, I don't know those answers. Maybe some of you have insights. But I don't know the safety significance at this point. This is just what we calculate.

So, yes, some of the limitations of the study is, although it's a pretty new approach with a

pretty high level of detail that we've achieved, we're completely relying on TRACE to provide boundary conditions from FRAPTRAN. And we don't have active coupling between the two codes. That's one limitation.

And, you know, TRACE has really improved a lot in the recent months in terms of the fuel rod models that it has. So that gives us more confidence in some of the predictions that we're getting. But early on a lot of the fuel detail a was not in TRACE. So that was also something that maybe limited the accuracy of the predictions.

We have some averaging that takes place. We're not modeling every rod in the core. Let's be clear. So we may not be capturing the very peak rod at the core. But maybe we're overestimating for some rods that are at a lower power. So, you know, maybe on the average we're doing an okay job. But we might be missing out on some very peak rods.

And again, the predictions vary a lot depending on what you assume for these thresholds. And we don't have a quantified uncertainty at this point. I mean, there's a little bit of scoping analysis to look at sensitivities. But we don't have anything very well defined.

In terms of the BWRs, Ian Porter, who I was mentioning earlier at University of South Carolina, did this work. He completed a BWR/4 for large break LOCA and small break LOCA. He did small break at the beginning, middle one end of cycle, large break only at middle of cycle, because that happened to be the worst for the small break.

In short, the temperatures that were predicted were way too low to get any kind of ruptures. I think there was not even any ballooning predicted. So we didn't have any issues. We didn't pursue this particular analysis further. But we will take one train of ECCS out in the future to see if that changes these results significantly or not.

MEMBER SCHULTZ: What about small break LOCA in a PWI?

DR. RAYNAUD: That is on our list. But we haven't done that yet.

MEMBER BANERJEE: If you want to do a BWR do a MELLA+.

(Laughter)

CHAIRMAN ARMIJO: You've got your sights on him.

DR. RAYNAUD: We're limited by what decks we have available, and what plants and what

information we have. And so we can't always do every transient we could dream of. We're limited by what was already existing.

MEMBER POWERS: Tell him that you can't do MELLA+ at all.

DR. RAYNAUD: We don't want to give him that coverage.

(Laughter)

DR. RAYNAUD: Some of the recent works though, we're updating the PWR study with, now instead of doing some averaging we're modeling every assembly individually. And we're doing beginning and end of cycle also.

We found some differences, slightly higher PCTs with the new versions of TRACE and the more detailed modeling. So that will change some of the predictions that we have here.

We need to complete the dispersal analysis for the new PWR that we modeled. We're also looking at whether we should break down even finer for the high powered assemblies to look at, within the assembly, some power variations over the course of variation that would result in some fuel rods that have much higher 11:01:51 pressure than some others within that fuel rod.

In the past we've averaged it. So essentially we're trying to capture those peak rods that we haven't captured up until now. And we want to try and do a B&W and a CE plant also, because pretty different, potentially. We're working on the CE currently. We haven't started the B&W.

For BWR, we'll do the one train of ECCS inoperable. And I think we would like to look at a BWR/2 and 3. We don't think that the fives and the sixes will have issues if the fours don't have issues.

For the sake of time, I don't think I'll read these conclusions. The summary is essentially what I've just talked about in my presentation. And that's all. Thank you.

CHAIRMAN ARMIJO: Patrick, if the cladding failed earlier, let's say more brittle, we've been driving the industry toward more ductility, this problem would tend to go away, because you'd have very, very small cracks as opposed to big balloons.

If it fails early, releases the gas pressure, there's no driving force for ballooning. And even if you got a lot of fines, very little of it would get out.

DR. RAYNAUD: That's probably true, assuming that that rupture doesn't have other

consequences on the future behavior of the rod during the transient --

CHAIRMAN ARMIJO: Yes. Well, that was a big argument. You know, if you fracture the rods and you might lose a coolable geometry on a much larger scale.

DR. RAYNAUD: If it's a pinhole, you're probably right. But if you're grossly fracturing the rod then we're back to this problem.

CHAIRMAN ARMIJO: Yes, yes.

MEMBER POWERS: The problem has always been a concern about unzipping the rod. That could go to full length tests. That's all there is to it.

DR. RAYNAUD: The grid spacers will have a lot of influence on what you see for dispersal, I think. Because they tend to restrict the strain at those locations.

And it's also not clear to me whether you can continue to unzip a fuel rod past the grid spacer. Maybe you can. But in any case, I think you'll restrict the axial mobility of the fuel at the grid spacers. And so you'd probably be limited by the span where the rupture occurs anyway, as a conservative sort of bounding.

MEMBER RICCARDELLA: Could you conceivably

get a circumferential rupture instead of an axial?

DR. RAYNAUD: I mean, I supposed anything is possible. But that's not typically what is seen in these tests.

MEMBER RICCARDELLA: Okay. I couldn't think of anything --

DR. RAYNAUD: Oh, I hate to, very, very high --

MEMBER RICCARDELLA: When using the grid spacing, I worry about the discalculability in stress around the grid.

MEMBER POWERS: Yes. We do see the double hump bubbles around the grid spacer. And of course the local stress in there is just astronomical.

MEMBER RICCARDELLA: Yes. And maybe you don't have that in the tests.

DR. RAYNAUD: We don't. And they're talking about adding a grid spacer in some future, I forget if it's Studsvik or Halden, maybe both, to look at that.

MEMBER BALLINGER: When you cross over the 762 or whatever the phase transformation boundaries, you get very, very different behavior above and below. So if you can stay below that 762 --

DR. RAYNAUD: Well, if you can stay below

the point of ballooning and rupture, you know, none of this occurs. Phase transformation temperature actually varies from rod to rod because a different amount of oxygen, the cladding from rod to rod. And it can have a pretty big impact.

MS. FLANAGAN: And you have to remember that the LOCA criteria of 17 percent oxidation and 2,200 fahrenheit are designed to keep the general material properties ductile. And so, I mean, a fracture could occur, but one of the designs of the LOCA criteria is to keep the material relatively ductile so that that kind of fracture due to localized stresses won't occur.

MEMBER BALLINGER: I think that criteria, and Dana will of course correct me if I'm wrong, those criteria prevent fragmentation on the reflood.

MEMBER POWERS: They're just ductility --

MEMBER BALLINGER: I mean, it's basically having the rods stay together when you get --

MEMBER POWERS: Yes. That's the idea, is that if you want to preserve ductility and not have a pile of rubble, I mean, that's the way they were formulated. And I think they're just ductility requirements. I don't think it's fragmentation. I don't think we can calculate fragmentation.

MEMBER BALLINGER: Well, many of the fuel rods died brittle, in a brittle matter on the reflood.

MEMBER POWERS: Yes. And that's good to do that.

MEMBER SKILLMAN: Michelle, let me ask you this. You made a very strong presentation that the contained gas when the pressure decreases actually fractures the pellet. Is there a preferred gas?

CHAIRMAN ARMIJO: We don't have a choice.

MS. FLANAGAN: No. I mean --

DR. RAYNAUD: We don't know.

MS. FLANAGAN: No, I don't think there are.

CHAIRMAN ARMIJO: We don't have a choice in this case.

(Off microphone discussion)

MEMBER SKILLMAN: Are they all the same? Do they all behave the same?

MS. FLANAGAN: All the gases?

MEMBER SKILLMAN: Yes.

MS. FLANAGAN: I mean, I described it as the fission gases. But what we're looking at is the porosity of the fuel. And so we don't know a lot about what is in --

MEMBER SKILLMAN: Oh, you know, the gas is

in there and it will expand when the pressure's reduced.

MS. FLANAGAN: Right. There are some studies in the future that might measure the gas that is coming out at the moment of rupture. And if that happens, we might see some breakdown of what is released at the moment of rupture.

But right now it's just an empirical observation that this porosity, all throughout the pellet in these regions that are what I call vulnerable to fine fragmentation, and that those we know contain very high pressure gasses.

CHAIRMAN ARMIJO: Well, PWR rods in this burnup range for fragmentation of, you know, 60 or in that range, what fraction of the gas is helium versus fission gas?

DR. RAYNAUD: At the end of irradiation?

CHAIRMAN ARMIJO: At that point, you know, we pre-pressurize them, and people have worked very hard to keep fission gas release down. And what's the rough idea? Is it mostly helium still? Or is it --

DR. RAYNAUD: I would say it's still at least half helium.

MEMBER BALLINGER: It's got to be more than that, right?

DR. RAYNAUD: I think we maybe have like 70, 80 percent helium. Does that sound about right?

(Simultaneous speaking.)

DR. RAYNAUD: For a high burnup rod, again, this is just from remembering, you know, maybe a print out of a calculation somewhere. It's like it'll vary, but maybe 70 or 80 percent is still helium, maybe even a little bit more than that. Does that sound about right?

(Simultaneous speaking.)

CHAIRMAN ARMIJO: The industry's been working really hard to keep fission gas release down.

MEMBER POWERS: Now, what you do get is, with a small amount of xenon and krypton, you know, has dramatic effects on the thermodynamic activity.

DR. RAYNAUD: At least the fact that it's not lower.

MEMBER POWERS: But it's not a very high percentage of --

CHAIRMAN ARMIJO: We have a comment from Burt Dunn of AREVA just maybe--

MR. DUNN: Yes. I was just going to say if you look at the green or fresh fuel pin pressure at the LCO conditions you're going to get about 1,200, 1,400 PSI. If you look at the pin pressure in a LCO

condition for a rod at 45 to 50 you'll get on the order of 2,500 PSI. So the fission gas fraction, assuming the other stuff is equal which it won't be, is probably on the order of 50 percent.

CHAIRMAN ARMIJO: Okay. So we still have a lot of helium in there.

DR. RAYNAUD: The rod volume would have probably decreased significantly also, right, if the gap is closed? So ,I mean, it would --

MEMBER BALLINGER: Not significantly, but yes, it would have decreased.

CHAIRMAN ARMIJO: Helium should rush right out of there, but it doesn't.

MR. DUNN: Most of the rod volume is in the plenum.

CHAIRMAN ARMIJO: Oh, yes. Okay, thank you. Thank you, Patrick. If there's no more questions, we'll move on to the next presentation. That'll be EPRI. Ken, are you --

(Off microphone discussion)

MR. YUEH: Can I start?

CHAIRMAN ARMIJO: Go ahead please.

MR. YUEH: My name is Ken Yueh. I'm a project manager at the Electric Power Research Institute. I'll give a very short talk focusing on

the phenomenon of fuel fragmentation.

So the presentation is sort of at high level whether you have severe fuel fragmentation or not or we're not getting the details where you have the chain, severe fuel fragmentation and no fragmentation.

So just briefly from a background review of the recent test results, and some of our observations from the experiments, and our thoughts on potential impact on fuel performance in the event of a LOCA, and then some of our own preliminary test results and what we plan to do in the future to evaluate the mechanisms behind fuel fragmentation.

So in the interest of time, I'll skip the first slide. This is a summary of most of the other tests. There is a total of 14 tests. But I only have data to Test 12.

The Halden test is conducted with nuclear heating and very subsistent with electrical heating, external electrical heating. Because the nuclear heating is not enough to bring the cladding to the desired temperature.

What I want to show on this slide is the several instances of severe fuel fragmentation at high burnup, you know, above 83 gigawatt-days per MTU. And

then we have some tests with lower burnup, up to 72 where you do not see severe fuel fragmentation.

And one thing that brought up earlier is --

CHAIRMAN ARMIJO: Ken, I guess I don't agree with you. I'm looking at Test Number 12. Is that what you're talking, the picture is very fuzzy. So how can you tell that that isn't just a lot of powder?

MR. YUEH: Well, I think it looks, the neutron radiography looks like this test, Number 7.

CHAIRMAN ARMIJO: Okay.

MR. YUEH: So this is not sand. That's what I'm, you know, the statement I made earlier, I'm looking at the higher level where you have total fragmentation.

CHAIRMAN ARMIJO: So you're saying there are clear exceptions to the assumption that maybe even at very, very high burnups you have -- the data that Michelle showed kind of led me to believe that you'd always have fine fragmentation at these very high burnup levels. And you're saying that's not the case?

MR. YUEH: Oh, no. I'm not arguing against some limited fine fragmentation. Even any radial fuel pellets, once you breakup, you may

generate some fine fragments.

CHAIRMAN ARMIJO: We're talking lots of fine fragments.

MR. YUEH: Yes. But, you know, in this case, comparing for example Tests Number 7 and 12, compared to the NRC sponsored Studsvik test, there's a big difference in terms of fragment size distribution.

CHAIRMAN ARMIJO: Yes.

MR. YUEH: So this is the order of magnitude change that I'd like to discuss.

CHAIRMAN ARMIJO: But that's electrically heated, right?

MR. YUEH: All the tests have some electrical heating.

CHAIRMAN ARMIJO: Oh.

MR. YUEH: So even the Halden test, it's electrically heated from the outside as well. It's about 50 percent of the heat is from electrical heating, 50 percent from nuclear.

CHAIRMAN ARMIJO: Okay.

MEMBER REMPE: Has there been any discussion about nuclear heating and quenchability of the fuel. And I missed earlier today, so perhaps it was discussed --

CHAIRMAN ARMIJO: Yes.

MEMBER REMPE: -- earlier.

CHAIRMAN ARMIJO: You know, can you really use the data sets, you know --

MR. YUEH: I can talk a little bit about that on the next slide. So one thing I want to point out is, where you have severe fuel fragmentation, you know, this is Tests 4, 5 and 9, what I call severe fuel fragmentation, the fragments are much smaller than, for example, Tests 7 and 12.

So these rods, they have special power history. The reason they got to this high burnup was because most likely they were transplanted from one sampling to a fresher sampling and operated at high power near the end.

Specifically these tests, the last cycle of power, all of them were higher than 15.5 kilowatts per meter. And if you have regular high burnup fuel, it's most likely that the power level you can achieve may be five or something on that order.

The latest couple of exceptions, some people like to put a depleted fuel assembly right in the center of the core to make it a little bit higher, but not necessary this high.

MEMBER BALLINGER: So you're saying may.

You don't have the records to know the power history for those?

MR. YUEH: These are the known power history for the last cycle. And in a few slides later I'll talk about why the last cycle is important.

MEMBER BALLINGER: Okay.

MR. YUEH: Okay. I think it's related to the thermal stress, some of your product.

MEMBER BALLINGER: Well, that's what Sam is bringing out too. When you electrically heat plus nuclear heat you change the gradients everywhere. So hopefully we could normalize that out somehow.

MEMBER SCHULTZ: Can the burnup ranges you report here, they appear somewhat higher than what we saw in Michelle's slides earlier, that is four, five and nine, are above 80.

MR. YUEH: These are the published data from the Halden program, not by any translation. This is what they reported.

MEMBER SCHULTZ: No, that's fine.

MR. YUEH: And these are the segment average.

MEMBER SCHULTZ: Segment average.

MR. YUEH: Just one second.

CHAIRMAN ARMIJO: That's all very high

burnup rates.

(Simultaneous speaking.)

MEMBER SCHULTZ: And I think Michelle was using a different average or value. Thank you.

MR. YUEH: Okay. And then I want to point out, you know, the reason you do not see fine fragmentation on Test Number 12, it may be because it was operated at very low power in the last cycle.

The last cycle, you know, started pretty high, maybe around eight or nine. So by the time the cycle finished, it was maybe 0.3. So in terms of thermal stress, when you shut down, it's very low thermal gradient being used in and outside for this.

MEMBER SCHULTZ: And this is the last cycle of how many cycles of operation?

MR. YUEH: This one, probably seven cycles.

MEMBER SCHULTZ: Yes.

CHAIRMAN ARMIJO: In the meantime, in a BWR to get seven cycles --

MEMBER SCHULTZ: To get those burnups, yes, need more than seven.

MR. YUEH: Now, you know, the NRC sponsored test at Studsvik, it's externally heated

entirely. Initially there were, you know, for me there was some concern because of external heating. You can introduce reverse temperature gradient. It's hotter on the outside than inside.

I did some evaluation with that based on the heating rate that was reported, I think 5 Celsius per second. The temperature beneath the inside near the cladding, between the outside cladding and the inside, was a load of 15 degrees Celsius. A thermal grade, it's not really large.

So that's maybe why the results are pretty much consistent between the Halden tests and then the externally heated test at Studsvik.

CHAIRMAN ARMIJO: But the gradients are different.

(Simultaneous speaking.)

CHAIRMAN ARMIJO: But it's not big, you're saying.

MR. YUEH: Not big. Yes.

MEMBER BALLINGER: But the external heating, you're right, the temperature drop across the cladding is minimal compared to the fuel.

MR. YUEH: Yes, it's the, I'm talking, the fuel temperature at the clad to the interior, it's about 15 degrees difference. I took the heating rate.

If you heat up faster, it's going to degrade.

MR. YUEH: But the heating rate that was applied in the test, it was about 15 degrees.

MEMBER REMPE: But there's more from back in the days of loss versus semi-scale, the ability to quench the fuel was different if it was electrically heated versus nuclear heated. And so I'm just wondering, for the part I was here this morning, I didn't hear the people talking about are the data really prototypical.

MR. YUEH: If you quench, I guess, very early in the LOCA cycle it could be different. You know, the inside could be hotter than the outside. And I do not know how long it takes. Maybe Bert can say how long it takes for the entity to flatten up.

MR. DUNN: What, in quench?

MR. YUEH: Yes, in the pellet.

MR. DUNN: Probably not too long, five or ten seconds.

MR. YUEH: So if that's the case, it probably doesn't make any difference. You know, it's only 15 degrees on the inside and outside. If it's nuclear heated, it's 15 degrees, it's flat.

MR. DUNN: These tests were designed to look at thermal shock. I'm primarily interested in

the first part of the transient where they're looking at the heatup and the rupture. It occurs in the first 100 seconds of the transient.

And then later on you go into a different phase where you're coming in, flooding up from the bottom. And you get to the point where you put the cladding through a quench position and create thermal shock at that point.

MEMBER BALLINGER: Do you know what temperature the bursts occurred at? I'm sure it's there somewhere. I just don't remember.

MR. YUEH: Yes, Michelle probably needs the answer for these. It's close to 800, right, sound right?

MEMBER BALLINGER: Close to 800. Do we have an estimate of the actual temperature at which those burst occurred?

MS. FLANAGAN: Yes, we have them.

MEMBER BALLINGER: So just compare a number, compare Studsvik 70 with Studsvik 61. Same temperature?

MS. FLANAGAN: The temperature of rupture?

MEMBER BALLINGER: Yes, at rupture.

MS. FLANAGAN: It'd be similar. And they both were generally consistent with the behavior. And

they're in the same range, between 700 and 800. And they're consistent with the known stress criteria that we had back earlier.

MEMBER BALLINGER: Okay. I'm still coming up to speed. Because the difference between 700 and 800 is significant.

MR. DUNN: But there's a tremendous amount of scatter on the table.

MEMBER BALLINGER: Yes. I mean, you're above and below the phase transformation here.

MR. DUNN: Well, between 700 and 800, right, at least in the pristine Zircaloy path.

MEMBER BALLINGER: I don't mean to interrupt, Ken, but we've talked about the phase transition temperatures being a point.

MR. DUNN: I'm not disagreeing, I'm sure --

MEMBER BALLINGER: It is a point in equilibrium. But it spreads out over a couple of hundred degrees during the heating transient.

MR. YUEH: It's an all wide spread up if it appears accordingly at a single point. But it's --

MEMBER BALLINGER: But, I mean, there's a lot more plasticity going on in the 70 gigawatt-day one than there is in the 61.

CHAIRMAN ARMIJO: It may not have anything to do with burnup.

MEMBER BALLINGER: It may not. I'm just trying to separate things out.

MR. YUEH: I think the hydrogen for both samples is very low. So the ductility may not be that different.

CHAIRMAN ARMIJO: Yes. Okay.

MR. YUEH: So what I want to point out --

CHAIRMAN ARMIJO: Go ahead, Ken.

MR. YUEH: What I want to point out in this, you know, the NRC Studsvik test I think Michelle reported as a little bit lower. What I'm reporting, 61 is the LOCA burnup. So I think, again, Michelle reported the rod average burns. There's actually 61.

And associated with this, the picture, the black and white picture on the top right hand side was one of the Halden tests where they put the fresh fuel inside those nine radials. So you can see the fragment size is similar to the Studsvik radaii at 61. I think they're comparable in size. There was very little degradation.

Now, we have since conducted further testing with the same rod I will show later. There was no degradation from exposure to high temperatures.

And as I pointed out, the Studsvik test, the 70, the high burnup, the last cycle also had 15 kilowatts per meter.

CHAIRMAN ARMIJO: So they're high burnup, high power in the last cycle.

MR. YUEH: Yes. It was transplanted to a different assembly.

CHAIRMAN ARMIJO: So it was a special kind of irradiation to get it up to those powers.

MR. YUEH: Yes.

CHAIRMAN ARMIJO: Okay.

MR. YUEH: It was based on this test. These are some of the observations. So we have seen severe fuel fragmentation above the licensed burnup limits. But all these have unusual power histories. They were, you know, the last cycle, both of them had high power. And I will get to this a little bit later, the impact of high power with the internal stress they generate.

And then we already talked about IFA650.12. It's not as severe. It's fragmented, but it's not severe up to 72 gigawatt-days per MTU. And based on the 761 gigawatt-day Studsvik test, it does not seem to be a fragment size change as a function of burnup as long as you are below the threshold,

assuming that there is some threshold. We do not know what that is.

The last point is most of the balloon and burst size are pretty small, below the licensed limit. Even the although the tests were designed to maximize ballooning, especially the Halden test, some of them still end up with very small ballooning bursts. And that, I also have a slide on that as well later.

So this is a potential explanation maybe why the Studsvik 70 gigawatt-day per MTU turned into sand, while the IFA650.12 did not. I mean, obviously, it's high burnup. The last cycle for the NRC test was at, you know, high power. It's bound to model by the fission gas distribution compared to the other.

You know, the fission gas distribution, it's typical to study the full pressure, people have reported maybe 30 megapascal. But it's probably the green boundary gas more important to the fragmentation process.

And we don't know how that is distributed, how about the pressuring in there. So one thing I tried to explore is the high internal stress due to thermal expansion that was talked about earlier.

CHAIRMAN ARMIJO: Ken, I want to ask you, this rod this IFA650.12 rod, was that a PWR rod?

MR. YUEH: BWR rod.

CHAIRMAN ARMIJO: B?

MR. YUEH: BWR.

CHAIRMAN ARMIJO: Was it a re-fabricated rod?

MR. YUEH: It's re-fabricated. So you take it from a parent rod in the sections into a rodlet and then test it --

CHAIRMAN ARMIJO: And then you refill it with what you believe is the equivalent fission gas. Or do you refill it just with helium?

MR. YUEH: I think this is filled with a gas, maybe helium. I do not know what gas.

CHAIRMAN ARMIJO: Helium-argon or helium-krypton or something like that, in an attempt to bring it back to what might have been the condition before it was punctured and re-fabricated.

MR. YUEH: Well, they're trying to condition the test to generate the maximum balloon.

CHAIRMAN ARMIJO: Oh.

MR. YUEH: So it's not typical. That's one of the complaints people have against the Halden test here.

CHAIRMAN ARMIJO: Okay, okay. So devil's in the detail.

MR. YUEH: Yes.

MEMBER REMPE: You're saying even if you did have a sensor that could detect real time what composition and pressure of the fission gas it wouldn't be enough for you. Because the French do have something like that as a function of time. But you want it to be distributed. You won't be happy if it's just a number plenum.

MEMBER SCHULTZ: The consideration is that fission gas in the fuel itself, in the fuel matrix.

MEMBER REMPE: In the matrix, not at the top of the rod?

MR. YUEH: That is correct. The gas that contributed fuel fragmentation is in the fuel itself. Where it is --

MEMBER REMPE: That'd be hard to get.

MR. YUEH: -- you know, what is the pressure of that, we don't have that. There is some data that had actually reported on the pressure inside the pores. But I say the pore is not as important as what's in the green boundary.

MR. CLIFFORD: Hello, this is Paul Clifford. I'd like to add something. According to what is used for fuel management and reactors. Rods are allowed to operate. I'm not saying they do. But

safety analysis would allow them to operate up to seven kilowatts a foot at end of life and up to about 3,000 PSI rod internal pressure.

Now that seems to be above what the tests were performed at as far as internal pressure and above power level of what is being said here. You mentioned earlier that it was 15 kilowatts per meter.

