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NUCLEAR REGULATORY COMMISSION

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ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

(ACRS)

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SUBCOMMITTEE ON MATERIALS, METALLURGY AND

REACTOR FUELS

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TUESDAY, JANUARY 14, 2014

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ROCKVILLE, MARYLAND

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The Subcommittee met at the Nuclear Regulatory Commission, Two White Flint North, Room T2B1, 11545 Rockville Pike, at 1:00 p.m., J. Sam Armijo, Chairman, presiding.

COMMITTEE MEMBERS:

J. SAM ARMIJO, Chairman

RONALD G. BALLINGER

JOY REMPE

PETER C. RICCARDELLA

MICHAEL T. RYAN

STEPHEN P. SCHULTZ

GORDON R. SKILLMAN

NRC STAFF PRESENT:

ZENA ABDULLAHI, Designated Federal Official

BOB EINZIGER

MICHELLE FLANAGAN

RICHARD LEE

MERAJ RAHIMI

PATRICK RAYNAUD

HAROLD SCOTT

A G E N D A

P R O C E E D I N G S

1:00 p.m.

Opening Remarks and Objectives

CHAIR ARMIJO: 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.

ACRS members in attendance today are Dick Skillman, Steve Schultz, Ron Ballinger, Mike Ryan, Joy Rempe and I suspect Dr. Riccardella, Peter Riccardella, may come in a little bit later. Zena Abdullahi is the Designated Federal Official for this meeting.

In today's meeting, the Research staff will brief us on ongoing research in the area of reactor fuels, and the purpose of the meeting for the Subcommittee is to aid in the -- to get information to aid us in writing up our biannual safety research report for the Commission.

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

This is an open meeting, and we have open telephone bridge lines. However, to minimize disturbance, the line will be kept in a listen-in only mode. The Designated Federal Official will check and inform the chairman if we have people who want to speak to us on the bridge line.

I will now proceed with the meeting, and I call upon Richard Lee, Fuels and Source Term Code Development Branch chief, to begin the presentation. Richard.

Staff Opening Remarks

MR. LEE: Thank you, Sam. We're glad that the staff can talk to you about our fuel research today. I prepared this overall chart to show you how all the fuel research, which is -- okay. This doesn't work any more. Okay, never mind.

On the left hand side, you will see that those are the programs that we have over here, and today concentration is discussion about the research program. This is not to -- for example, the box will show you what program we have, and what are the major outcomes from these programs, and how it got fed into the course of validation, and this side of the chart shows you all the applications that span over the NMSS and NRO.

But today's information is not to discuss the applications, because there are other focus meetings that you have. For example, fuel disposal was discussed last month, and I'm sure in the future you will see the extended storage and all these other things. Especially in the high burnup area that is our focus at this time, and those will be discussed at appropriate times.

So today, we'll be focusing on these programs, and as you know, some of the program is no longer exists. We just left in here, for example, the Kurchutov Institute that we collaborated with Russians long time ago, that produced a lot of information that we needed for the 10 C.F.R. 50.36 rulemaking stuff, much earlier back in the time John Mobeley (phonetic) was still here, but he retired.

But also show that is the, for example, the Japan Tokai facility, which is the JEA, we have extensive engagement with them, and for a while we lost, since the Fukushima accident we lost the contact because they are dealing with the recovery of the facilities.

But we are start to engage with them fully now, and also with the GNES, which is formerly NUPAC (phonetic), and GNES facilitators yesterday and the facilitators are here today listening to the presentation.

CHAIR ARMIJO: Richard, just a quick

question. Did the test reactors in Japan, were they also shut down as a result --

MR. LEE: I believe that they came back up on 9/9.

CHAIR ARMIJO: Yes. So NSRR is operational?

MR. LEE: Back online.

CHAIR ARMIJO: Okay.

MR. LEE: As far as we know. That's what the JEA representative told us recently.

CHAIR ARMIJO: Okay.

MR. LEE: You read in the media that JEA is going to be conducting some experiment on severe accident. It's a single-rod thing. Just wanted to let you know that this is really -- they tried to develop the staff expertise in conducting severe accident research.

So it was nothing has to do with giving you new idea or severe accident or anything. This is really building up capability within the JEA to conduct severe accident experiments.

MEMBER REMPE: I thought you brought that up, because I wasn't planning to do that today. But isn't that a bit different for them to be doing things with prototypic uranium dioxide in the tests over there, and then do they plan to go further and have additional tests?