MR. YUEH: And then the seven kilowatts --

MR. CLIFFORD: That doesn't seem to be extremely above what the --

CHAIRMAN ARMIJO: Five, five --

MR. CLIFFORD: Five kilowatts per. So that doesn't seem to be above where rods could operate when they have a very aggressive fuel management strategy.

MR. YUEH: Well, the rod, Test Number 12 that did not fragment, more typically it was below most of the cycle, the last cycle was below seven.

MEMBER BALLINGER: In the last cycle, a lot of these rods are being driven. They're not driving anything. They're being driven, right?

MR. YUEH: Yes. So this is where --

MR. CLIFFORD: If I could add one more thing, the ones loading the fuel may not be a third cycle. With extended power uprates and long cycles,

most reactors are not loading their cycle except on the periphery. So rods are being driven very hard for two cycles and then discharged.

MR. YUEH: Yes. I do have a slide on the survey of several plants.

CHAIRMAN ARMIJO: Yes.

MR. YUEH: So, I guess these slides are schematics illustrating internal stress. So beginning operation, we can. This is a representation of, these are the size and then the temperature. It's hot on the inside.

So suppose you shut down the plant, right? The inside is hotter, so it's going to shrink more. So that's going to generate a lot of internal stress, the inside will be in tension, the outside in compression.

And then in a LOCA where everything heats up, the outside equilibrium dimension is a temperature of maybe 350, 400 degrees Celsius. And now you're heated to almost 1,000 degrees. It's going to expand more on the inside. Because the inside equilibrium condition is at 1,000 degrees Celsius.

So this is the source of some of the internal stress. And when I calculate between a high power operation and a low power operation, just over a

distance of ten micrometer, you know, the temperature gradient, you could generate greater than one megapascal stress.

If you look at across the grain, the grain in the pellet, and imagine one side of the grain is stretched X amount, the other one is X-plus, the temperature gradient, it's one megapascal more. So it's going to tend to open up the grain and induce cracking.

You know, balloon and burst, there's a lot of discussion on that. I think a lot of the existing modalogy is based on non-irradiated fuel cladding. So naturally you can generate a very big balloon.

But the test results that we see in the lower burnup has shown that you may not necessarily get the big balloon or the burst. In fact, I think most of tests do not generate a big balloon. Even when they pressurize the plenum region to high pressure, the gas is not distributed in a form so that you don't necessarily get the big balloon.

And the schematic on the right is where we illustrate the fuel bulging effect, but the gas is not able to communicate all around the circumference. Then you essentially may have stress concentrations, a local spot where the pressure is applied through the

fuel fragments that still attach to the cladding. And then you may have local burst, sort of like, you know, this test.

Based on the fuel thermal expansion coefficients and the cladding, below 750 degrees Celsius, I would almost like to say 800 Celsius, the thermal expansion coefficient of the fuel pellets and the cladding is almost the same. So you don't expect that they should expand together.

So there's a lot of manipulation behind, you know, balloon and burst, how that can be modeled.

MEMBER BALLINGER: So are you saying the pellet expansion coefficient below 800 C of UO2 and zitc is the --

MR. YUEH: It is the same.

MEMBER BALLINGER: Geez, okay.

MR. YUEH: It's only above this temperature. Then the fuel expands a lot quicker than the cladding.

MEMBER BALLINGER: Yes. I thought you got gap closure due to differential thermal expansion, that the gap closed up when you heated the fuel rod up. And you're certainly operating below 800 C. Well, anyway, okay.

MR. YUEH: Well, in normal operation, when

you start with fresh fuel there's a gap there, because everything out the gap was designed there at room temperature.

MEMBER BALLINGER: Right.

MR. YUEH: So when you're operating inside of the pellet, it's very hot. So that expands more. But in this scenario, when you start from room temperature, if the fuel hasn't fragmented then when you increase the temperature, you know, they expand together.

MEMBER SCHULTZ: Because the thermal effect is a mechanical effect.

MR. YUEH: Yes.

MEMBER BALLINGER: Yes.

MEMBER SCHULTZ: So, yes, the fuel will be pressing against the cladding at power.

CHAIRMAN ARMIJO: We probably have to keep moving to make sure that Bert has time for his presentation.

MR. YUEH: We conducted survey of several plants, in this case nine PWR plants are plotted. This is a plot of radial peak power as assembly level. Our plot is a function of burnup.

And, you know, all result, survey showing that by the time you get high burnup where your fuel

fragmentation is possible, the power level is too low to burst. So essentially the fuel, even if you fragment, they should not be able to leave the fuel rod.

MEMBER BALLINGER: What's the axis radial peak? Is that peak to average or what is that?

MR. YUEH: This is a radial peak at a assembly level, the maximum node at assembly level. So this plot is made up of all the fuel assemblies in a core if it's one, maybe a quarter or 1/8th symmetry.

MEMBER BALLINGER: Okay, so I understand burnup. But radial peak, the units are directed to power. Both have power --

CHAIRMAN ARMIJO: Peak to average is 20 percent, peak to average.

MEMBER BALLINGER: Okay.

MR. YUEH: We have started to do our tests to better evaluate the mechanisms behind fuel fragmentation. So what we ended up doing is heating pellets in air just to be able to generate parametric data, just to zero in on where is the important burnup we need to look at.

So this is not meant to be the final test. But it's an evaluation. And two types of tests we have done is to see the fuel pellets, two pellets,

without slit and then another experiment with the slits.

And we have completed the scope and test at 70 gigawatt-days per MTU burnup. So this is the same rod, parent rod. It's the NRC test.

Now this is a video. Unfortunately it doesn't work in this presentation.

CHAIRMAN ARMIJO: Before we go on, are these irradiated pellets, un-radiated pellets --

MR. YUEH: They are --

CHAIRMAN ARMIJO: What are they?

MR. YUEH: -- irradiated. They came from the same parent rod as the NRC Studsvik test.

CHAIRMAN ARMIJO: Okay. So you took irradiated pellets somehow, managed to get them out of the fuel cladding and put them into --

MR. YUEH: Oh, no, they stayed in the cladding.

CHAIRMAN ARMIJO: Oh.

MR. YUEH: I just had a slit in the cladding.

CHAIRMAN ARMIJO: Oh, okay.

MR. YUEH: Just to simulate balloon to relieve the irradiated strength.

CHAIRMAN ARMIJO: Okay, thank you.

MALE PARTICIPANT: That's a heroic effort.

CHAIRMAN ARMIJO: I don't know how he could get it out.

MR. YUEH: I have to move out of this to show you the video. The video shows some of the mechanisms, you know, what is happening during the heatup.

CHAIRMAN ARMIJO: We'd be happy to see that.

(Video playing)

MR. YUEH: Okay. So the pellet is sitting here, it's even pushing aside. And soon we're going to be looking from the end, looking to the furnace. And you can see the gas release.

So this starts about 650 degrees Celsius. You can see the fuel being kicked up by the gas bubbles blowing out. So this would be consistent with the NRC observation that at the burst temperature a lot of the fuel came out.

CHAIRMAN ARMIJO: Is this real time? Or is this --

MR. YUEH: This is real time.

CHAIRMAN ARMIJO: So you're getting bursts of gas coming out? Is that what we're seeing?

MR. YUEH: Yes.

CHAIRMAN ARMIJO: It's burping instead of coming out all at one time.

MR. YUEH: That's right. And we do have tests planned to pull the sample out at different temperatures just to see how the pellet looks like. So by the time you get to AM and 20 most of the gas is released. It's very little activity.

CHAIRMAN ARMIJO: That's very interesting. Where did you do these tests?

MR. YUEH: Studsvik.

CHAIRMAN ARMIJO: Okay.

MR. YUEH: So this is our chemical test. In the case of an intact sample, intact cladding, the pellet pretty much stayed inside. And you see a lot of fine cracks on the inside, consistent with the picture I think Michelle showed earlier. So it's cracks on the inside. This may support the internal stress theory that it's intentionally inside.

In the case with the slit, where we try to simulate balloon, most of the fuel on the inside fell out. And particle size is similar to what NRC reported for the integral tests.

MEMBER BALLINGER: So the bursts come from basically blowing stuff off.

MR. YUEH: The bursts that you see?

MEMBER BALLINGER: Yes.

MR. YUEH: I think so. It's because of the gas release.

MEMBER BALLINGER: Yes. If you've ever tried to do any --

MEMBER SCHULTZ: But the first test is --

MEMBER BALLINGER: -- glazing on a cement floor you can, this is kind of what happens.

MEMBER SCHULTZ: Ken, the first test is, just in terms of the geometry, the pellet end is open.

MR. YUEH: Open.

MEMBER SCHULTZ: And in the second test it looks constrained.

MR. YUEH: Well, the ends for both tests are open. In the second test, there's a slit cut axially.

MEMBER SCHULTZ: Okay.

(Simultaneous speaking.)

MR. YUEH: We'll go up here.

MEMBER BALLINGER: So is there any reason to believe that underneath those pockets that are blown off with the constrained test that there hasn't been a lot of fracturing that we haven't seen?

MR. YUEH: Well, there's some fracturing.

MEMBER BALLINGER: In other words, because

of the slit now you can blow stuff out, right, which is what looks like what happened there.

MR. YUEH: Down here, yes.

MEMBER BALLINGER: But on the one on top, down underneath --

MR. YUEH: Yes. This is the cross section of the sample underneath, in the middle.

MEMBER BALLINGER: Oh, okay.

MR. YUEH: So a lot of internal cracks, just like the other one.

CHAIRMAN ARMIJO: But it doesn't look like there's a lot of fine stuff there in that picture. But maybe you can't tell. Maybe it's --

MR. YUEH: Well --

CHAIRMAN ARMIJO: -- compressed fine.

MR. YUEH: When the clad is intact, even though you have the crack, they don't necessarily fall apart. Because it's been held together by the cladding.

CHAIRMAN ARMIJO: But are those big cracks, big fragments or small fragments? In the constrained test have you gotten the same degree of fragmentation as you have in the unconstrained test?

MR. YUEH: In the unconstrained case, it fell to pieces here.

CHAIRMAN ARMIJO: That's my point.

MEMBER BALLINGER: Well, what Ken is saying is if you were to push out the fuel out of that one after the test would it fall apart like sand --

(Simultaneous speaking.)

MEMBER SCHULTZ: It looks like there's been some erosion there, powdery erosion.

MR. YUEH: You know, it looks like --

CHAIRMAN ARMIJO: I just want to know when the fine particles form.

MR. YUEH: Well, what we can do is we may --

CHAIRMAN ARMIJO: Before it bursts or after it bursts?

MR. YUEH: We may still have a section of this sample. What we can do is ask them to cut it axially and see what happens.

CHAIRMAN ARMIJO: Yes. And if it all turns to sand, you knew that they were already --

MEMBER BALLINGER: Because, you know, if you look at the unconstrained part versus the top of the one that was constrained, if you allow a lot of area where you've got it unconstrained and you start getting blown out stuff, if you then uncover the interior after you've blown out stuff, you just keep

blowing stuff, keep blowing stuff out.

MR. YUEH: Well, we will do a test when we blow the sample out before we started with this new approach. And I want to see what happens in between.

CHAIRMAN ARMIJO: Look, I'm probably the worst culprit, but we're falling behind schedule, Ken. And we want to make sure Bert gets a chance to --

MR. YUEH: The sample was made up of two pellets. There's a whole intact pellet on the inside and then two half pellets on the outside.

MEMBER REMPE: So maybe two inches long or something?

MR. YUEH: I think less than that.

(Off microphone discussion)

MR. YUEH: So it's probably an inch, a little over an inch. So, you know, we have encouraging results consistent with the NRC test. We have set out to do a couple of validation tests for the technique, you know, sort of as a scoping parametric study to evaluate the phenomena.

So one of the tests we have completed now is using the same NRC tested rod, 61 gigawatt-days per MTU, and keyed it with the slit. And I'll show pictures of that later.

And then we have another test we will do,

the high burnup rod, 70 gigawatt-days per MTU in an inert gas environment. A couple of people expressed concerns with UO2 to U308 conversion. And I don't think it matters, but people --

CHAIRMAN ARMIJO: Well, in the time frame that you're talking about, but it's better to do it in an inert --

MR. YUEH: Well, we'll see if that's a factor or not.

MEMBER BALLINGER: That's kind of interesting. That's very interesting. Because now you see evidence on the unconstrained side of sort of much more finer fragmentation than on the other side. I don't know what that rim is.

MR. YUEH: Oh, here? This is a separate test. So this is the test we have recently done. Michelle witnessed this test. This is where we took the same section of the rod, from the same rod she tested. And we cut a slit and subjected to exposure to 1,000 degrees Celsius in air.

So this is the sample, the phase before the test. This is after exposure. And you can see that the major cracks are pretty much the same. There's no change. You don't' see any small microcracks. So when you are below the threshold

there is very little change to the fragments.

CHAIRMAN ARMIJO: So it was slit before you did the test?

MR. YUEH: Before I did the test, yes.

CONSULTANT SHACK: It's unconstrained?

CHAIRMAN ARMIJO: It's unconstrained and it didn't blow anything out. It kind of just sat there.

CONSULTANT SHACK: But at 61 gigawatt-days.

CHAIRMAN ARMIJO: Yes.

CONSULTANT SHACK: So is the only difference between that and the previous slide where it didn't disintegrate was just the burnup?

MR. YUEH: The burnup and the power history for the different, but I think for this rod it's below the fragmentation threshold. It's probably a threshold --

(Off microphone discussion)

MEMBER BANERJEE: What is that? Is that just an optical artifact, that --

MR. YUEH: It's not an optical artifact. We do not know what that is. I think it's maybe when they cut the slit that some contaminate got on the

surface. We will cut this pellet up transversely and look inside if there's anything there.

CHAIRMAN ARMIJO: Okay.

MR. YUEH: There was a last slide. So we will complete that 70 gigawatt-days per MTU test in an inert gas.

And we planned additional tests trying to better isolate the fragmentation threshold with the pellet heating test, you know, better understand the mechanism, evaluate the power history facts and then whatever an effect of that may influence fuel fragmentation threshold.

And eventually, hopefully, once we have zoomed in, you know, these important primaries and where the threshold is, then we'll think about doing some verification tests at the Halden or at Studsvik.

CHAIRMAN ARMIJO: Okay. Well, I don't want to encourage anymore questions, because we're about 15 minutes behind schedule. And I want Bert to have plenty of time for his stuff.

MR. DUNN: Thank you. While he's trying to find me, my name's Bert Dunn. I'm an advisory engineer at AREVA in the area of loss and accident predictions and fuel of accident evaluations.

I'm going to be pretty quick here. I

think I can probably boil it down to maybe under ten minutes.

We've investigated cladding swelling and rupture in the industry and included it in our LOCA calculations since the 1973 rule.

Our relocation has recently been covered by LOCA evaluations, relocation inside the fuel rod itself I'm talking about here, either by direct calculation in some circumstances or as was done at AREVA by indirect evaluation of model conservatisms.

NRC is now requiring direct calculation of the relocation in the fuels. So that aspect of 50.46(c) is no longer new to us. We can't get past the reviewers any longer without doing a semi-mechanistic calculation of the implications of relocation inside the cladding.

Dispersal outside the cladding has never been treated by the LOCA models, although we've, you know, you have to envision the possibility to dispersal as early as 1973.

Most experts would agree that the fuel particles will be well cooled. There may be a dose situation involved, but fuel particles would be well cooled within the reactor coolant system.

And there's a slight caveat on that if it

was possible to collect a large number of them, have them build up on a grid structure or on a floor or something like that.

That could be a little bit different. But as long as they're not accumulating strongly and are out in the coolant, they will be cooled. Even when the rupture opening is large, the fuel assembly would tend to restrict the dispersion of fuel particles into the coolant stream.

When we look at most of our tests, most of our tests are single pin tests, they tend to ignore that possibility, as was mentioned by Patrick, that the strain shape of the cladding would start to square off or turn into a cloverleaf of some sort. Cladding adjacent would tend to support it. We don't actually follow that in the calculations, but I think it would happen.

In general, the position is going to be that studies should continue. But I would like to suggest that we continue to keep in mind some rationality of the boundary conditions.

We've seen tests here at 90, 95 gigawatt-days per metric ton. That's a very high exposure for a fuel rod. And consequences from it, although we're studying, shouldn't be brought back into the licensing

world or the design basis accident world, I don't think.

We've also seen situations for the calculation of the effects of relocation when the material stays within the rod structure that have been produced, I'll say largely in Europe.

But I won't guarantee that that's the only location where super conservative assumptions have been applied, and then the consequences have run away from us with those conservative assumptions.

Current expectations for our mechanistic evaluation model, which is now under review with the NRC staff, is that the cladding temperature will not be increased through various mechanisms of --

CHAIRMAN ARMIJO: So the idea is that in an intact rod you have actual relocation. And where does it go, into the gap? Where does all this actually relocated fuel wind up?

MR. DUNN: Well, you have the balloon. And I guess, at this time, we're envisioning that it can't fill out the rupture. So we're not letting it fall out the rupture. We're just assuming that the balloon is intact at its base at the maximum strain. And so it falls, the material falls down in --

CHAIRMAN ARMIJO: So it fills it up.

That's the conservative, super conservative thing that you mentioned --

MR. DUNN: I suppose it is.

CHAIRMAN ARMIJO: -- that it fills up the balloon or, I'm just trying to find out what your concerned about.

MR. DUNN: I think it was largely in the combination of packing factor and strain, et cetera, that the calculations that show 400 to 500 degrees increase I think are wrong.

CHAIRMAN ARMIJO: Okay.

MR. DUNN: And they don't generally include any turbulent enhancement or droplet interaction with the cladding surface to provide extra cooling. And those things will occur.

Again, AREVA mostly agrees with research opinion and result on this. I think that's generally held by the industry. I have to say mostly because the industry is not one unit. It's got all sorts of different opinions.

(Off microphone discussion)

CHAIRMAN ARMIJO: Diversity is a good thing actually.

MR. DUNN: One thing I would like to point out is that the concern may be, and you've heard this

from industry before so don't get too bored with me, largely an artifact of the conservative modeling that we utilize in the approach to deciding what happens.

If we look at realistic evaluations for BWRs, or semi-realistic evaluations even, there's no possibility of rupture. And I think that agrees with what Patrick showed you.

The mean temperature for an RLBLOCA, these are results from my current evaluation model, I'm considering Westinghouse three and four-loop and combustion engineering plants here, is about 1,500 degrees F. Embedded conservatisms in that model are worth about at least 200 degrees F or more. And I have not tried to pull all of them out of there.

We wind up with a mean expectation of around 1,300 degrees F which will not lead to rupture. It will probably lead to strain but not rupture. Without rupture, we're not going to disperse into the reactor coolant stream.

MEMBER SCHULTZ: What is an RL?

MEMBER BANERJEE: Realistic.

MEMBER SCHULTZ: Realistic large break LOCA?

MR. DUNN: Yes.

MEMBER SCHULTZ: Now what is a realistic

large break LOCA?

MR. DUNN: A realistic large break LOCA is a misnomer.

(Laughter)

MALE PARTICIPANT: We'll buy that.

CONSULTANT SHACK: But I mean, it's no single failure, no loop, it's just a break?

MR. DUNN: There are a great many conservatisms in a realistic large break LOCA that are left in there from the standpoint of simplifying the calculation.

By and large, your sampling, or I say allowing, a probability density function to control the results of heat transfer processes, break size, sometimes decay heat, in our case not on the decay heat, initial condition from the fuel code --

CONSULTANT SHACK: Okay. But you just mean an ordinary realistic large break LOCA for design as accepted by the NRC for LOCA analyses?

MR. DUNN: Yes, that's true. I think this would be characteristic of AREVA's model and characteristic of Westinghouse's model both --

CONSULTANT SHACK: It's not the ideal model that Patrick was talking about where he turned off the single failure and he turned off the loop.

MR. DUNN: Well, I would argue that the single failure doesn't really mean much, particularly in a PWR. In a small break it'll mean something. In a large break, as long as one ECCS system is capable of bringing it down from our full --

CONSULTANT SHACK: It seemed to make a big difference in his calculations.

MR. DUNN: Also the other water isn't meaningful. Excuse me?

CONSULTANT SHACK: It did seem to make a big difference in his calculations.

MR. DUNN: Well, yes. But the NRC sometimes doesn't share those calculations with me. And I haven't had an opportunity to dig into his. Perhaps we will have that in the future.

CONSULTANT SHACK: Okay. At least I know what you mean by a realistic large break LOCA now.

MR. DUNN: Yes. Well, that's why there're still embedded conservatisms in here. The probability of a large break is low? So I think the, you can kind of back that up a little bit with the recent NRC effort to remove large break LOCA from the design basis.

I forget what the NUREG is that provides us the probability. But, you know, you've got various

opinions on that. What I'm trying to say is I don't think that there is a real safety concern associated with fuel dispersal provided the plants are operated in the fashion that they're operating today.

MEMBER POWERS: I got the impression, without anybody explicitly saying that, that the real interest in the stuff the research presented to us was what happens. What kinds of things do we, the NRC, have to look at if the industry approached us with a proposal to go to 75 gigawatt-days per ton limits? And so when you say everything's fine now, that really doesn't address that.

MR. DUNN: No, it doesn't. It doesn't address the fact that if I remove some of those conservatisms from my model that one of the things that will happen earlier, very early, is the utilities will try to push the local power levels up.

MEMBER POWERS: Sure.

MR. DUNN: So it is very much, I'm just saying that there is some time to get the analysis and the study done, let me say correctly, to not let what happened in relocation inside the fuel rods happen.

Let's see, the AREVA perspective, I think by and large this would be supported by my friends at Westinghouse and Global.

MEMBER BANERJEE: Is there something you can do to the pellet about the fine fragment. Is there something you can, I mean, let's look at it another way. There's always a solution to a problem, at least actually there is. Are there things you can do to the pellets so they don't form these fine fragments?

MR. DUNN: I'm thinking that I've heard people talk, that the chromium doping would do something like this or tend to hold the pellet together. I'm not really sure about that. There are things we can do to the cladding. I'm not free today to talk about them. There are --

MEMBER BANERJEE: But let's forget the cladding. I mean, is there something you can do with the pellets?

MR. DUNN: Well, there's a research effort out of DOE to look at various things. One of them is putting some fibers inside the pellet to help conduct energy and lower the pellet energy so that we don't have the consequences of the LOCA.

(Simultaneous speaking.)

MR. DUNN: I don't know.

MEMBER BANERJEE: It's clearly a push to --

(Simultaneous speaking.)

MEMBER SCHULTZ: Not from what Ken showed. I mean, those are real fuel cycle development results.

MR. DUNN: Fifteen years ago there was a real strong push to go to higher burnup.

CHAIRMAN ARMIJO: Yes.

MR. DUNN: You sense that it's building again. But I don't know that it's there yet. But we --

MEMBER BANERJEE: Shouldn't we do some innovation? Well, I always get stuck in this position. It's the same with GSI-191. Instead of innovating on how to filter and figure out how not to allow the fines into the core, you know, we go on and on doing all sorts of things on the side. And, you know, I don't mean to be having a diatribe on this. But --

(Simultaneous speaking.)

MEMBER BALLINGER: How do we avoid, you know, getting around this in some way or the other instead of just innovating?

CHAIRMAN ARMIJO: Innovation is very hard. It takes a lot of time and a lot of money.

MEMBER BANERJEE: If you have a lot of

money, but if it --

CHAIRMAN ARMIJO: If there's a commercial advantage, a benefit, people will do it. And if there's a low cost way to solve the problem it would have been done already.

MR. DUNN: And I think all of the vendors, I know we do, all of the vendors do have a program to look at that and, like I mentioned, I think it's the DOE program has this pellet. It's called accident tolerant fuel. And we're all exploring it.

MEMBER BALLINGER: Oh, and cladding. So that's looking at the pellet and the cladding.

CHAIRMAN ARMIJO: But even on geometry, the annular pellet thing --

(Off microphone discussion)

MR. DUNN: No, probably not, because this is still relatively new on the --

CHAIRMAN ARMIJO: Okay, Bert, I'm afraid you have to --

MR. DUNN: Let me finish up here. The fuel dispersal requires a large break LOCA. Now, that's my way of saying that in a small break arena we've probably got the conservatism to drive almost all small breaks below the occurrence of rupture.

There are a few plants that might be close

to that. But 95 percent of our plants will be down in the 1,100, 1,200 degree Farenheit range.

There's another thing that, you know, jumping into the regulatory arena with this at any time could lead to use of extreme conservatisms like, I think, has happened with GSI-191, and pull us down a road that we really don't need to go down.

MEMBER BANERJEE: So you like those little strainers they used to have for the sites?

CHAIRMAN ARMIJO: I think you shouldn't have mentioned GSI-191.

(Laughter)

CHAIRMAN ARMIJO: We only have a few days here in Washington. So, Bert, are you finished?

MR. DUNN: I did.

CHAIRMAN ARMIJO: Okay. Any questions from members of the committee? Any questions from people in the audience, comments? Did we ever get anyone on the bridge line?

MS. ABDULLAHI: Yes, we did before. I don't know if they're still on.

CHAIRMAN ARMIJO: Can we open the bridge line?

MS. ABDULLAHI: I don't know.

CHAIRMAN ARMIJO: Is there anyone on the

bridge line who would wish to make a comment?

(Off microphone comments)

CHAIRMAN ARMIJO: I guess I'll just make one, give them a little time. But while we're waiting, first of all I would really like to compliment the staff for a terrific presentation, a lot of information.

Ken, those experiments are very interesting. I just encourage you to keep going on this thing. Data is far better than just speculation. And I think that's going to help us really break the extent of the problem, you know. But is it a real problem or not a real problem?

MEMBER BALLINGER: I have one question which I should know the answer to. But I forgot. Is there any cooperation between the NRC and EPRI on some of these projects, collaboration meaning money changing hands?

MR. YUEH: No, no.

CHAIRMAN ARMIJO: No.

MR. DUNN: But there is cooperation between EPRI and industry on the physics or the understanding of what happens. That's been true forever.

(Off microphone discussion)

CHAIRMAN ARMIJO: Michelle, you have to speak in the microphone. We can't hear you.

MS. FLANAGAN: A lot of the data that both of us shared is coming from shared collaborative programs. And even though there's not a bilateral or trilateral program, the information is coming from resources that both NRC and the industry are using, for the most part.

CHAIRMAN ARMIJO: Yes.

MEMBER REMPE: So in other words, NRC and EPRI both contribute to the Halden program or the Studsvik program.

MS. FLANAGAN: The Halden program, yes. At Studsvik we've been individually working on some bilateral work. But the Halden program is a program that we all are participating in.

MR. YUEH: Yes. For the data review, you know, it came from the same source. And we only started doing our own testing recently. So that would be just sponsored by EPRI.

CHAIRMAN ARMIJO: Apparently there's no one on the bridge line.

MR. LEWIS: I'm on the bridge line.

CHAIRMAN ARMIJO: Oh, okay. Well, I was hoping that somebody would identify themselves.

Please go ahead.

MR. LEWIS: Well, my name's Marvin, M-A-R-V-I-N, Lewis, L-E-W-I-S. And I'm very pleased to hear all of this material coming out, because I have written several comments about fuel.

One of the things that I've written about is the fuel, okay, well, all right. It was talking about spent fuel pools when you talk about fire. But that's in another question.

The question I have in my mind is the control on the alloy, I do not know if the alloying of the Zircaloy is occurring, or aluminum alloy, well, how and when will effects of that -- I had a very poor time finding out base change, base change diagrams with some contamination.

And I hope that you guys will look into that. Thank you, bye.

CHAIRMAN ARMIJO: Okay, thank you very much for your comments. Is there anyone else on the bridge line?

Okay, hearing none, unless the members want to raise one last question, again, thank you very much to all the presenters. I think it was a very, very interesting meeting. And we are now adjourned. Thank you.

(Whereupon, the hearing in the above-entitled matter was concluded at 12:05 p.m.)

Fuel Fragmentation, Relocation and Dispersal Under LOCA Conditions: Experimental Observations

Michelle Flanagan
RES/ DSA/FSCB

ACRS Fuel and Materials Subcommittee
December 4th, 2013

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Presentation Overview

- Background
- Observations
- Proposal
- Conclusions

Background

Over the past 10 years fuel dispersal results have evolved:

2002-2006

Results are so unexpected that explaining them as non-typical was reasonable

2006-2010

Results are repeatable, but very limited

2010-2012

Results cannot be ignored and are the subject of international meetings, experimental programs and analytical efforts around the world

Despite a number of experimental observations of fuel fragmentation, relocation and dispersal, the segment properties and conditions in each test were scattered, making it difficult to identify trends.

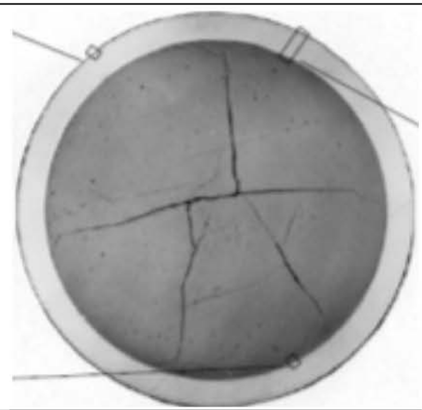
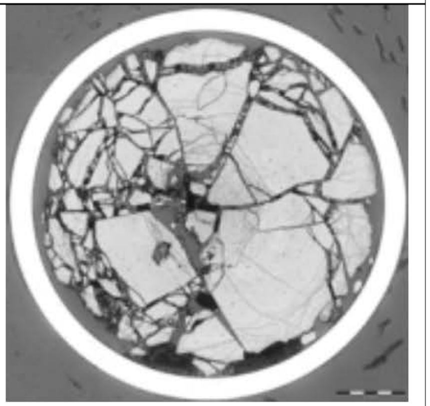
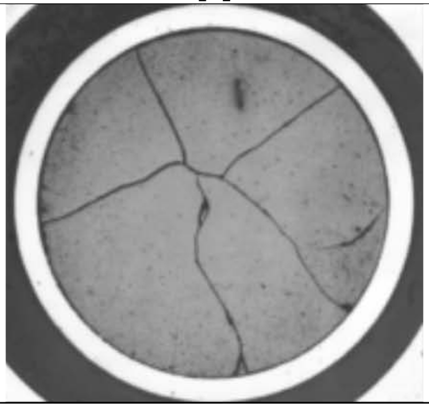
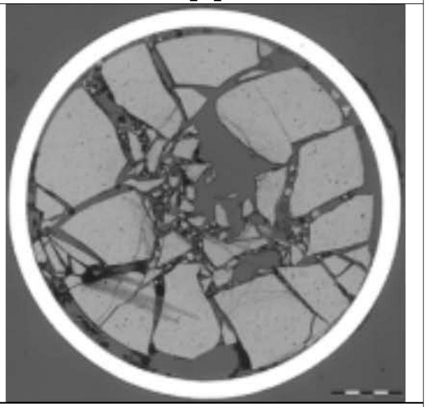
Therefore, NRC, in collaboration with the Halden Reactor Project, Kjeller Hot-cell Laboratory and Studsvik Hot-cell Laboratory, completed a detailed reassessment of experimental results. One goal of this reassessment was to improve the understanding of the mechanisms and conditions causing the fine fuel fragmentation seen in testing of very high burnup rods.

Observations

1. Extensive fragmentation was not present before testing
2. The extent of relocation and fragmentation is correlated with local strain and proximity to rupture location
3. A significant change in fragmentation size is observed between high (≈60 GWd/MTU) and very high (≈70 GWd/MTU) burnup
4. Pressure transducers in the plenum measured a slow depressurization after rupture in select tests, indicating restricted gas flow between the plenum and rupture region in these tests.
5. For high burnup (≈60 GWd/MTU) LOCA tests, most fine fragments appear to originate from the periphery of the pellet while for very high burnup (≈70 GWd/MTU) LOCA tests, fine fragments appear to originate from all radii.

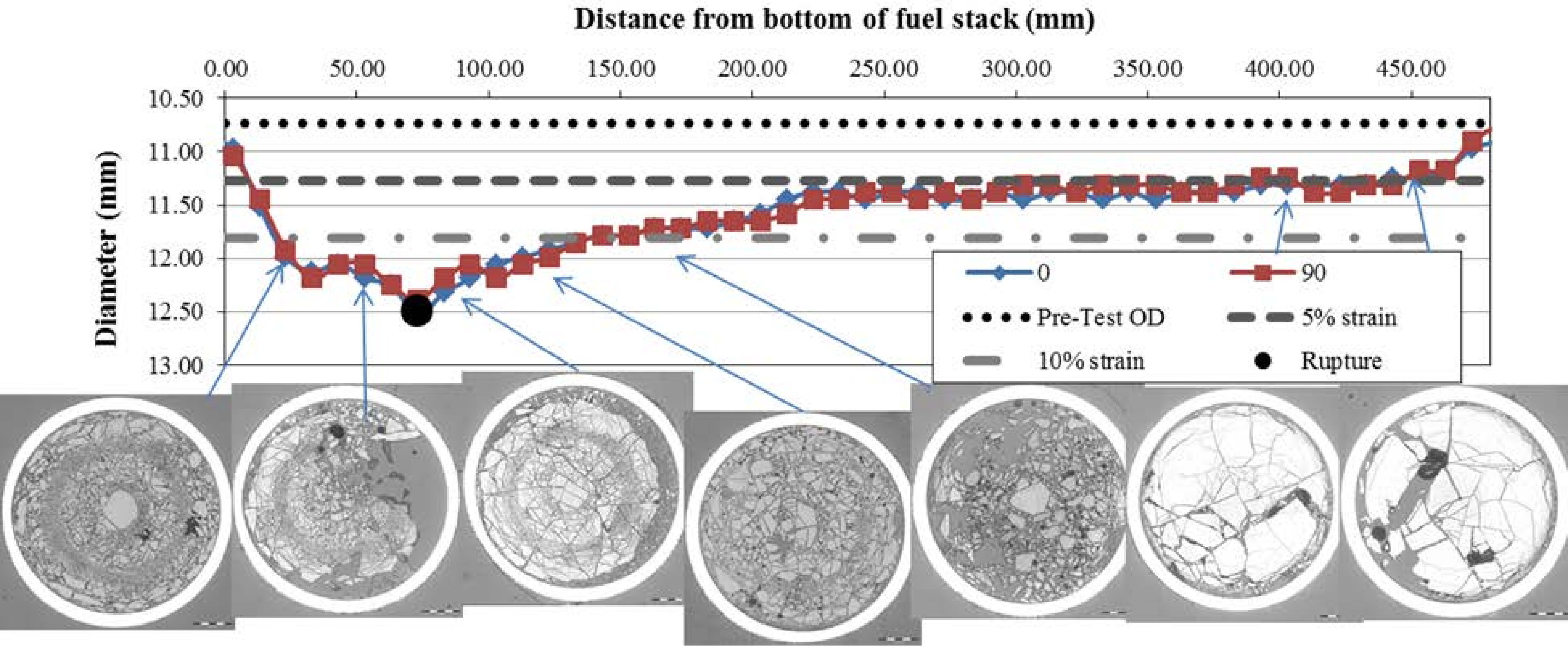
Observation #1

Extensive fragmentation is not present before testing, suggesting it occurs during the LOCA simulation transient

Test/Laboratory	Pre-Test	Post-Test
IFA-650.3, Halden		
Reference	[2]	[3]
IFA-650.7, Halden		
Reference	[4]	[5]

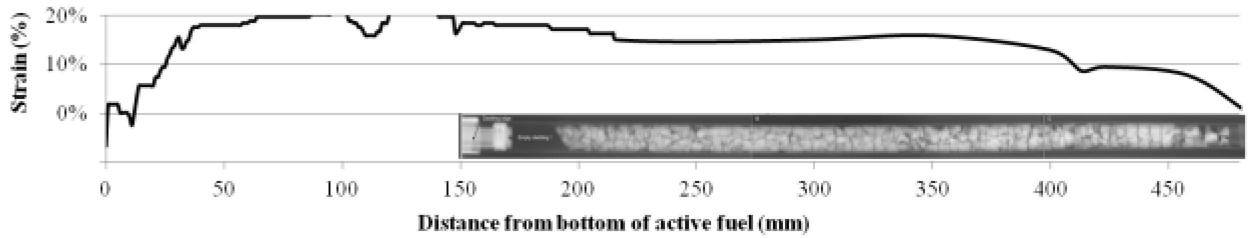
Observation #2

The extent of fragmentation appears to be related to local strain

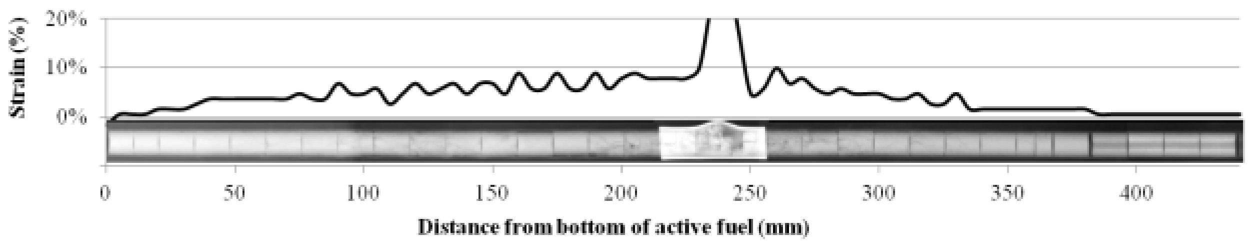


Observation #2

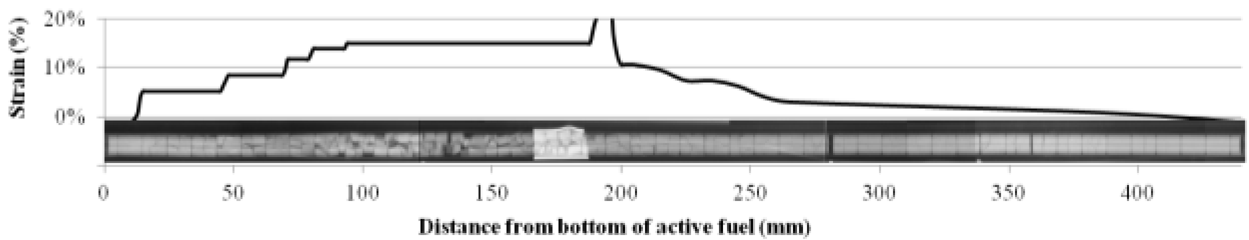
The extent of fragmentation appears to be related to local strain



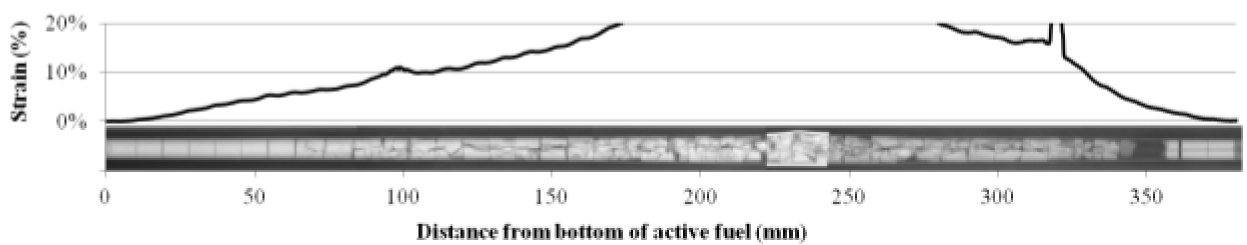
IFA-650.7
44GWd/MTU
BWR



IFA-650.10
60GWd/MTU
PWR



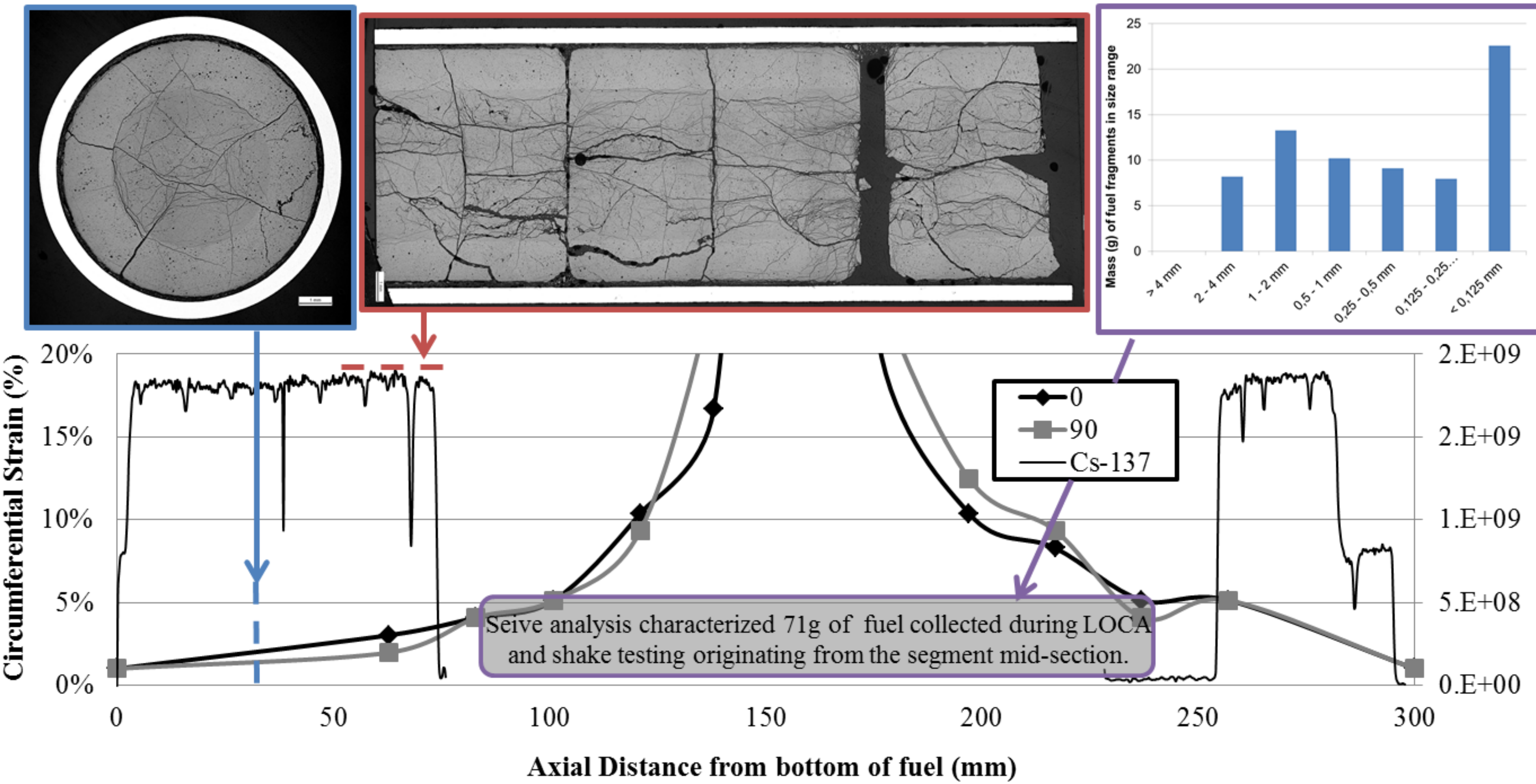
IFA-650.11
56GWd/MTU
VVER



IFA-650.12
72GWd/MTU
BWR

Observation #2

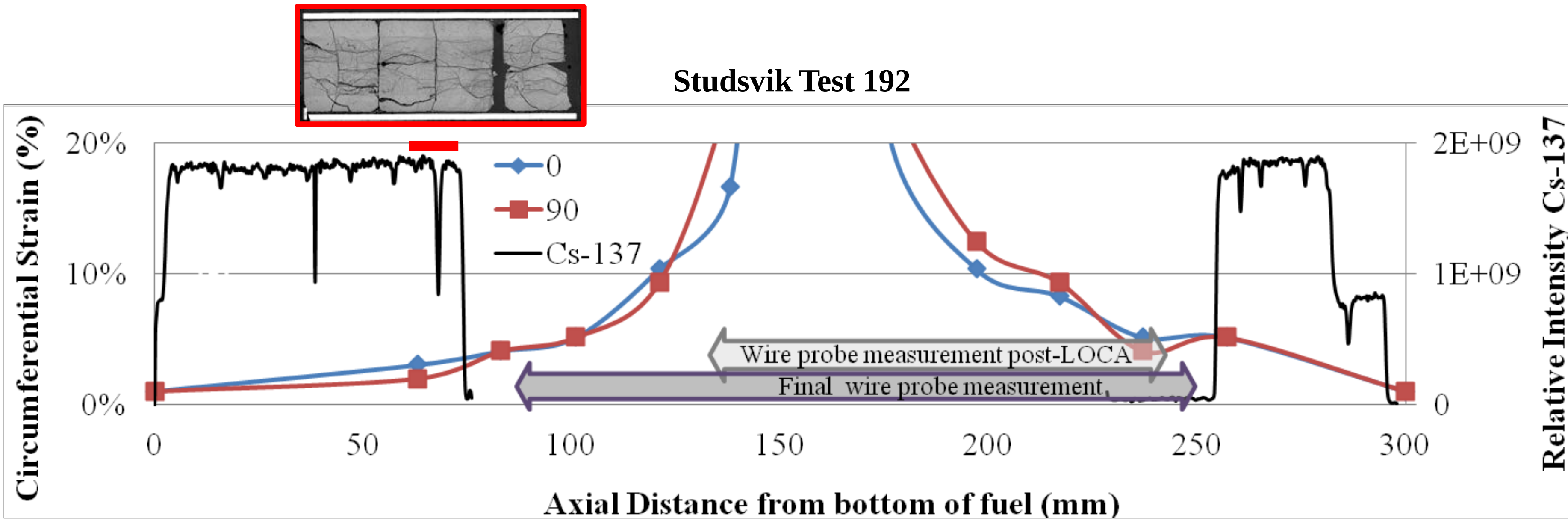
The extent of fragmentation appears to be related to local strain



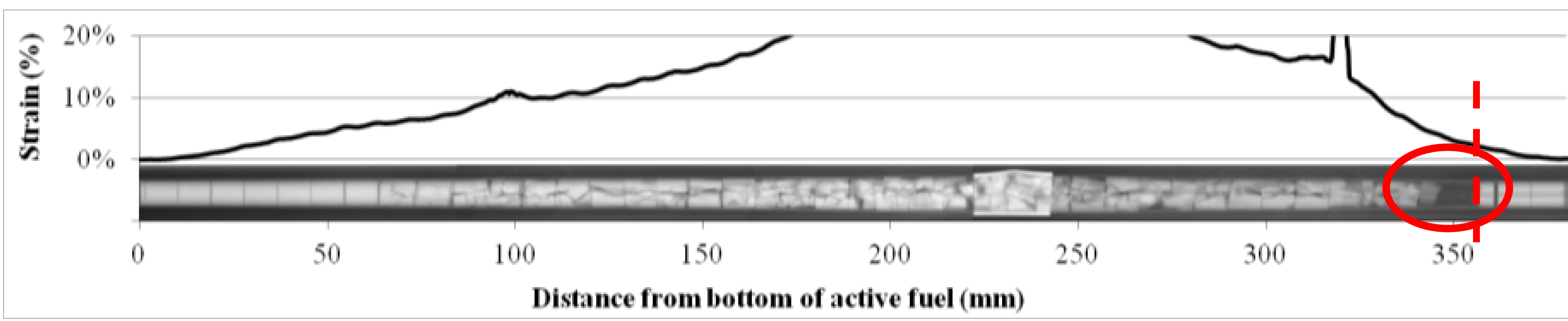
Studsvik Test 192

Observation #2

The experimental results suggest a boundary for axial fuel relocation.