MR. LEE: Yes. There is a plan that span out to, you know, a five-ten years long term plan, with increasing difficulties in looking at severe accident melt progressions.

MEMBER REMPE: So you think they will actually go and do something with like a core plate or something with a full assembly?

MR. LEE: Yes. Last August, a JEA representative came to Sandia and discussed what Sandia back in the 90's on the severe accident melt progression. They want to take that further in looking at the reactions of the melt in the lower plenum parts.

MEMBER REMPE: Good.

MR. LEE: But that will require a lot of expertise in development. We are continuing to engage with them. So I just wanted to let the committee know that in that area, yesterday GNES came to discuss about the LOCA criteria. So we will be engaged on severe accident, as well in every area.

MEMBER REMPE: At the beginning of the Materials presentation, Mike mentioned how his budget has gone down and --

MR. LEE: Mike who?

MEMBER REMPE: Case.

MR. LEE: Okay.

MEMBER REMPE: And he was saying that he can't --

MR. LEE: He the most budget in our --

MEMBER REMPE: But he was saying that he couldn't --

(Laughter.)

CHAIR ARMIJO: He didn't ask that the Fuel budget be transferred. He's just complaining about his own.

MEMBER REMPE: The question is is are you being able to meet all the User Needs now? Is your budget going down? How is that -- could you give us a similar type of overview?

MR. LEE: Well, let's put it that way. I mean the research budget, in the sense, is shrinking. It's true. For example, the Studsvik program, the Halden programs are increasing. So we had to look at how to cut back and what are the minimum amount we needed to support our regulatory confirmatory research.

MEMBER REMPE: Do you have concerns you're not -- there's certain things you really wish you could do and you aren't able to because of the decreasing budget?

MR. LEE: Well, I think you can play the

budget game either way. Initially, you can have a small budget but when mid-year comes, when my office don't need the money, we get them all. So we can fund a lot of things afterwards.

MEMBER REMPE: Okay.

MR. LEE: We'll continue to do that.

CHAIR ARMIJO: It's the way of life with R&D people. You're always fighting the budget problem, and you always find a way to get the most important stuff done.

MR. LEE: And for example, the FRAPCON, I wrote maintenance, but there's some development going on that Patrick is also taking an in-house development, in conjunction with the contractors. So that also save some money on that aspect.

And then if the -- in the fuel disposal are as you heard previously, we are developing the interface between TRACE and FRAPCON ourselves, so that doesn't require external help. That's also true in the severe accident area. We do a lot of in-house analysis and jointly with the contractors.

CHAIR ARMIJO: Right.

MR. LEE: That's included in the Level 3 PRA analysis. We are doing a lot of the in-house analysis supporting DRE.

CHAIR ARMIJO: Good.

MR. LEE: So they should be transferring money from those two divisions to us.

(Laughter.)

CHAIR ARMIJO: That's one reason why we're supposed to stay out of money concerns, so the ACRS --

MR. LEE: If you have no more questions, they can start talking about these programs.

CHAIR ARMIJO: Okay. Are you on Michelle?

High Burnup Spent Fuel Fatigue Testing

MS. FLANAGAN: Yes. So I'm going to be giving this presentation jointly with Patrick, and because the topics kind of go between, Patrick and I will just handoff throughout the presentation on each topic.

CHAIR ARMIJO: Okay.

MS. FLANAGAN: So my name is Michelle Flanagan, and I work for Richard Lee in the Office of Research, Division of Systems Analysis, Fuel Source Term Code Development Branch, and we're going to be presenting a number of programs. The agenda includes all of the topics and they're listed here again, but I won't go into much detail, because we will be discussing each as we go on.

CHAIR ARMIJO: Sure.

MS. FLANAGAN: The first research program that I'll summarize is having to do with High Burnup Spent Fuel Fatigue Testing for Transportation applications. So this slide provides a lot of detail about what we're trying to accomplish, which is to understand how vibration normally incident to transport is accommodated by high burnup fuel.

It's a very complex question to answer. There is the cask itself is going to experience a certain input vibration from the transport, either the truck or the rail, and that is transmitted in some way to the fuel assemblies, based on the cask design.

Then each fuel assembly is designed slightly different, and can have each fuel rod experiencing a different load. This oscillation is transferred to the fuel elements in a different way. The fundamental property that we're looking at is on a fuel rod basis.