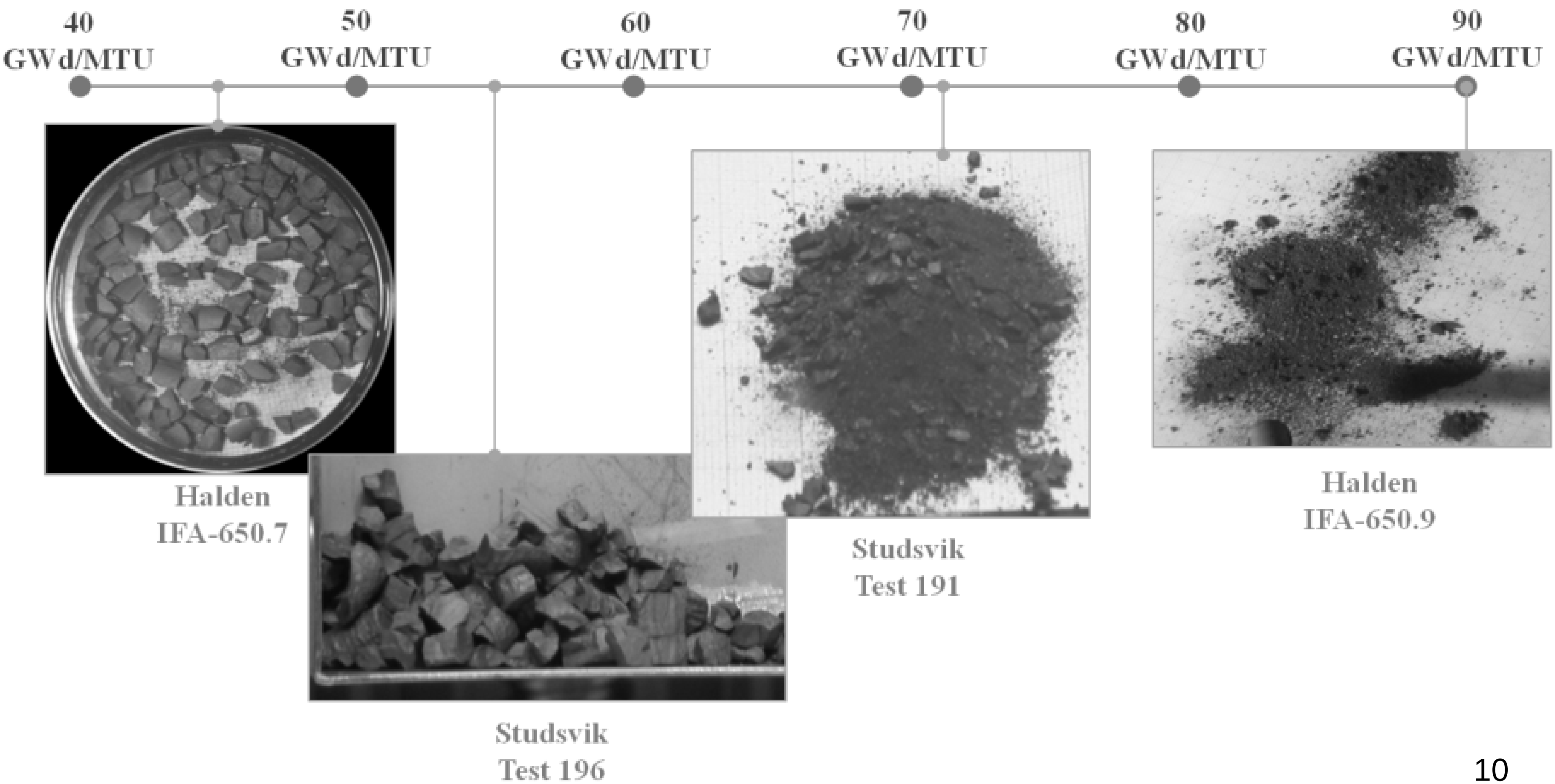


Halden Test 650.12



Observation #3

A significant change in fragmentation size is observed between high (~50 GWd/MTU) and very high (~70 GWd/MTU) burnup tests and the size distributions at Halden and Studsvik are similar



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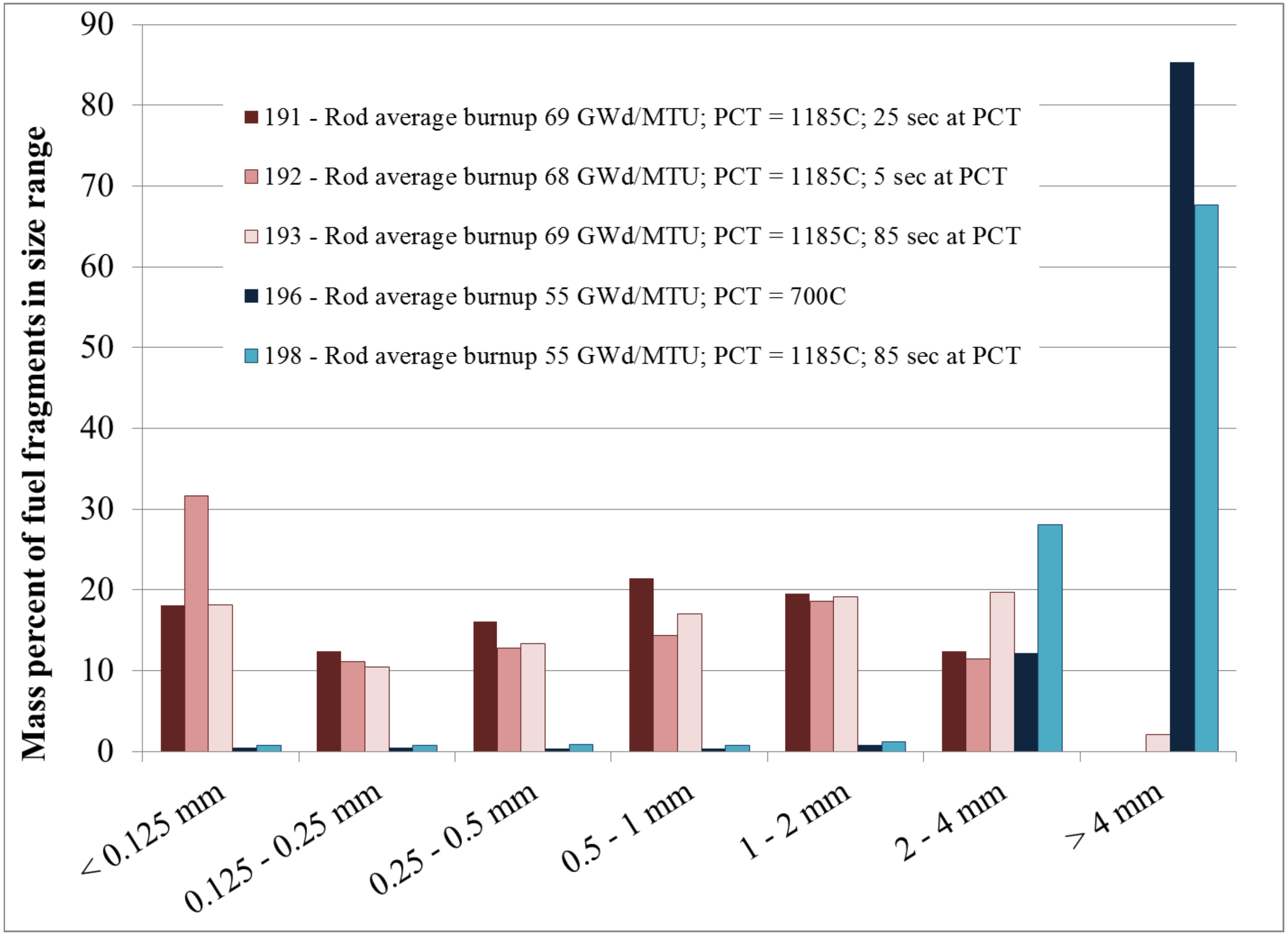
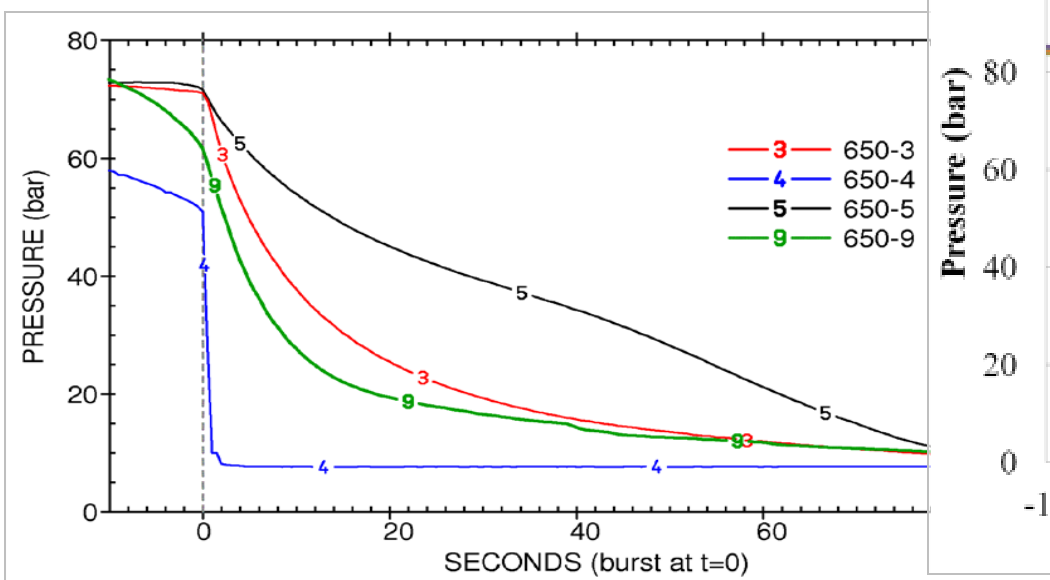


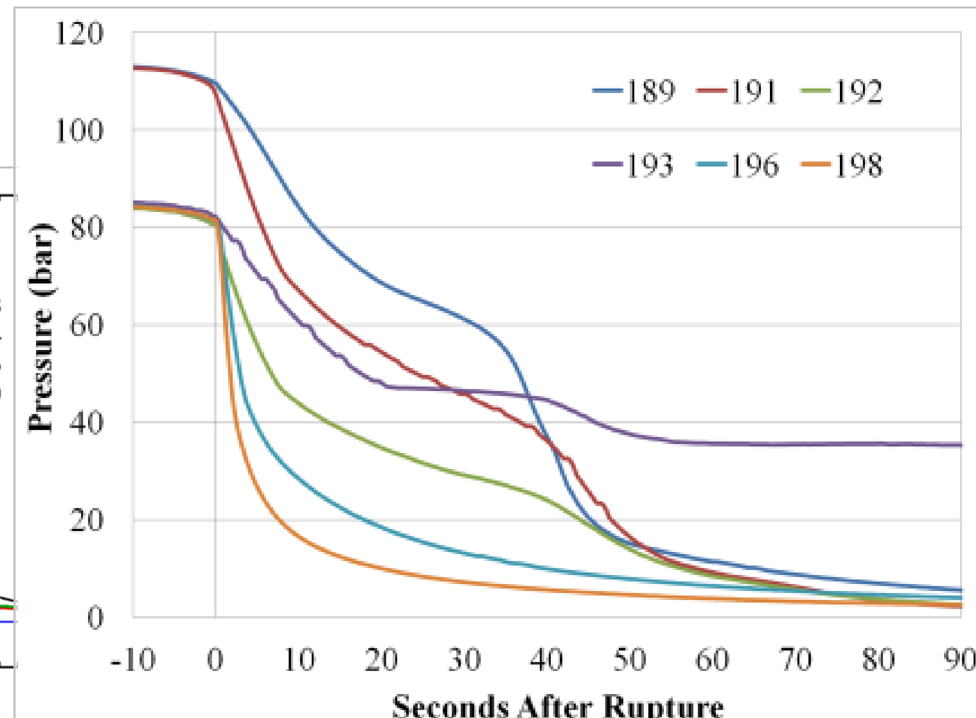
Observation #4

Pressure transducers in the plenum region measured a slow depressurization after rupture in a number of tests, indicating restricted gas flow between the plenum and rupture region.

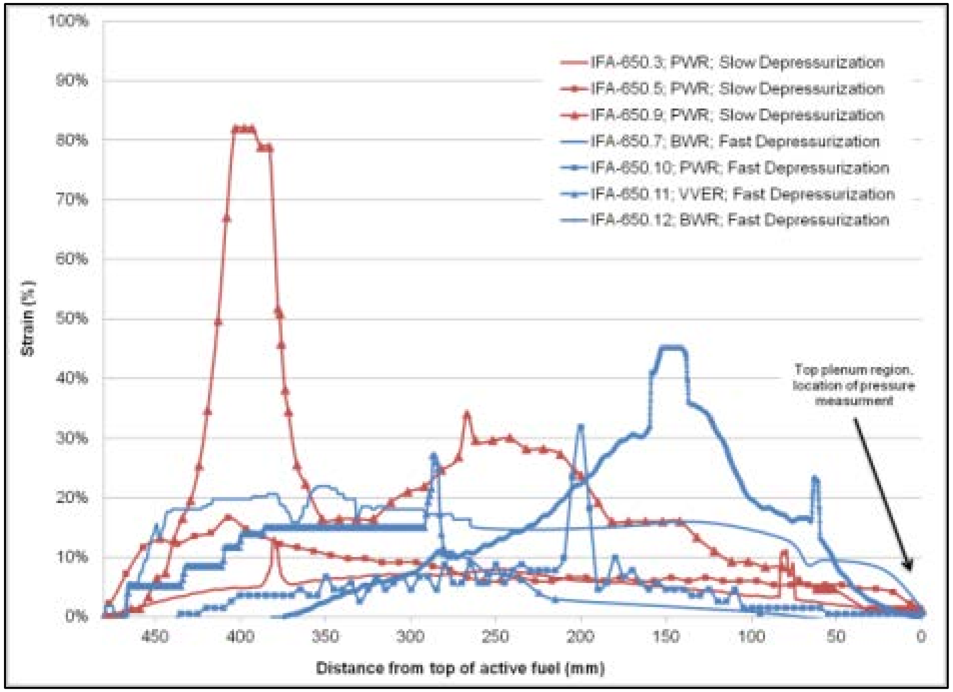
Below: Depressurization of top plenum in select Halden LOCA tests

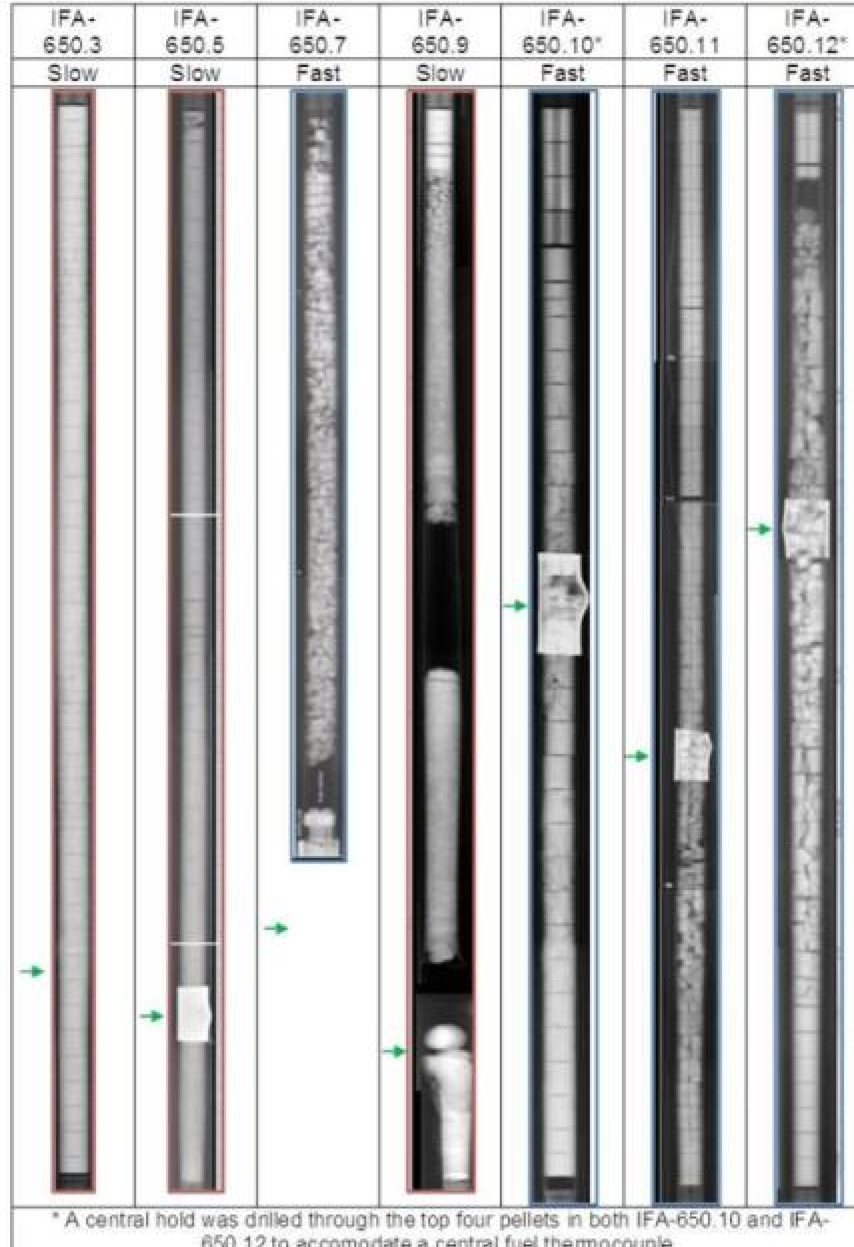
Right: Depressurization of top plenum in Studsvik LOCA tests





Observation #4 Continued



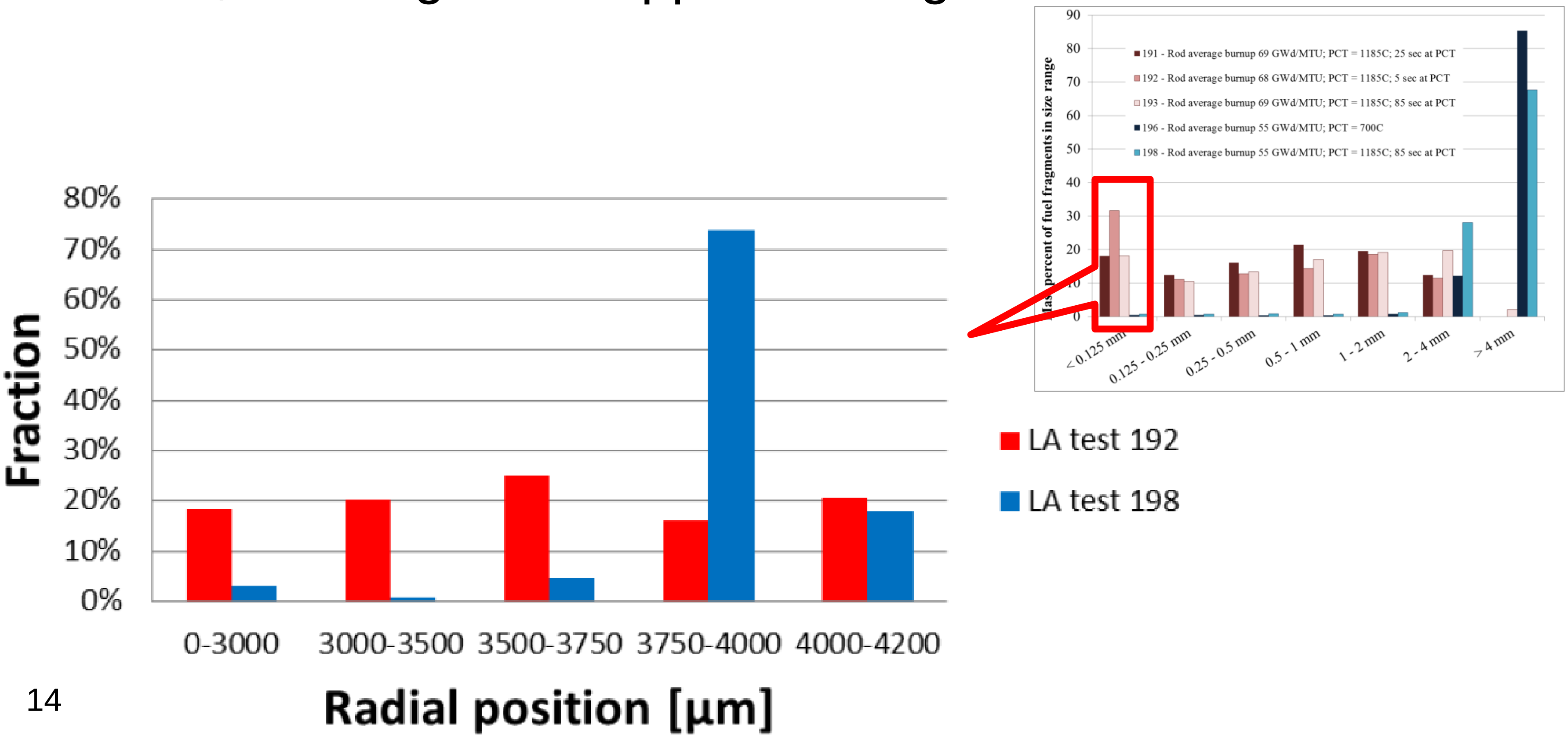


Above: Cladding Strain Profiles for IFA-650.3/5/7/9/10/11/12

Right: Neutron Radiography Results for 650.3/5/7/9/10/11/12

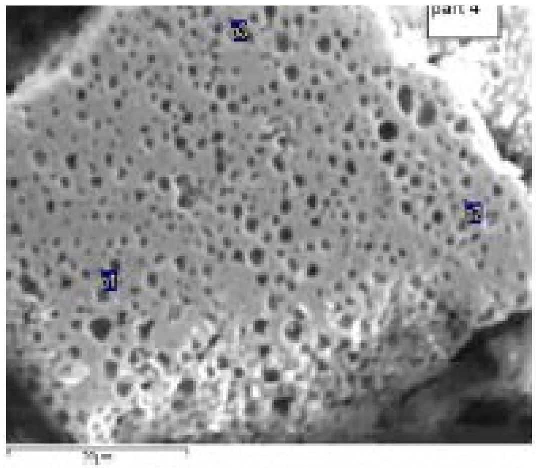
Observation #5

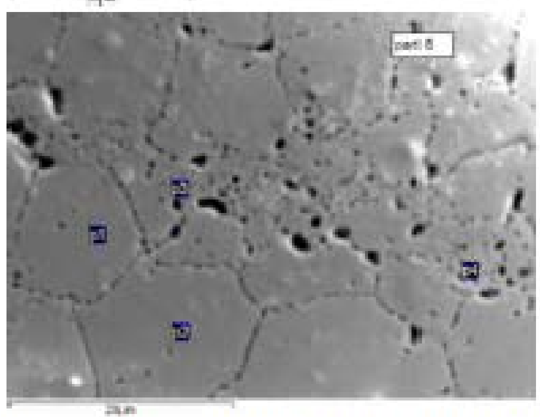
For high burnup (≈60 GWd/MTU) LOCA tests, most fine fragments appear to originate from the periphery of the pellet while for very high burnup (≈70 GWd/MTU) LOCA tests, fine fragments appear to originate from all radii.



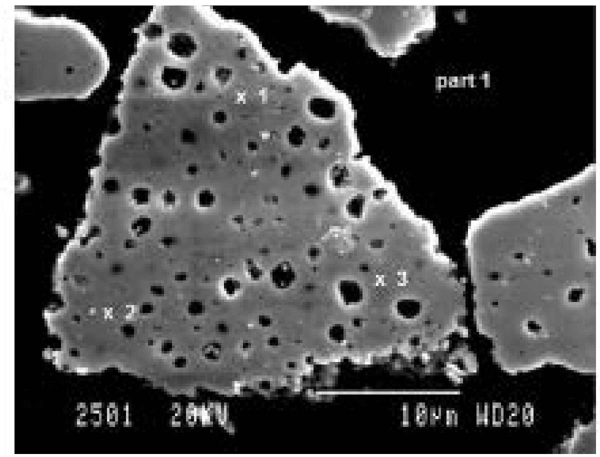
Observation #5 Continued

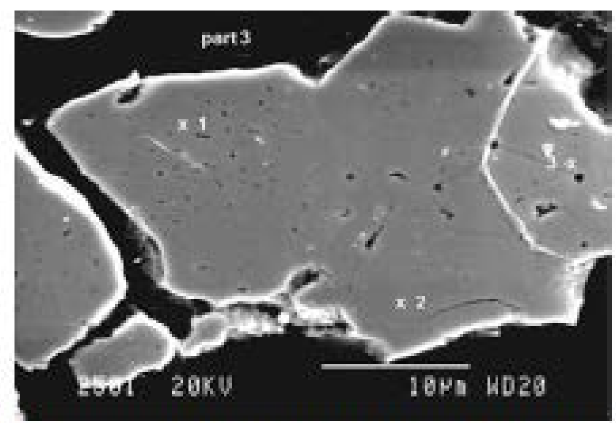
Test 198 (~60 BU)





Test 192 (~70 BU)



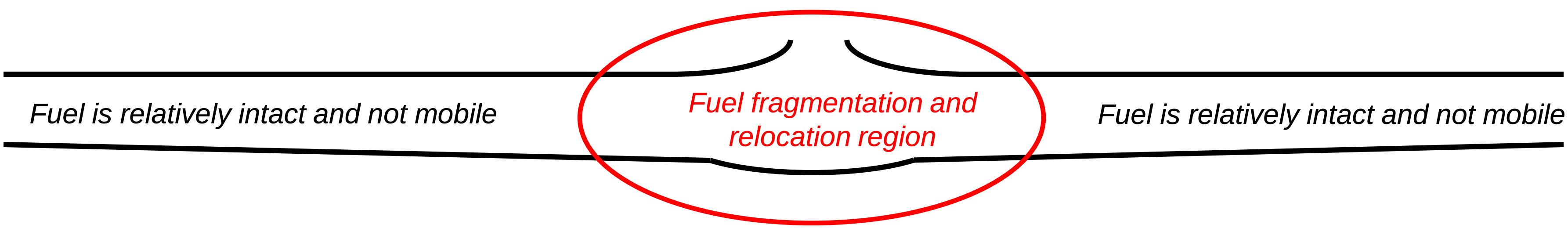


- Both samples have fine fragments with fully developed high burnup structure
- Both samples also have fine fragments that appear to retain the original grain size

Proposal

Fragmentation occurs during the LOCA simulation transient (rather than during operation) and is driven by retained fission gas in the fuel pellet. During heat-up, as the rod temperature increases, the fission gas expands and generates large internal forces throughout the pellet. Finally, at the moment of rupture, the fuel in the proximity of the rupture will experience a rapid depressurization upon rupture, causing pellet fragmentation.

Results suggest that a strain threshold exists for significant fragmentation and fuel mobility. Therefore, fragmentation and relocation will be limited to a region around the rupture where strain exceeds some strain threshold. Results suggest the strain threshold may be between 3%-7% cladding strain.

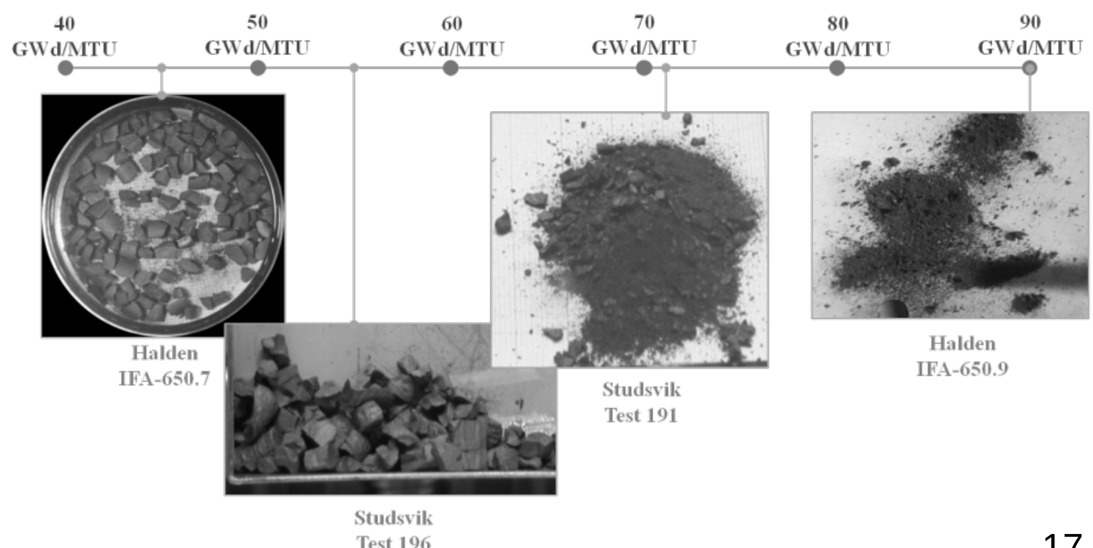


Proposal

The rapid change in fragmentation size is related to ***localized*** evolution of fuel structure at high burnup. At high burnup, a large amount of fission gas is retained at high pressure; these fission gas pockets and other characteristics of high burnup fuel make this material more vulnerable to fragmentation when subject to the depressurization event of rupture.

If the local strain is large enough to result in fuel fragmentation, the transition to fine fragmentation begins at a pellet average burnup of 50 GWd/MTU and be complete at a pellet average burnup of 80 GWd/MTU

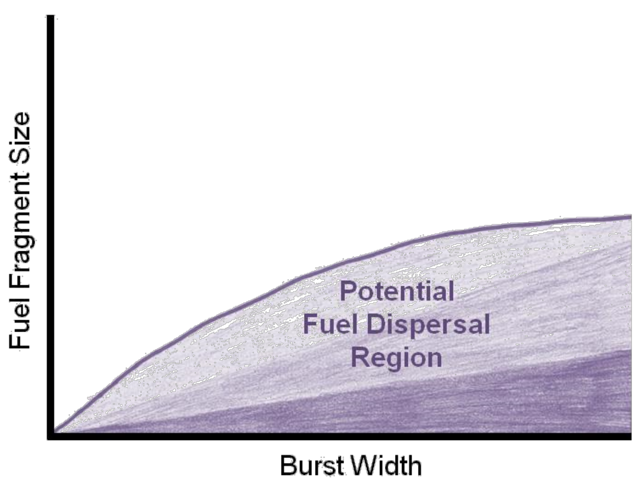
For high burnup (≈60) LOCA tests, most fine fragments appear to originate from the periphery of the pellet while for very high burnup (≈70) LOCA tests, fine fragments appear to originate from all radii.

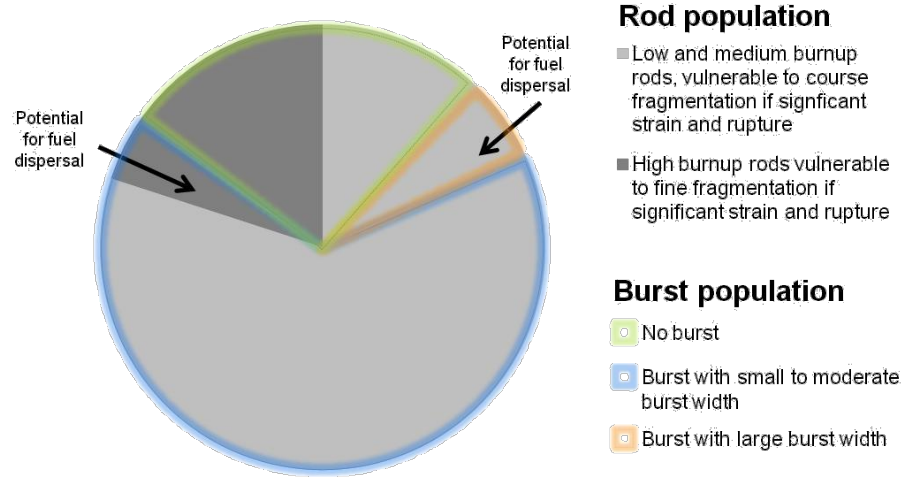


Proposal

If fragmentation, relocation and dispersal are related to burnup, strain and rupture, quantifying the occurrence of these phenomenon will require predictions of burst population overlaid with burnup information.

Predicting dispersal really should also consider the burst width together with the burnup dependent fragmentation size because only fuel fragments smaller than the burst width will be able to disperse. Fine fragments may disperse easily, even with small rupture openings. Fragmentation, relocation, and dispersal may also occur in rods with lower burnup if the strain profile and rupture opening are large enough. However, the fuel fragments from these rods may be large enough that significant relocation and dispersal is difficult to achieve.





Conclusions

- A detailed assessment of PIE results of LOCA tests performed at Halden and Studsvik was completed.
- This effort provided information to develop a proposal of the conditions and variables which control fuel fragmentation, relocation, and dispersal.
- The proposal can be used to define thresholds for the onset of fine fuel fragmentation in terms of fuel burnup and local cladding strain.
- *Based on the results reviewed, the burnup threshold for fine fragmentation is proposed to be somewhere between 50 and 70 GWd/MTU and the strain threshold for fine fuel fragmentation and relocation is proposed to be somewhere between 3-7%.*
- These threshold can be used in regulatory analysis to quantify fuel dispersal.

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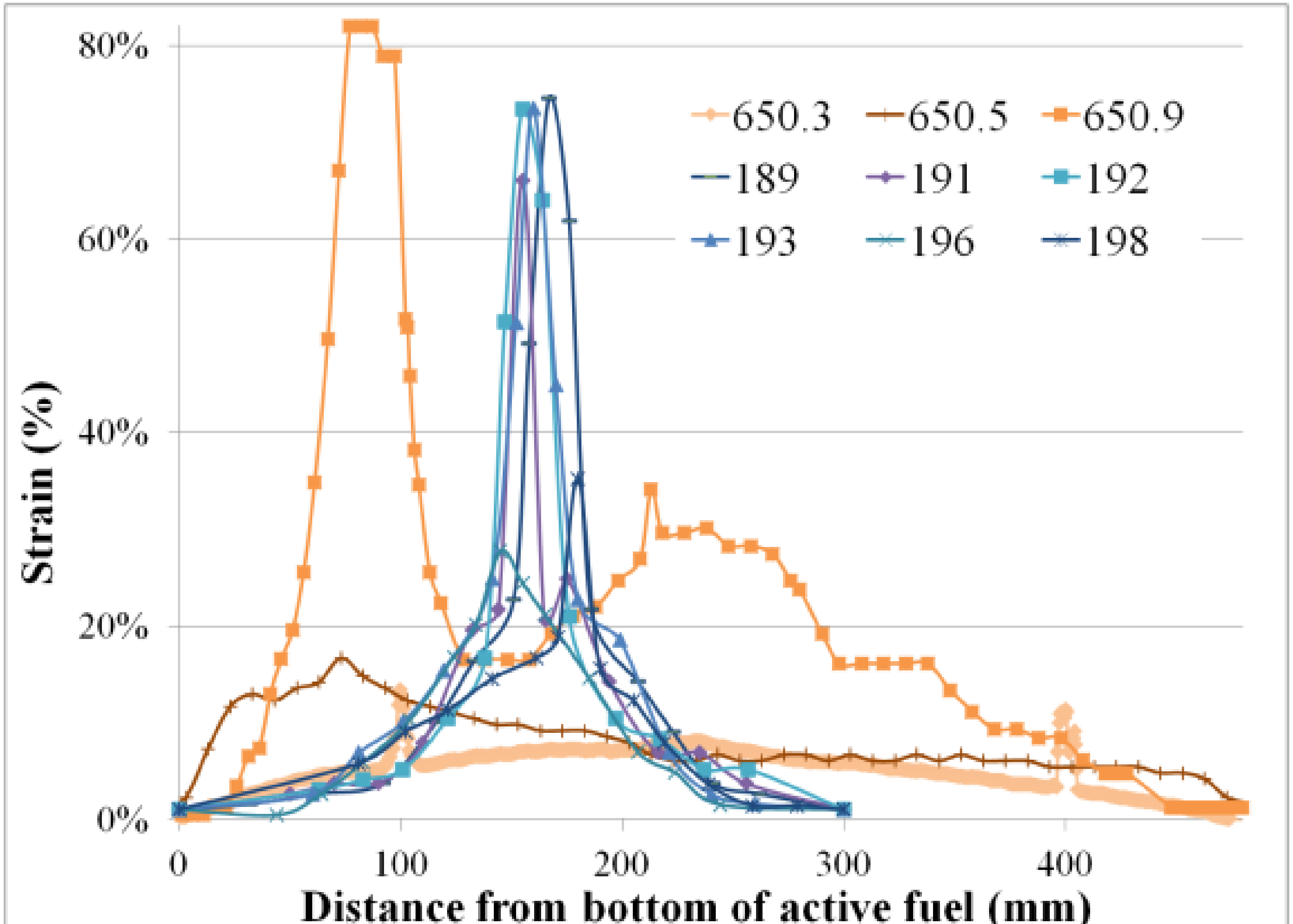
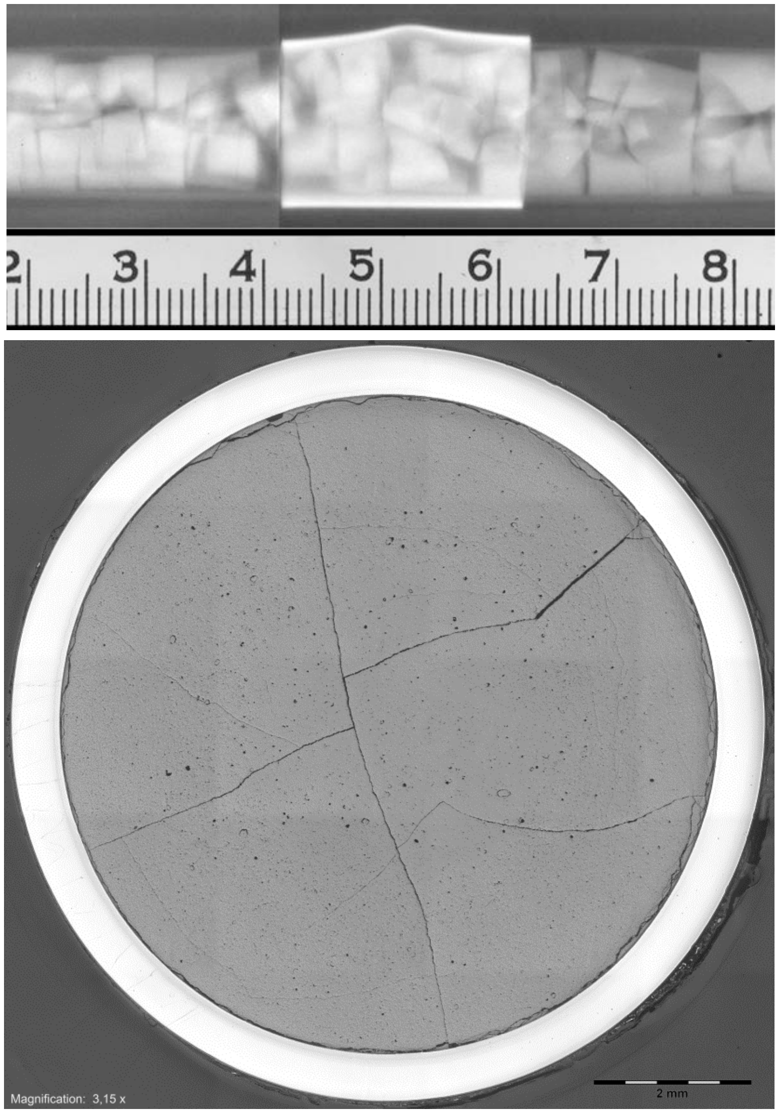
Backup

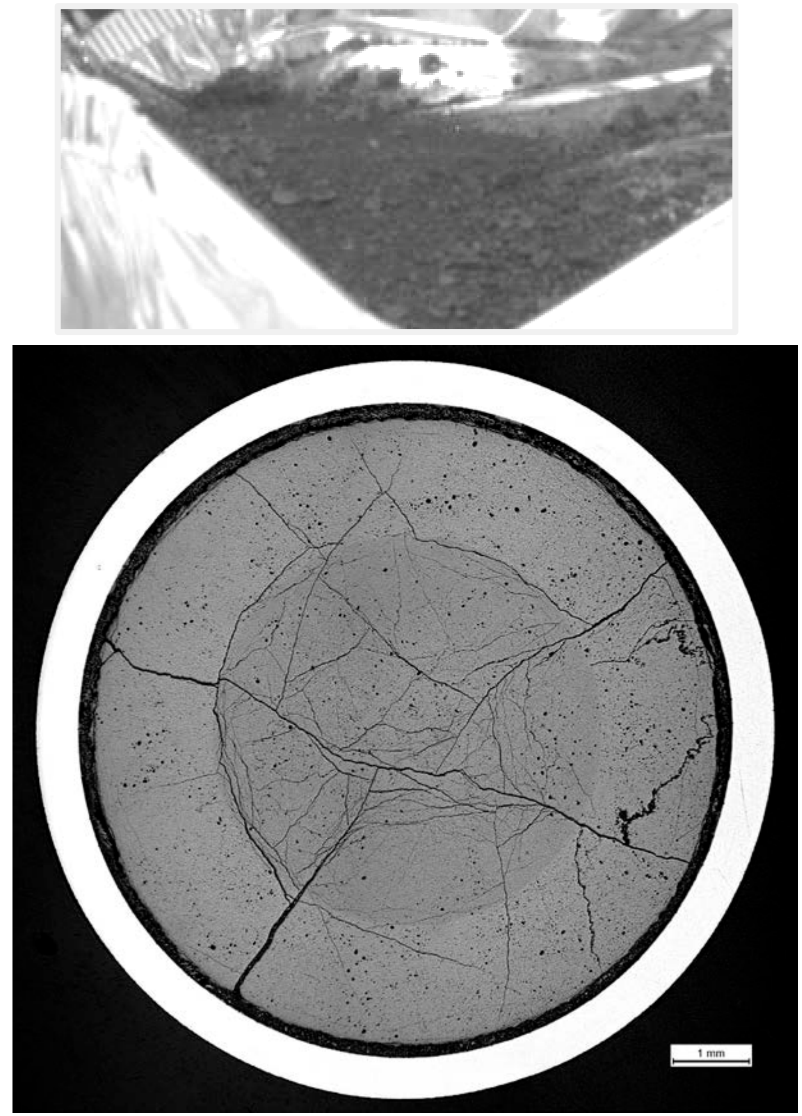


Comparison of cladding strain profiles for Halden LOCA tests (orange) with "slow" depressurization and Studsvik (blue) LOCA tests

Backup



Two regions, post LOCA, of IFA-650.12



Two regions, post LOCA, of Studsvik 192

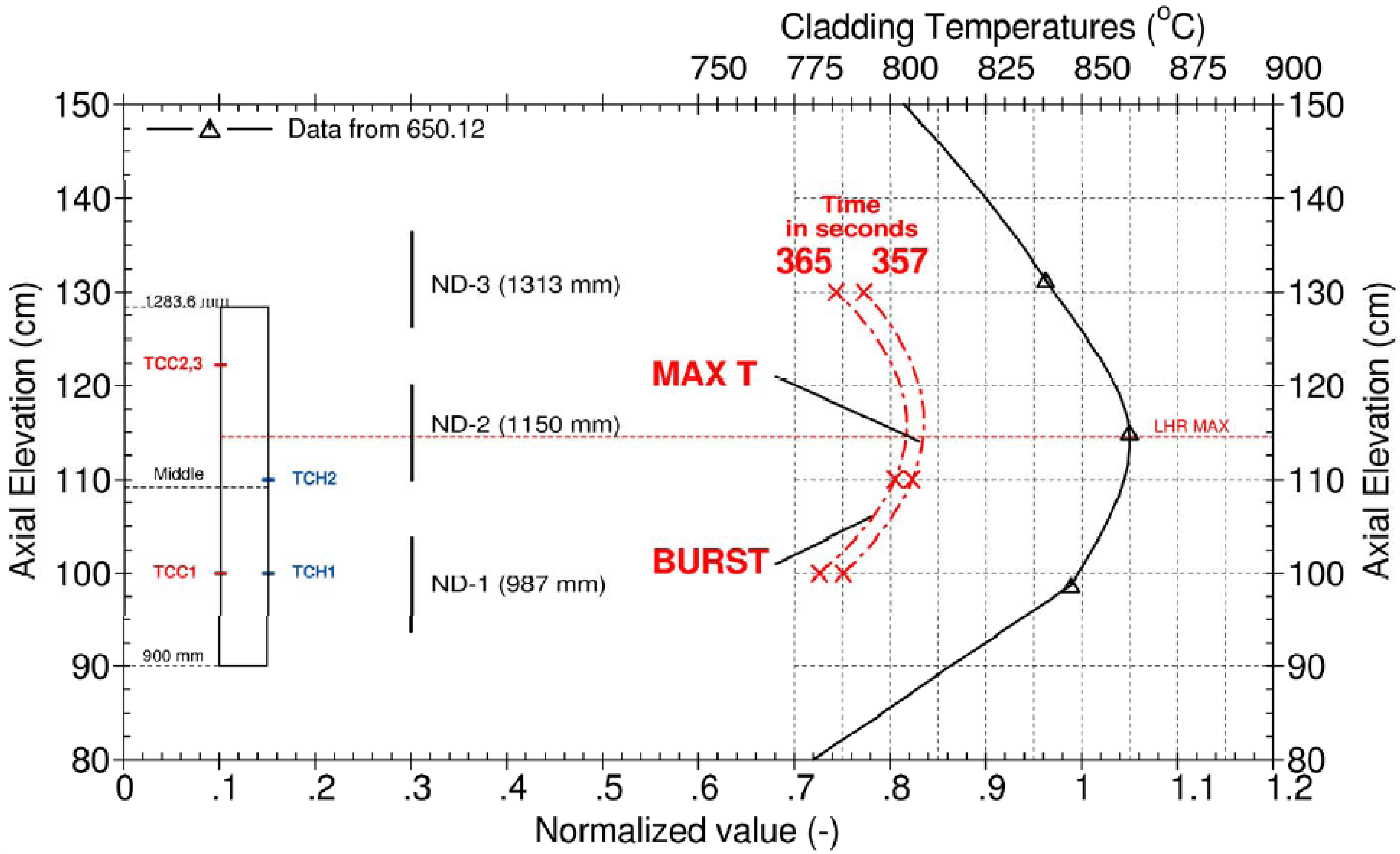
Backup

Test #	Rod Data				Observations	
	sister rods	burnup (GWd/MTU)	Segment length (mm)	Rupture Pressure (bar)	Time to 0.5*Rupture Pressure	Max Strain (%)
IFA-650.3	●	81.9	500	72	11.6	8
IFA-650.4	●	92	500	72	0.5	62
IFA-650.5	●	83	500	72	40	15
IFA-650.6	✚	55.5	450	65	0.5	49
IFA-650.7	◆	44.3	500	10.5	0.5	23
IFA-650.9	●	90	500	62	8	61
IFA-650.10	○	60	450	72	0.5	15
IFA-650.11	✚	56	450	58	0.5	25
IFA-650.12	◆	72.3	380	35	0.5	40
IFA-650.13	◆	7X.X	380			
189	■	72	300	109	34.5	48
191	■	71	300	104	20.5	50
192	■	72	300	81	12.5	56
193	■	71	300	81	44.5	50
196	□	55	300	81	4.5	25
198	□	55	300	81	2.5	25

Symbol:	●	○	■	□	✚	◆
Reactor Type:	PWR	PWR	PWR	PWR	VVER	BWR
Fabricated By:	Framatome	AREVA	Westinghouse	Westinghouse	TVEL	Westinghouse
Irradiated in:	Swiss Gosgen NPP	French Graveline NPP	US North Anna	US Braidwood	Finish Loviisa NPP	Swiss Leibstadt NPP
LOCA test in:	Halden	Halden	Studsvik	Studsvik	Halden	Halden

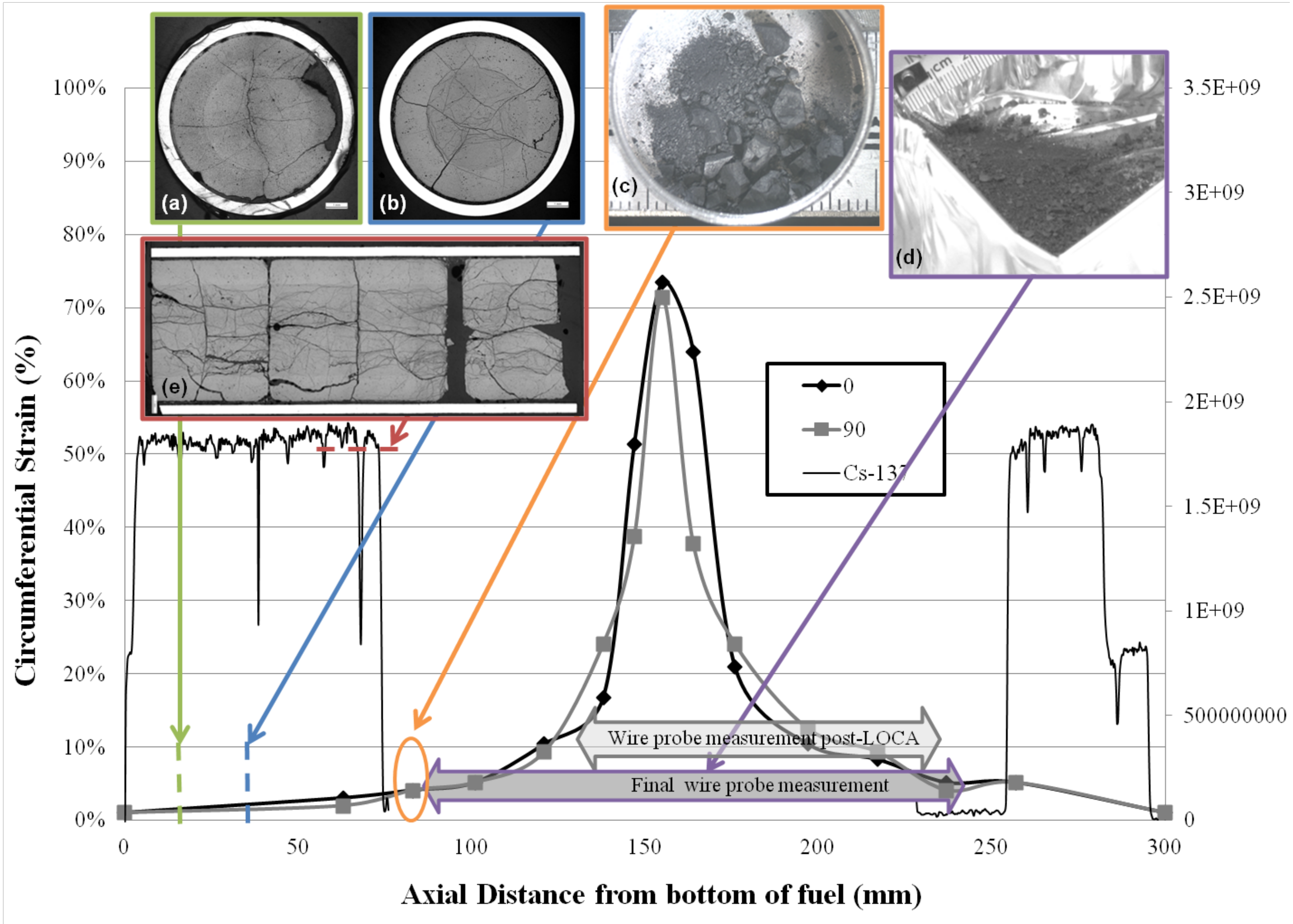
Backup

AXIAL DISTRIBUTION OF POWER AND CLADDING TEMPERATURES DURING THE TEMPERATURE TRANSIENT OF IFA 650.12



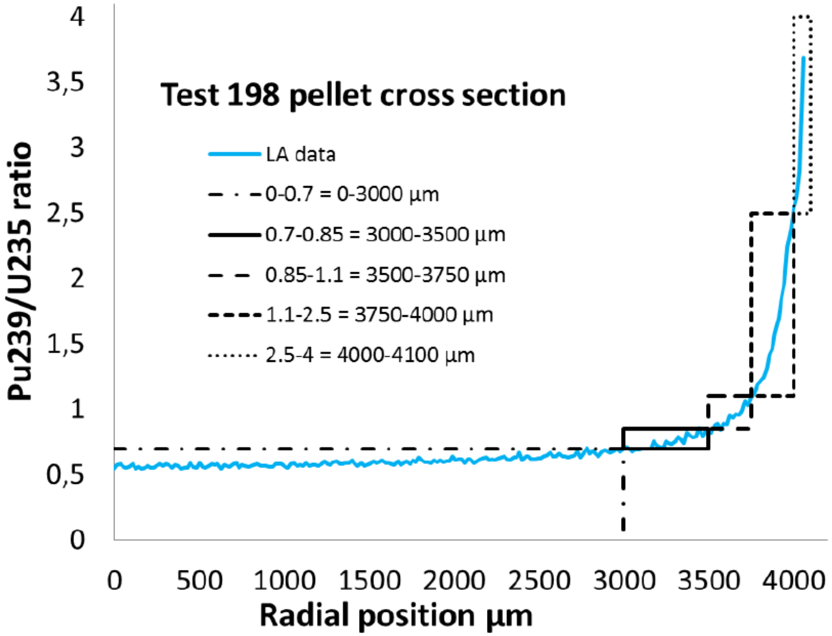
17.08.2011 Presented at EHPG Meeting Sandfjord 2-7 October 2011 17

Backup

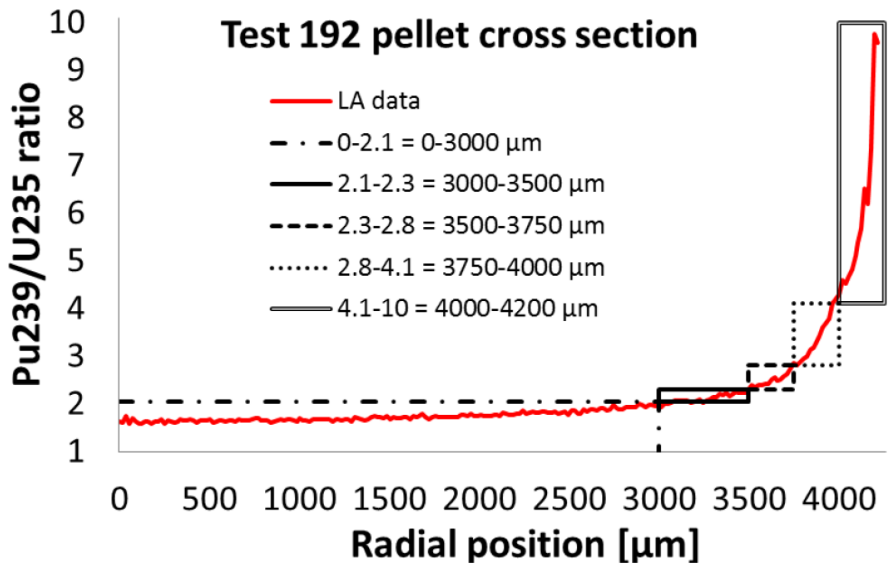


(a)
(b)
(c)
(d)
(e)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Circumferential Strain (%)
3.5E+09
3E+09
2.5E+09
2E+09
1.5E+09
1E+09
500000000
0
0
50
100
150
200
250
300
Axial Distance from bottom of fuel (mm)
0
90
Cs-137
Wire probe measurement post-LOCA
Final wire probe measurement

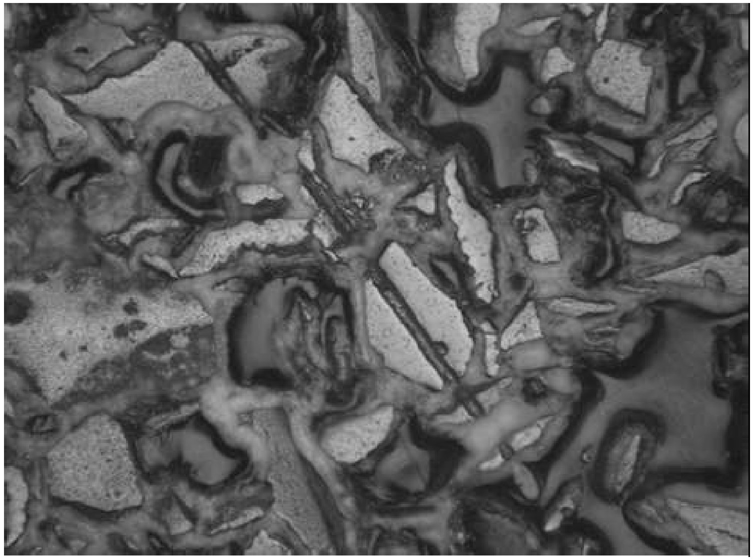
Backup

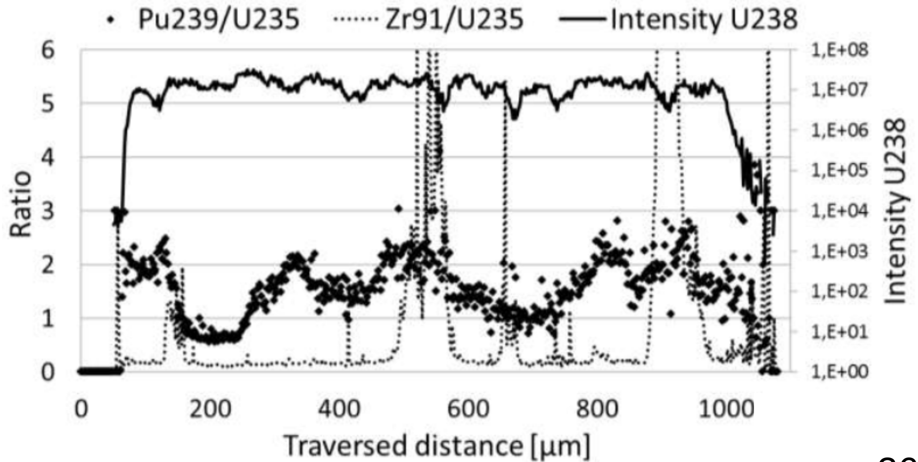


Test 198 pellet cross section
LA data
0-0.7 = 0-3000 µm
0.7-0.85 = 3000-3500 µm
0.85-1.1 = 3500-3750 µm
1.1-2.5 = 3750-4000 µm
2.5-4 = 4000-4100 µm
Pu239/U235 ratio
Radial position µm
0
0,5
1
1,5
2
2,5
3
3,5
4
0 500 1000 1500 2000 2500 3000 3500 4000



Test 192 pellet cross section
LA data
0-2.1 = 0-3000 µm
2.1-2.3 = 3000-3500 µm
2.3-2.8 = 3500-3750 µm
2.8-4.1 = 3750-4000 µm
4.1-10 = 4000-4200 µm
Pu239/U235 ratio
Radial position [µm]
1
2
3
4
5
6
7
8
9
10
0 500 1000 1500 2000 2500 3000 3500 4000





Pu239/U235
Zr91/U235
Intensity U238
Ratio
Intensity U238
Traversed distance [µm]
0
1
2
3
4
5
6
1,E+00
1,E+01
1,E+02
1,E+03
1,E+04
1,E+05
1,E+06
1,E+07
1,E+08
0 200 400 600 800 1000

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Core-Wide Estimates of Fuel Dispersal During a LOCA

ACRS Subcommittee Meeting

Materials, Metallurgy and Reactor Fuels Subcommittee

Fuel Dispersal

Rockville, MD – December 4th, 2013

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Background: Fuel Dispersal and Reactor Safety

- Proposed Generic Issue on fuel dispersal during a LOCA originated from NUREG-2121
- Fuel dispersal has become a central theme of LOCA research
  - Halden Reactor Project IFA-650 LOCA test series (14 tests)
  - NRC LOCA testing at Studsvik Labs (6 tests)
  - Discussions of LOCA testing in the Studsvik Cladding Integrity Program
- The safety significance of LOCA fuel dispersal must be evaluated
- NRC is performing experimental and analytical research to evaluate the potential impacts of fuel dispersal on reactor safety

➢ This presentation describes progress to date on the analytical studies on fuel dispersal during a LOCA

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Objective: Quantifying and Characterizing Fuel Dispersal

Experimental Research

- Fuel rod rupture conditions
- Fuel relocation conditions
- Burnup dependent particle size distribution
- ANL, Halden and Studsvik LOCA research, documented elsewhere

Fuel dispersal predictions

- Number, timing, and location of fuel rod ruptures during a LOCA
- Fuel rod characteristics at and near rupture
- Estimation of dispersed fuel based on experimentally determined thresholds

Consequence analysis

- Based on quantification and characterization of dispersed fuel
- Prediction of thermal hydraulic and radiological consequences
- Future analytical work

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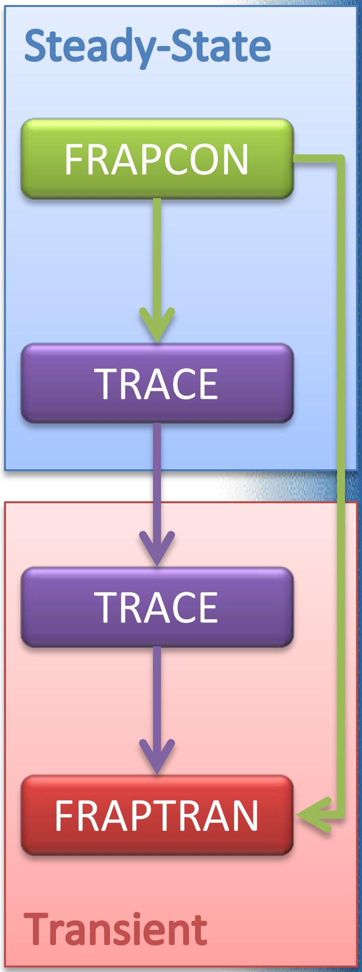
Modeling Strategy

- Steady-state fuel performance: FRAPCON
  - Initialization parameters for TRACE steady-state calculation
  - Initialization parameters for FRAPTRAN transient calculation
- Steady-state systems thermal hydraulics: TRACE
  - FRAPCON steady-state initialization
  - Initialization parameters for TRACE transient calculation
- Transient systems thermal hydraulics: TRACE
  - TRACE steady-state initialization
  - Initialization parameters for FRAPTRAN transient calculation
- Transient fuel performance: FRAPTRAN
  - FRAPCON steady-state and TRACE transient initialization



PWR Analyses

- Plant characteristics:
  - Reactor: 4-loop Westinghouse PWR (most common PWR in US)
  - Fuel type: typical 17x17 fuel, ZIRLO cladding
- Design Basis Accident: double-ended guillotine cold-leg break
  - Worst Large Break Loss-Of-Coolant Accident (LBLOCA)
  - Middle-of-cycle, full power operation
- Three variations analyzed:
  - As-designed 'ideal' plant response
  - Loss-Of-Offsite Power (LOOP)
  - Worst single failure: 1 train of Emergency Core Cooling System inoperable (1ECCS)
- Results dependent on plant, scenario, and choice of assumptions

FRAPCON: Base Irradiation Fuel Rod Performance

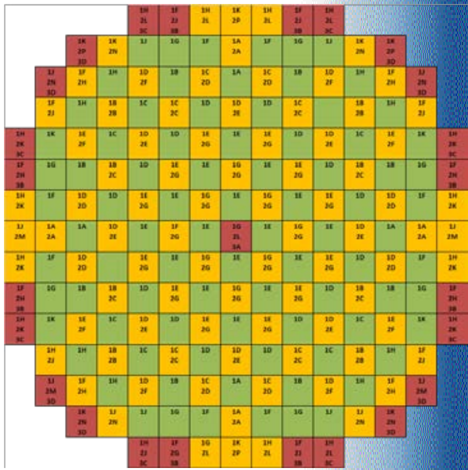
- Power histories from known assembly powers at BOC, MOC, EOC
  - 43 different power histories to represent the entire core at any given instant
- 193 assemblies

84 fresh	84 once-burned	25 twice burned
10 power levels	14 power levels	4 power levels

	R	P	N	M	L	K	J	H
1								
2					1J	1G	1F	
3				1H		1B		1A
4			1H		1C		1D	
5		1K		1C		1D		1E
6		1G	1B		1D		1E	
7		1F		1D		1E		1E
8			1A		1E		1E	

	R	P	N	M	L	K	J	H
1							2L	2P
2				2N				2A
3			2H		2F		2D	
4		2J		2B		2C		2E
5			2F		2E		2G	
6				2C		2G		2G
7	2K		2D		2G		2G	
8	2M	2A		2E		2G		

	R	P	N	M	L	K	J	H
1					3C	3B		
2			3D					
3		3D						
4								
5	3C							
6	3B							
7								
8								3A

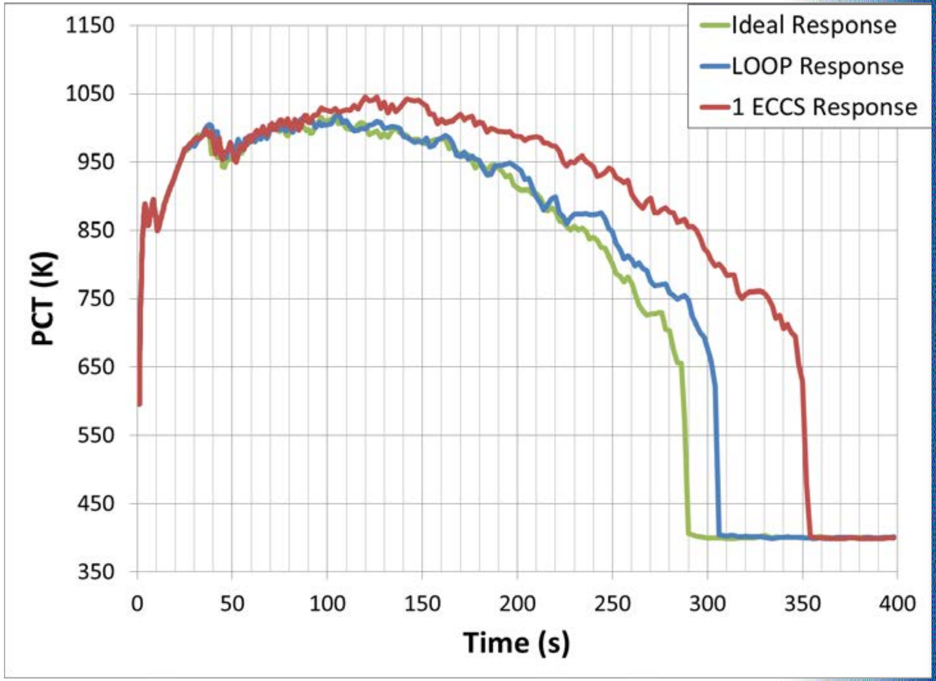


- Core-average discharge burnup: 51 GWd/MTU

TRACE: Transient Thermal Hydraulics

- Double-ended guillotine cold-leg break
  - Worst Large Break LOCA
  - Burnup dependent parameters from FRAPCON
  - Initial TH and systems parameters from TRACE steady-state run
- Three variations analyzed:
  - As-designed 'ideal' plant response
  - Loss-Of-Offsite Power (LOOP)
    - ➢ Delayed quench
  - 1 train of Emergency Core Cooling System inoperable (1ECCS)
    - ➢ Increased PCT and delayed quench

✓ Provided cladding surface temperature for all fuel rods and core-wide coolant conditions



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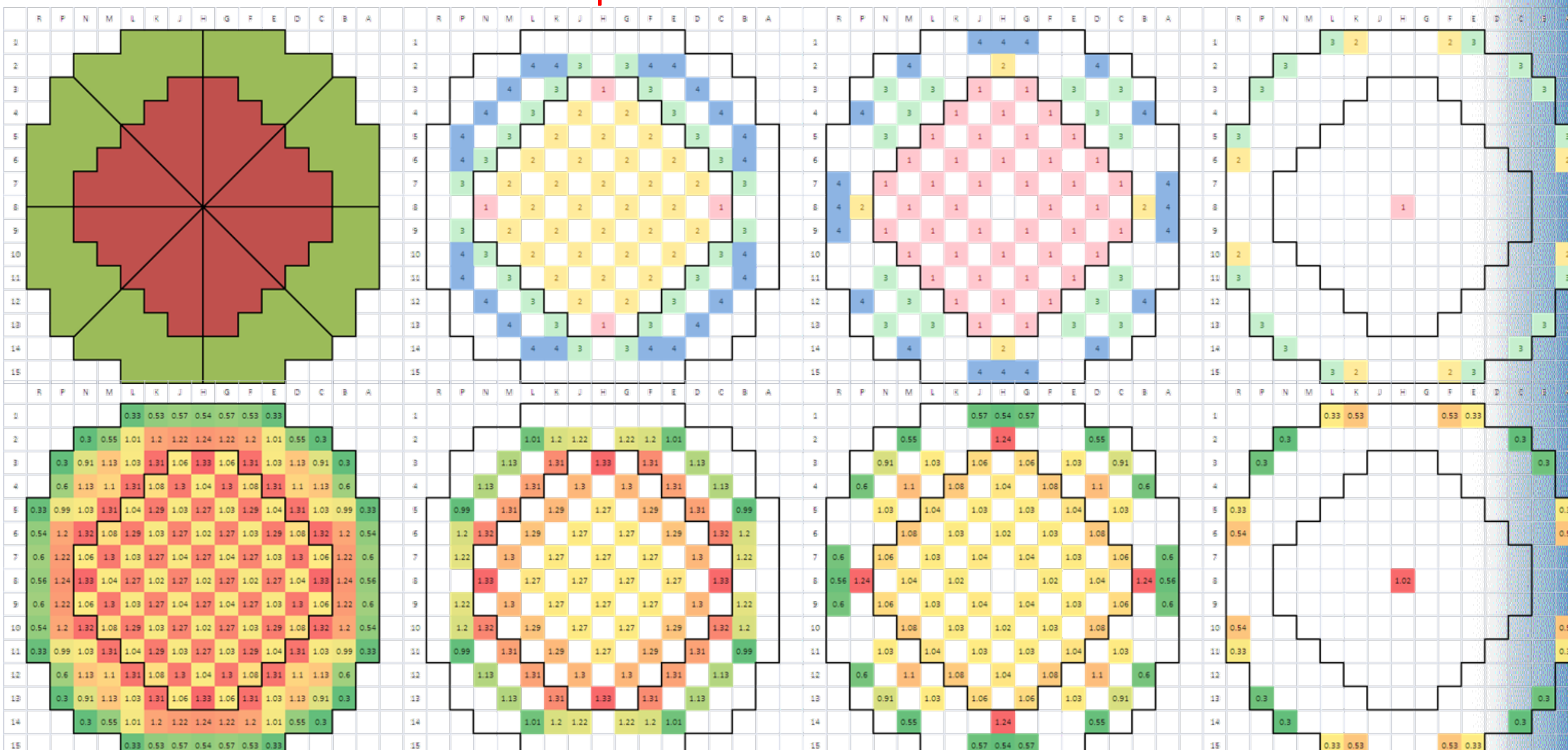
FRAPTRAN: Transient Fuel Rod Performance

- Cross-Referencing of 43 FRAPCON bins and 88 TRACE bins
  - 344 FRAPTRAN bins to represent all rods in the core



FRAPTRAN: Transient Fuel Rod Performance

- For each of the 344 FRAPTRAN bins:
  - Burnup dependent parameters from FRAPCON
  - Fuel rod surface temperatures from TRACE transient run

- Predictions of fuel rod thermal mechanical response
  - Cladding hoop strain and burnup along fuel rod
  - If burst, time and axial location, as well as balloon strain

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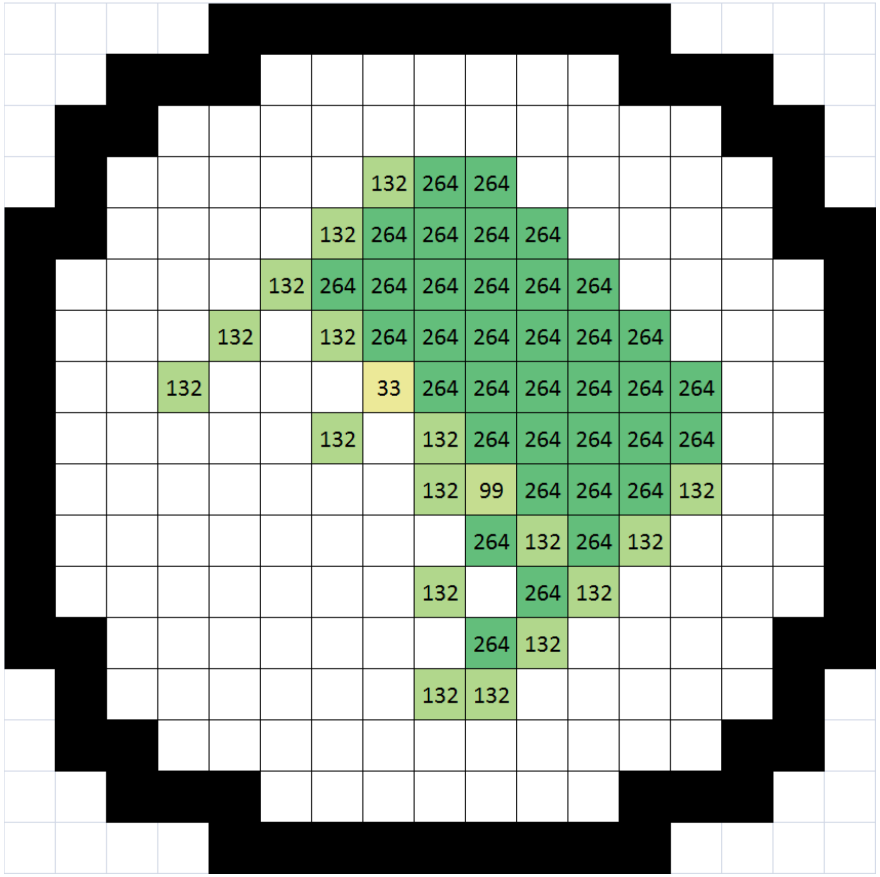
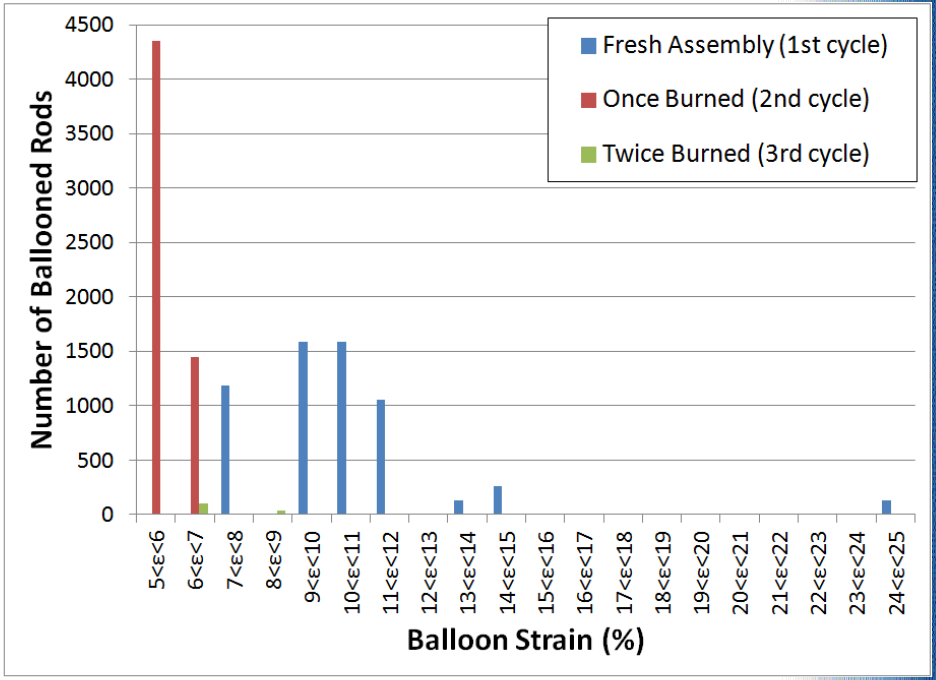
Fuel Rod Rupture Census
Ideal Plant Response

Ballooned rods per assembly (264 rods per assembly)

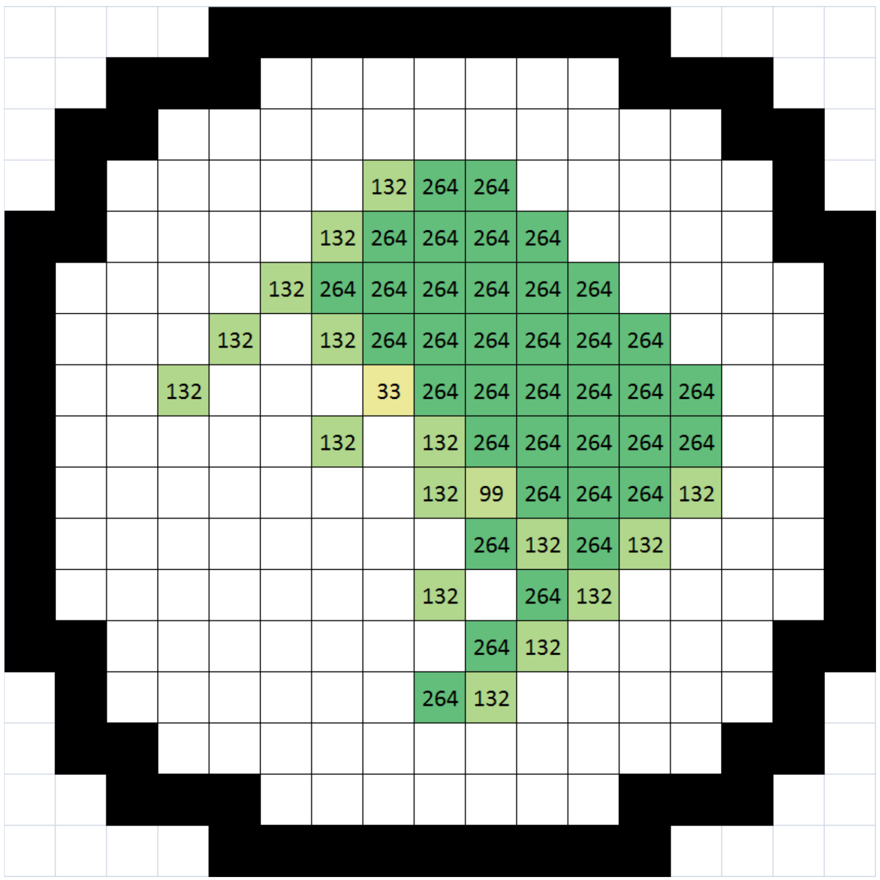


Calculated ballooning strains (rod to rod contact if strain ~38%)

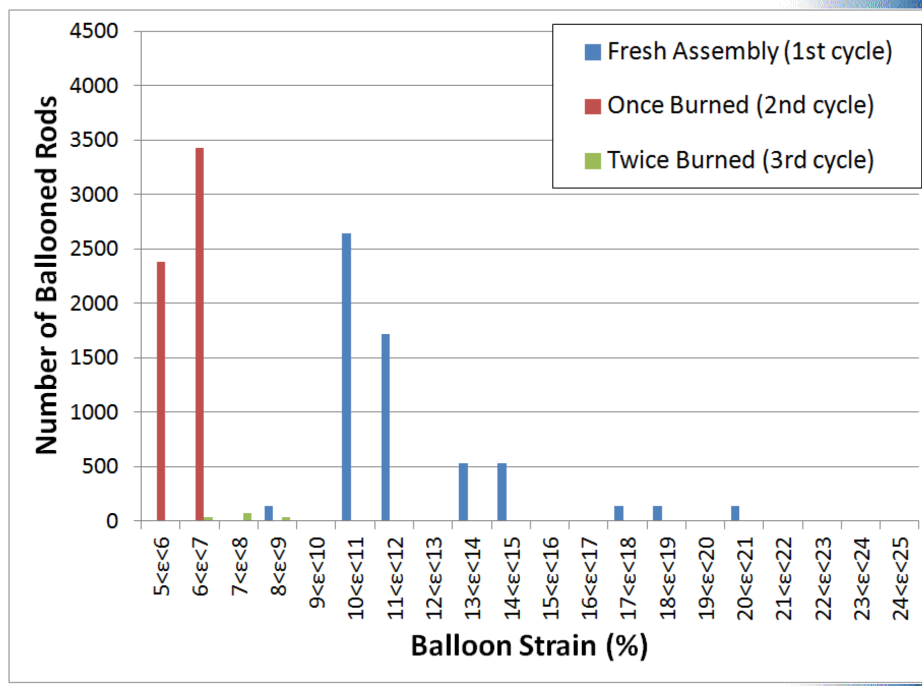


Fuel Rod Rupture Census Loss-Of-Offsite Power (LOOP)

Ballooned rods per assembly (264 rods per assembly)

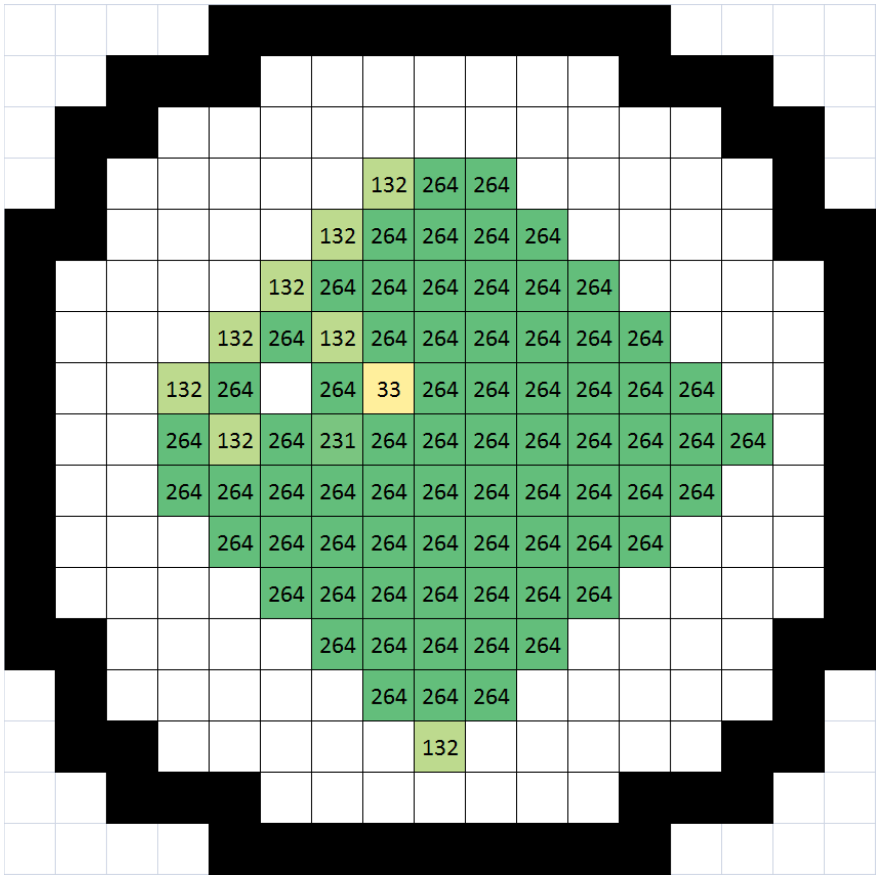


Calculated ballooning strains (rod to rod contact if strain ~38%)

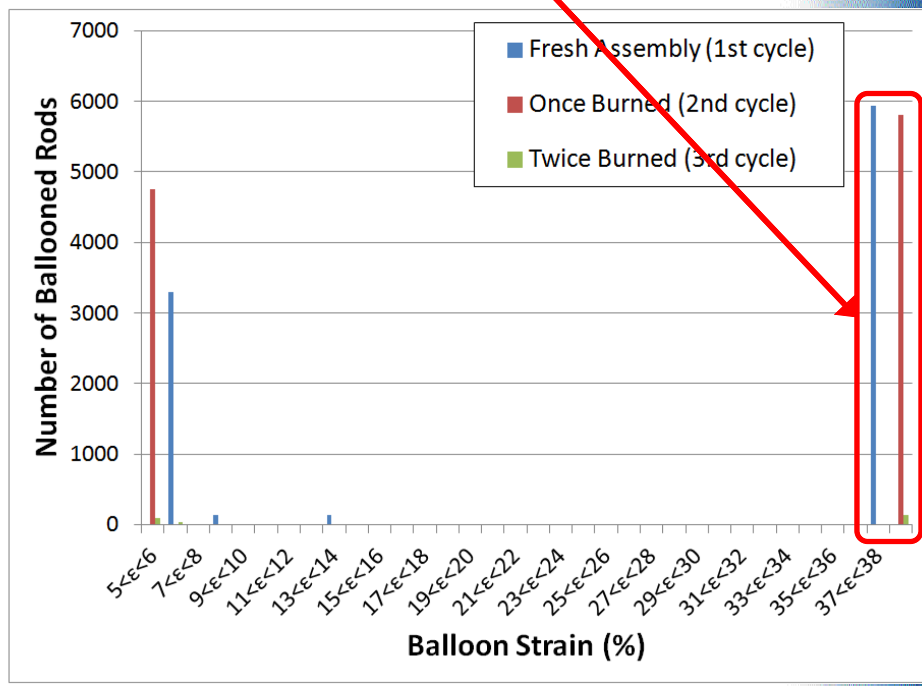


Fuel Rod Rupture Census Worst Single-Failure (1 ECCS)

Ballooned rods per assembly (264 rods per assembly)



Calculated ballooning strains
(rod to rod contact if strain ~38%)



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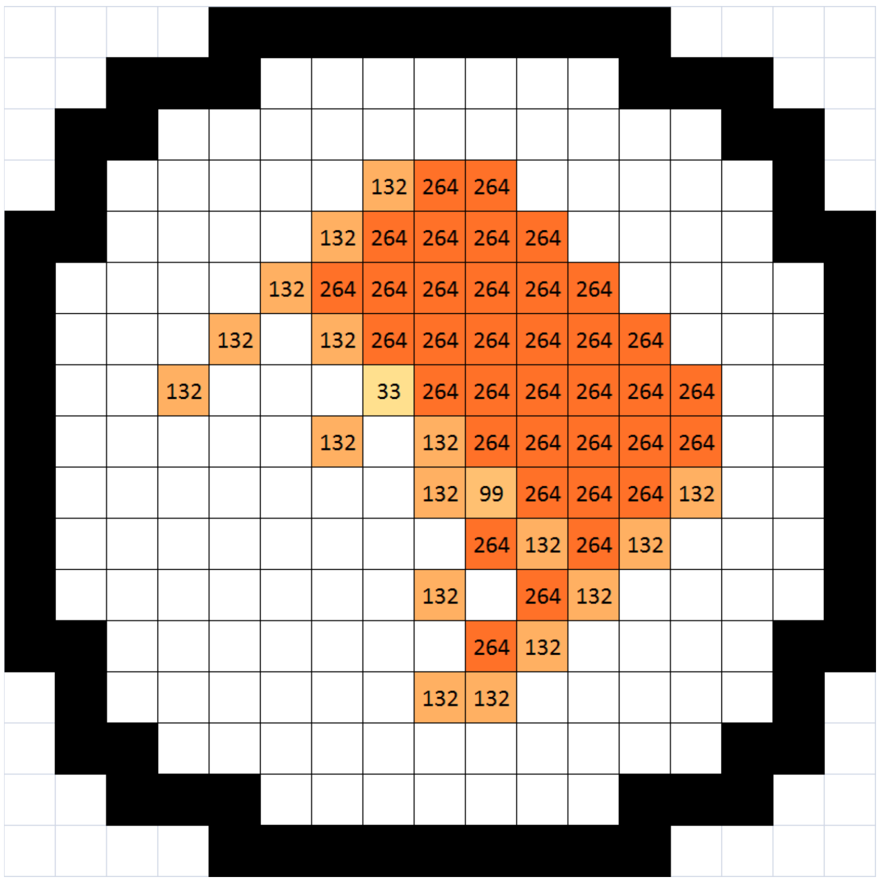
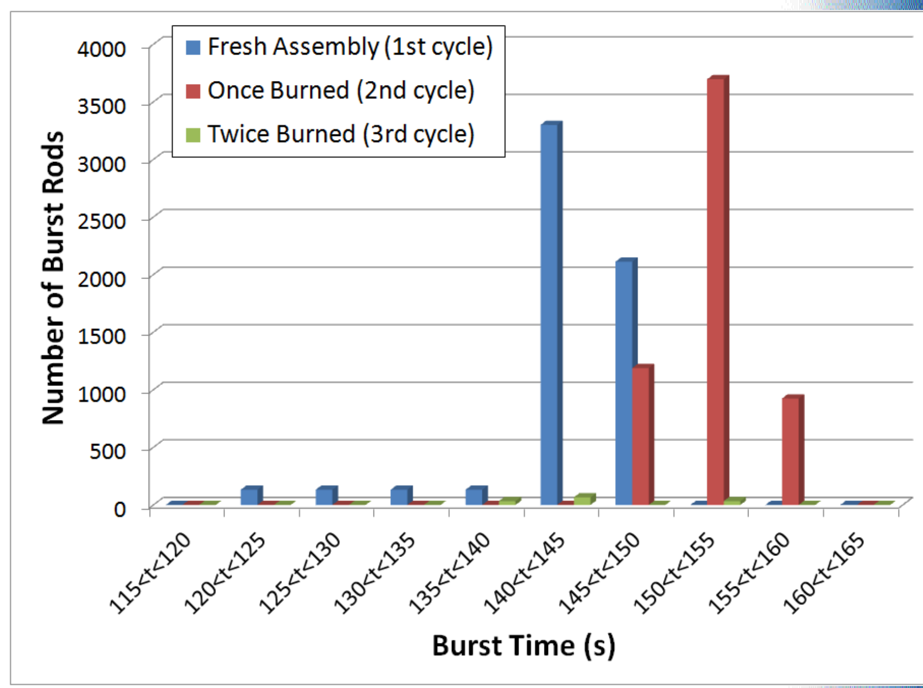
Fuel Rod Rupture Census Worst Single-Failure (1 ECCS)

Ruptured rods per assembly (264 rods per assembly)



Calculated rod burst time (PCT occurs at ~120 seconds)



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Fuel Dispersal Estimates Empirical Assumptions

1. Fuel rod rupture is required to enable fuel dispersal
2. Fuel fragments must be smaller than the rupture opening
   - Very difficult to predict fuel rod rupture opening size
   - Assume that all fine fuel fragments will be able to escape, but that large fragments will remain inside the cladding
3. Local pellet average burnup threshold for transition from coarse particle distribution to fine particle distribution
   - Burnup corresponding to the coarse to fine fuel particle distribution transition occurs between 50 GWd/MTU and 70 GWd/MTU
   - Likely to be gradual but centered around 60 GWd/MTU
4. Minimum cladding strain required near the rupture region for fuel to be mobile and thus dispersible
   - Mobility strain threshold could vary between 3 % and 7 % balloon strain
   - Most likely around 5 % ballooning strain

Dispersed Fuel Mass and Characteristics

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- For 'most-likely' thresholds of 60 GWd/MTU and 5 % strain, assuming that any particle with a size less than 1mm is a 'fine' dispersible particle
  - ➢ 6.7 kg of dispersed fine fuel
    - 35 grams per fuel assembly
    - 123 grams per assembly with cladding ruptures

Mass of Fine Fuel Dispersed (kg)		Fine-Enough-to-Disperse Size Threshold (mm)					
Fine Fragmentation Threshold Burnup (GWd/MTU)	Fuel Fragment Mobility Threshold Strain (%)	0.125	0.25	0.5	1	2	4
50	3	9.9	18.0	26.0	34.0	46.8	230.0
	5	3.0	5.5	7.9	10.3	14.2	69.3
	7	2.9	5.2	7.6	9.9	13.6	65.4
60	3	5.8	12.0	17.5	22.4	31.8	215.7
	5	1.7	3.6	5.3	6.7	9.6	64.9
	7	1.6	3.4	4.9	6.3	9.0	61.0
70	3	5.8	12.0	17.5	22.4	31.8	215.7
	5	1.7	3.6	5.3	6.7	9.6	64.9
	7	1.6	3.4	4.9	6.3	9.0	61.0

- Dispersed fuel mass is reduced if the burnup threshold increases
  - – No difference between 60 GWd/MTU and 70 GWd/MTU threshold because max assembly burnup is below 60 GWd/MTU
- The dispersed fuel mass is reduced if the strain mobility threshold increases
  - – Largest difference between 3 % and 5 % thresholds because of ballooning models
- The dispersed fuel mass is increased if the fine-enough-to-disperse size threshold increases
  - – Accelerates dramatically above a 2mm size threshold (realistic size threshold would likely be below 1mm)

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Perspectives and Limitations

- New approach to core-wide LOCA modeling
  - Higher level of detail achieved for fuel rod thermal mechanical response
  - One of few published studies aimed at predicting amounts of fuel dispersal
  - Timely predictions
- Results of the TRACE calculation feed into the boundary conditions in FRAPTRAN, but no coupling of TRACE and FRAPTRAN
  - TRACE fuel rod models have been greatly refined in latest beta versions, but are still not quite as detailed as FRAPTRAN models, particularly ballooning models
- Some averaging takes place when binning assemblies by power history
  - Further refining necessary to account for intra-assembly power variations
  - Calculations rely on assembly or bin average instead of peak rod average
- Fuel dispersal estimates vary depending on assumptions
- Uncertainty not yet quantified

BWR Analyses

Work by Ian Porter, PhD Candidate, U. South Carolina / NRC

- Full core BWR/4 completed assuming all systems available
  - Small Break LOCA at BOC, MOC, EOC
    - Break in recirculation line
    - 764 assemblies modeled individually in TRACE and FRAPCON/FRAPTRAN:
    - Resulted in PCT of 779 K (942.5°F) for 8 assemblies
    - No rod burst or ballooning, no fuel dispersal
  - Large break LOCA at MOC (highest temperatures in SBLOCA)
    - Quarter core symmetry: 191 assemblies modeled individually in TRACE and FRAPCON/FRAPTRAN
    - Double ended break of recirculation suction line
    - PCT of 824 K (1024°F) (45K hotter than SBLOCA)
    - Max Internal Rod Pressure 3.028 MPa
    - No rod burst or ballooning, no fuel dispersal
    - Significant differences between different fuel designs (mixed core)

Recent and Future Work

- Updated PWR study with latest version of TRACE, and performed BOC, MOC, and EOC TRACE calculations (work by Ian Porter)
  - MOC case showed small increase in PCT (7 K)
  - Increase in PCT for both EOC and BOC cases (~25 K)
    - Possible increase in # of ballooned & ruptured rods
    - Earlier times at which PCT is reached
  - Additional detail in Westinghouse 4-loop study: 193 assemblies modeled individually in TRACE
- Future PWR Analyses:
  - Complete fuel dispersal analysis for latest PWR analyses
  - Increased detail: sub-assembly binning to account for pin-by-pin power distributions
  - LBLOCA with 1 train of ECCS inoperable for B&W and CE designs
- Future BWR Analyses:
  - Run SBLOCA and LBLOCA at MOC with 1 train of ECCS inoperable
  - Run BWR/2 and BWR/3 cases (BWR/5 and BWR/6 expected to behave better than BWR/4)

Summary and Conclusions

- Analytical study of core-wide fuel rod ruptures was performed
  - FRAPCON was used to initialize both TRACE and FRAPTRAN
  - TRACE cladding surface temperatures were used as boundary conditions in FRAPTRAN
- 3 Large Break LOCA scenarios: 'ideal', LOOP, worst single failure (1ECCS)
  - 'Ideal' and LOOP did not result in any rod burst predictions
  - 1 ECCS scenario resulted in the failure of ~ 23 % of the fuel rods in the core
- Rod burst prediction from FRAPTRAN was combined with empirically derived assumptions to produce mass estimates of dispersed fine fuel particles into the core from the ruptured fuel rods
  - The 'most-likely' conditions for dispersal resulted in about 6.7 kg of dispersed fuel, equivalent to about 35 grams per assembly, or ~123 grams per assembly with ruptures
- The methods developed for the purposes of this study will be refined and used again in the future to produce more estimates for different plant types, fuel designs, and transient scenarios
- In addition, the information produced in these studies of core-wide fuel dispersal will be used in the future to study the consequences of fuel dispersal during LOCA transients in terms of reactor safety

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Protecting People and the Environment

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2. B. G. BEASLEY, "Acceptance Review of Proposed Generic Issue on Dispersal of Fuel Particles during a LOCA", ADAMS ML112910156, U.S. NRC (2011).

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4. K. J. GEELHOOD, et al., NUREG/CR-7022, ADAMS ML11101A005, U.S. NRC (2011).

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6. TRACE v5.0 Theory Manual, ADAMS ML120060208, U.S. NRC (2008).

7. M. E. FLANAGAN, et al., "Fuel Fragmentation, Relocation and Dispersal under LOCA Conditions: Experimental Observations," Proceedings of TOPFUEL 2013, Charlotte, NC, September 15-19, 2013, American Nuclear Society (2013), paper #8334.

Fuel Fragmentation, Relocation and Dispersal Current Understanding and Test Plans

Ken Yueh
Senior Project Manager

NRC ACRS Meeting
December 4, 2013

Contents

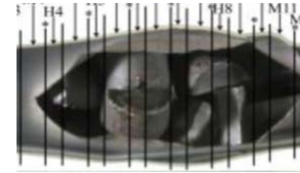
- Background
- Review of Recent Test Results
- Observations
- Impact on Fuel Performance
- Industry Test Results and Plans

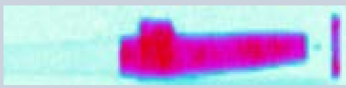
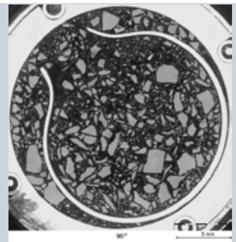
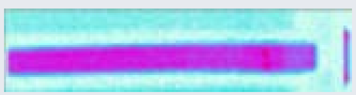
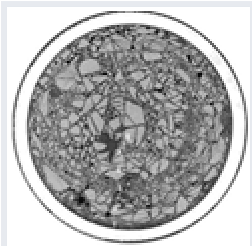
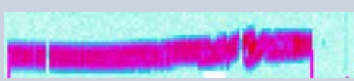
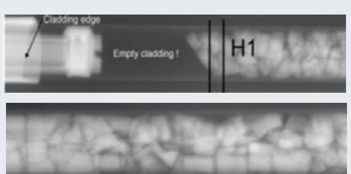
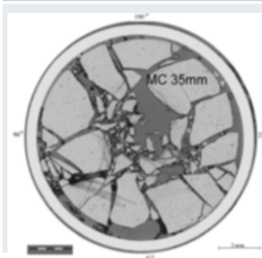
Background

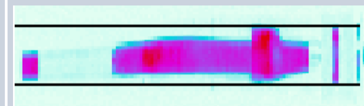
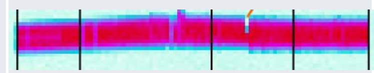
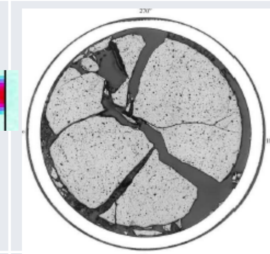
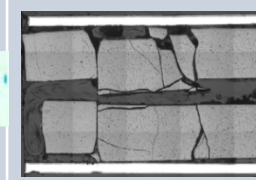
- Early LOCA testing conducted with fresh or low burn-up fuel showed
  - Slightly increased pellet fragmentation with burn-up
  - Weak dependence of fuel fragmentation on burn-up
- Fuel fragmentation and relocation have gained more attention because of recent Halden and NRC-sponsored Studsvik LOCA test results
  - Fuel fragmentation is more pronounced at very high burn-ups

Halden Test Results Overview

Nuclear and Electrical Heating

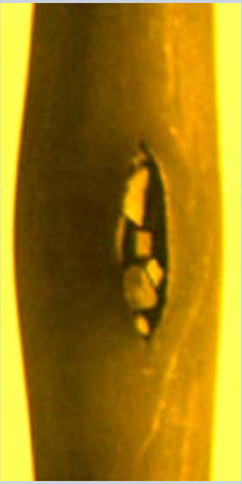
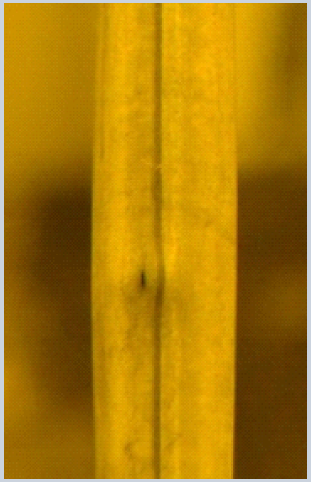
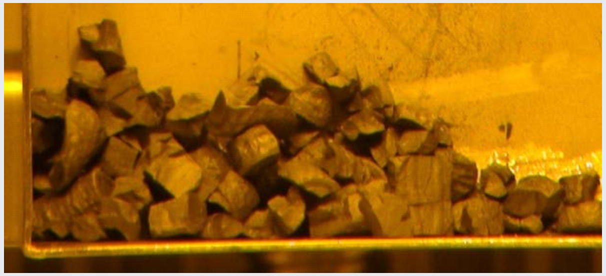
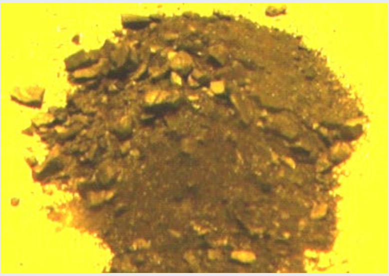


Test	BU		
4 800°C PWR	92	 Last Cycle: 16 kw/m	
5 1050°C PWR	83	 Last Cycle: 18 kw/m	
6 830°C BWR	56		
7 1150°C BWR	44		

Test	BU		
9 1100°C PWR	90	 Last Cycle:15.5 kw/m	
10 850°C PWR	61		
11 1000°C VVER	56		
12 800°C BWR	72	 Last Cycle: 7 kw/m average	

NRC-Sponsored Test Overview

External Radiant Heating

Lab.	ANL	Studsvik	Studsvik
Burn-up	56	61	70 Last Cycle:15 kw/m
Fuel Type	BWR	PWR	PWR
Ballooned Region		 	
Fragment Size			

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Observations

- Instances of severe fuel fragmentation have been observed above licensed burn-up limits
  - All have unusual power histories
- Halden IFA650.12 has demonstrated resistance to severe fuel fragmentation up to 72 GWd/MTU
  - Insufficient data to determine precise fuel fragmentation threshold
- Below the fragmentation “threshold” burn-up the fragment size does not appear to decrease with burn-up
- Most of the balloon and burst sizes of fuel under burn-up threshold limit have been small, with very limited fuel relocation/dispersal – tests were designed to maximize balloon size

NRC Sponsored Studsvik 70 GWd/MTU Test

- Result may be influenced by the special last cycle high power operation – since Halden IFA650.12 did not show severe fragmentation (high burn-up fuel normally should not be able to reach such power)
  - Modified fission gas distribution? More difficult to study
  - Higher internal stress due to thermal expansion

Operation
Equilibrium

Shutdown
Interior shrinks more due to higher temperature

LOCA
Interior in equilibrium but outside expands + gas pressure

Difference between low and high power operation can add > 1 Mpa stress over a flaw size of 10 μm

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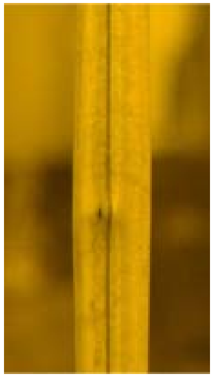
Balloon and Burst

- What influences balloon size?



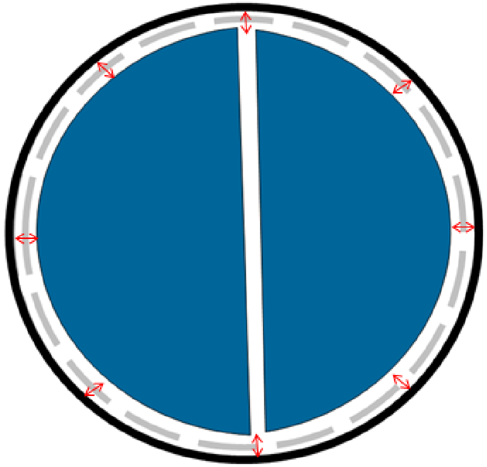
61 Wd/MTU
PWR

61 Wd/MTU
PWR

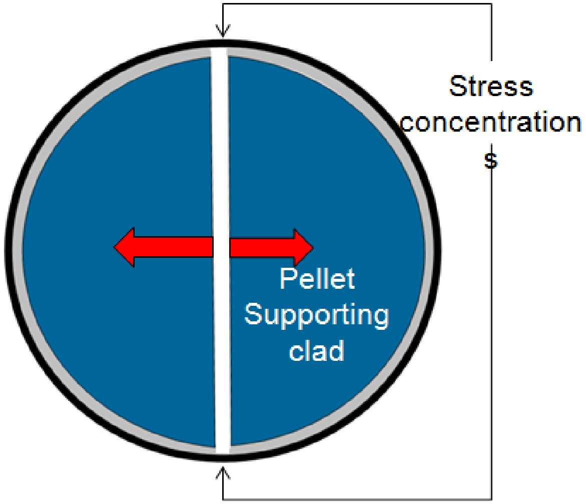
57 Wd/MTU
BWR

70 Wd/MTU
PWR

- Small balloon/burst observed for rods <61 GWd/MTU in Halden tests ←despite experiment designed to maximize balloon size
- Gas communication is generally accepted to impact balloon and burst size



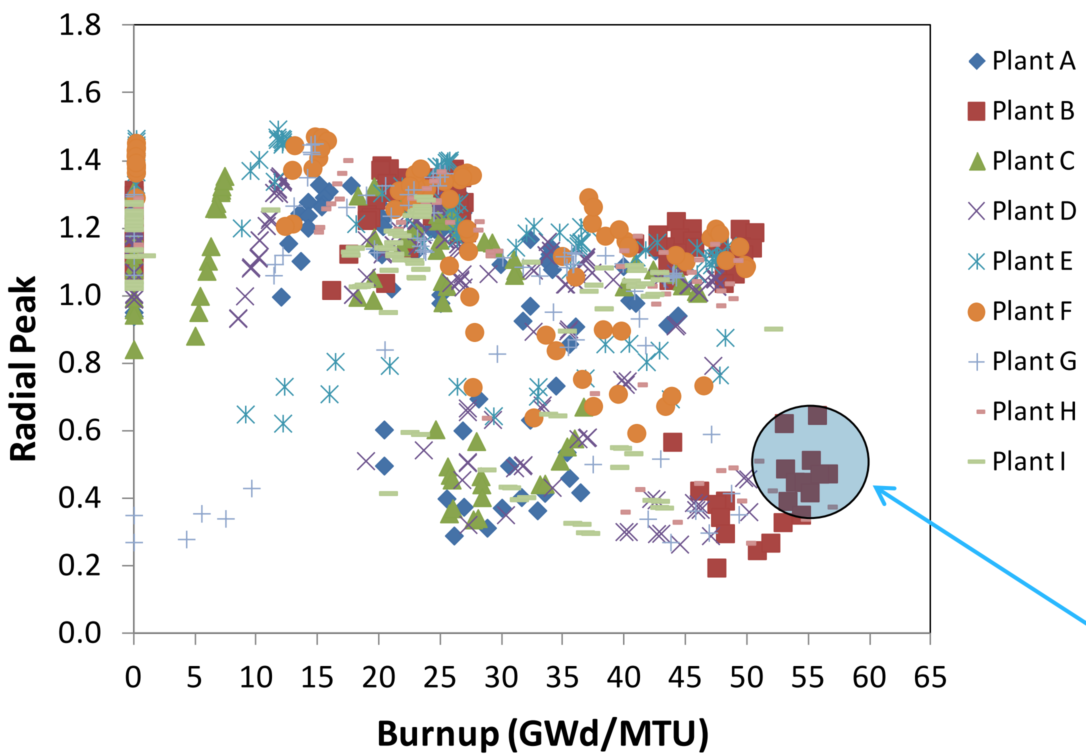
Ultra high burn-up fuel with good gas communication



Intermediate to high burn-up fuel with little gas communication

Impact on Fuel Performance

- Survey results of core burn-down of FA radial peak power of multiple plants indicates no or minimal burst potential above ~50 GWd/MTU for PWR - Even larger margin for BWR plants surveyed



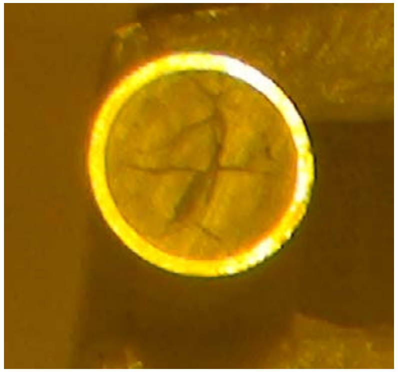
Fragmentation threshold is higher than 50 GWd/MTU or burst potential threshold

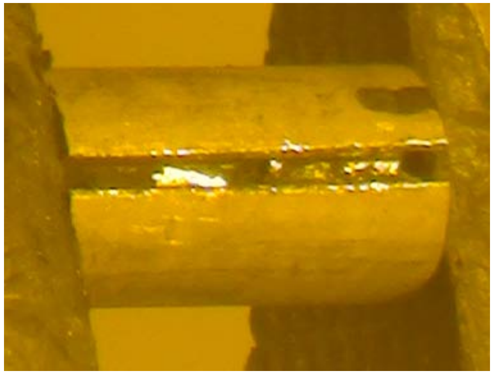
No Significant Safety Concern with Fuel Dispersal

Low power→low temperature

Industry Test Program

- Developing simpler tests to study separate effects to better understand fragmentation mechanisms
  - Heating pellet in air to LOCA temperatures (2 geometries)

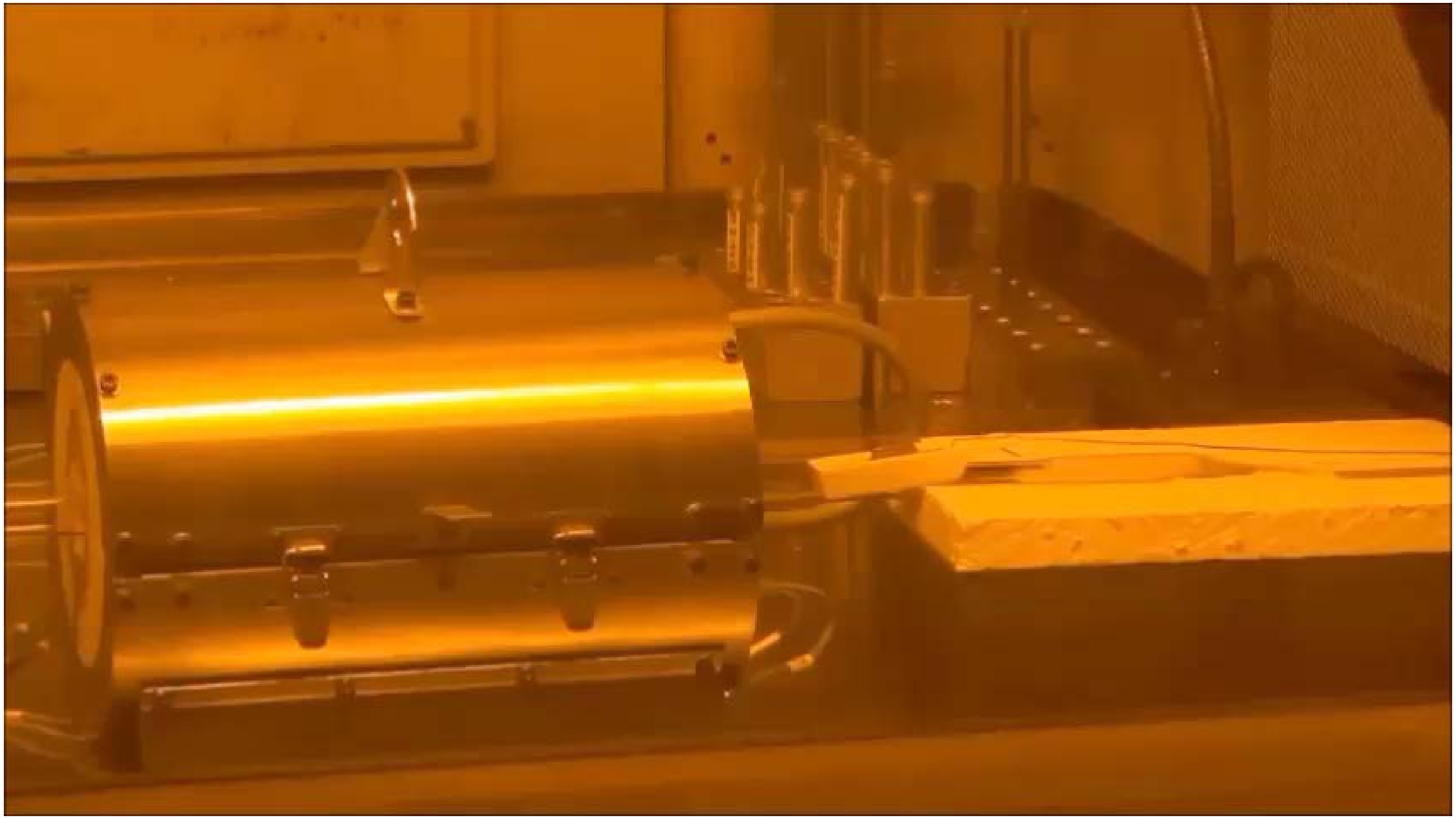




- Scoping test completed
  - Using same fuel material as NRC Studsvik 70 GWd/MTU

Pellet Heating Scoping Test

- Sample inserted into a pre-heated furnace at 1000°C



70 GWd/MTU – Same parent rod as NRC-sponsored integral test

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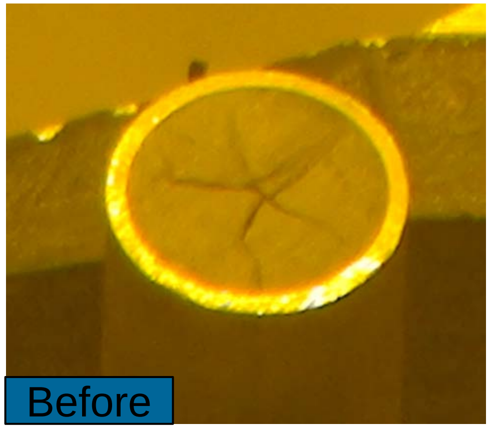
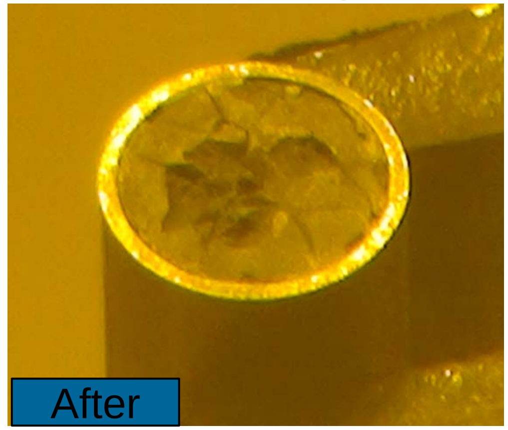
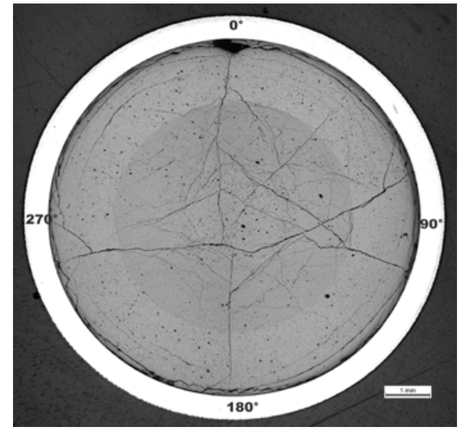
Scoping Test Results
Fuel Material From Same NRC 70 GWd/MTU Rod

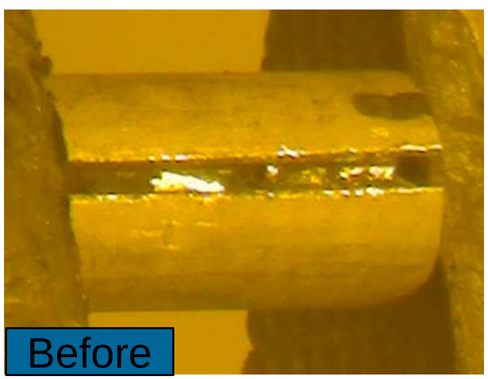
With Radial Constraint – fine cracks at pellet center

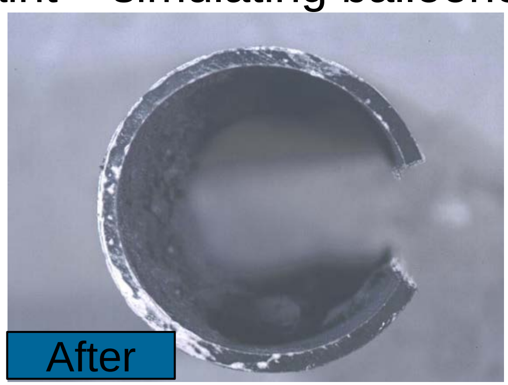


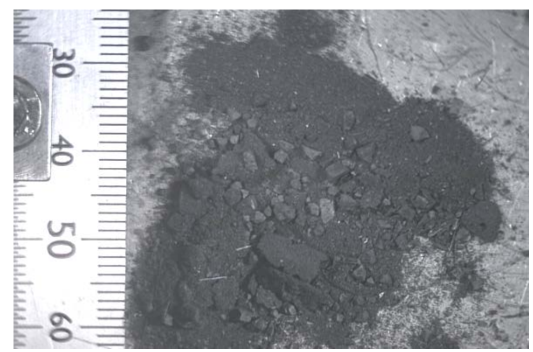




Without Radial Constraint – simulating ballooned condition







Fragments similar to NRC sponsored integral test

Technique Validation Tests

- Heat pellet material from NRC 61 GWd/MTU rod with a slit
  - Verify pellet stays intact as in the case of NRC Studsvik test
- Heat pellet material from NRC 70 GWd/MTU parent rod in an inert gas atmosphere
  - Concerns raised on UO_2 to U_3O_8 conversion
  - Significant conversion not expected since pellet is solid

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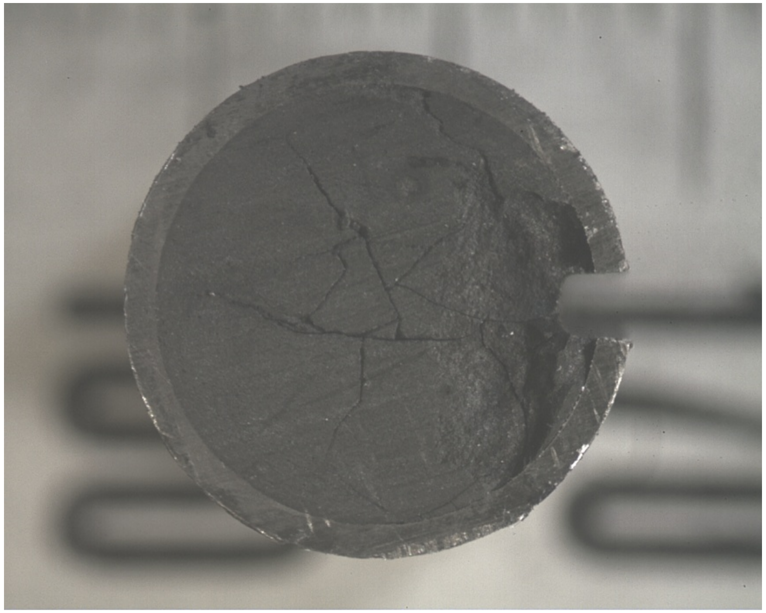
Pellet Heating

- Pellet samples sectioned adjacent to NRC Studsvik test rod elevation – 61 GWd/MTU



Before

After 1000°C Exposure

No significant pellet degradation due to exposure up to 1000°C
Results consistent with NRC sponsored Integral Test

Future Plans

- Complete inert gas heating test of 70 GWd/MTU fuel
- Additional tests to isolate fragmentation threshold with pellet heating
  - Study fragmentation mechanisms
  - Identify factors that influence fragmentation threshold
- Verification of pellet heating tests
  - Full integral test at Studsvik or Halden test reactor
  - Opportunity to evaluate packing factor

Together…Shaping the Future of Electricity

Perspective on Fuel Fragmentation and Dispersal During LOCA

Bert Dunn
Advisory Engineer
Lynchburg, VA

AREVA

Introduction

- **Cladding swelling and rupture have been treated by LOCA evaluation models since the 1973 rule**
- **Relocation has recently been covered by LOCA evaluation models**
  - Direct calculation
  - Indirect evaluation of model conservatism
- **NRC is now requiring direct calculation**
- **Dispersal outside the cladding never treated in LOCA models**
  - Most experts agree that fuel particles would be well cooled in the RCS
  - Even if the rupture opening is large, the fuel assembly geometry will essentially limit the dispersal to fine particles
  - Studies should continue but with reasonable boundary assumptions

Observations

- **AREVA mostly agrees with NRC Research on fuel dispersal**
- **The concern may be largely an artifact of conservative modeling**
- **Realistic evaluations for BWR show no rupture**
- **Mean PWR RLBLOCA results**
  - Cladding 1500ºF
  - Embedded conservatisms > 200ºF
  - Expected true mean < 1300ºF
  - No cladding rupture
- **Probability of LBLOCA is low**
  - NRC effort to remove from design basis
  - With the low probability of the event combined with that of rupture, the probability of dispersal is very small

AREVA Perspective

- **The opinion is that only limited amounts, nearly all fine particles, will be dispersed into the RCS.**
  - Fine particles will flow within the RCS and be cooled effectively
  - Limited dispersal of larger fragments, if trapped in the assemblies, can be cooled there
  - Only large accumulations would pose a significant risk of over heating
- **Fuel dispersal requires a LBLOCA – Low probability**
- **Modeling using currently available data may lead to extreme conservatisms**
- **Conclusions regarding fuel dispersal should await further studies and evaluations of the potential impacts**

AREVA

Acronyms/Nomenclature

LBLOCA	Large Break Loss of Coolant Accident
LOCA	Loss of Coolant Accident
RLBLOCA	Realistically Evaluated LBLOCA
NRC	Nuclear Regulatory Commission
PCT	Peak Clad Temperature
PIE	Post Irradiation Examination
RCS	Reactor Coolant System