So we are looking at the number -- the number of cycles to failure at a number of stress levels, to develop I wouldn't say a fundamental mechanical property, because it is a system of fuel and cladding. But it is a measurement of the SN curve for a high burnup fuel material.

This is all because the regulations require that vibrations only incident to transport (phonetic) is analyzed, and that the casks are analyzed to understand the impact and the fuel under these conditions.

CHAIR ARMIJO: Now what have people been doing up to now, who have transported fuel? They've used some sort of a rule of thumb or --

MS. FLANAGAN: So I'll get into a little bit -- or maybe I don't have a slide on that. But the loads that would be seen on much lower than the yield stress. So typically the argument is made that the stresses are so far below yield that vibration isn't an issue.

However, with high burnup fuel, there's other aspects that probably need to be investigated integrally. So not just as a mechanical property of the cladding, but because the fuel and the cladding start to act as one unit, there's a question about how high burnup fuel responds.

And NMSS staff is here to answer more specifics. So I don't want to get into it too much. But the --

CHAIR ARMIJO: Okay. So are you going to be working on something, not just the material properties of high burnup cladding or is this a deposit of bonded fuel? Or is it -- I'm trying to understand what the scope of that is.

MS. FLANAGAN: The scope of this research is to look at a segment of high burnup fuel, which has the fuel in it. It's high burnup cladding. It has very high hydrogen contents. We're looking at the higher range of hydrogen contents, and we're looking at the higher range of hydrogen contents and not side layers.

And the material is tested as a system, a fuel cladding system, and part of the reason is that we want to understand the actual contribution of the fuel to the fuel rod stiffness.

So a lot of the codes that are used to answer this question now look at cladding properties, and they -- there's very little understood how about how the fuel actually interacts with the fuel rod. So this program will also provide insight in that area.

CHAIR ARMIJO: Got it.

MS. FLANAGAN: So the objective of this research -- sorry. Okay. The objective of this research program is to look, to develop a HN curve for high burnup spent fuel, and also to look at the contribution of fuel in a fuel clad system.

In order to do this testing, there was a number of challenges that had to be overcome. We did not want to create a gauge section on the samples.

We wanted to leave the fuel rod intact, which meant that we couldn't machine it in any way. So in order to have a valid test that fractured in a location that we could, you know, use for analysis, we had to develop a very innovative test apparatus.

In addition, it's high burnup fuel. It has the fuel still in the cladding rod. So this is a very high radiation environment. So there was a number of challenges just to develop a piece of equipment that could handle that, the exposure of the sample, and also high burnup fuel is very expensive.

So we wanted to look at small segments, and we weren't able to test an entire fuel rod or an entire assembly. So there was a number of challenges that we had to deal with, and this slide summarizes a couple of them but --

MEMBER SKILLMAN: Michelle, before you proceed, let me ask this. Your opening comment is that the goal of this is to produce an SN curve.

But an SN curve for a BWR fuel assembly might be very different than an SN curve for P, because the spacing can be different. There might be differences in spatial grids and in the clamps, in the way the internals of the fuel assembly attach to each other and the rods, the tie rods.

So the question is why choose an SN curve versus something that might be more generically appropriate? It seems to me an SN curve must be very highly specialized for a particular fuel design, fuel type and maybe burnup, whereas another parameter, such as maximum g forces, maximum lateral forces, the function of burnup-weighted impact forces, might be more appropriate for where I think this is going. That is, how do you move this old stuff around?

MS. FLANAGAN: Right. My understanding is that there's two aspects that I'll say. One is that the intention of the program was to characterize a portion of the fuel segment, and many of the questions that you're asking about the effect of the grid space or span or the spacing between fuel rods, all of that is handled through finite element analysis, after the SN curve is available.

So it's treated analytically, when you model -- when you take the fuel segment property and then scale it up to the impact on an assembly, and then on the cask. Another thing I'll say is that even -- although it's to develop an SN curve, but it's also -- it's more to develop a methodology to generate an SN curve.

So if we complete the program and we say that we've gotten valid results. We understand this particular cladding better, and we need to know more about, for example, other burnups or other claddings, then we've validated a method of making this measurement, that then can be used to test other materials.

So there has been discussion about what we'll need to do once we complete the scope that we have in mind now. First, we have to make sure we can even do that, that we have a valid apparatus, that we trust the results, we can interpret them and we can use them.

MEMBER SKILLMAN: Yes. So basically, you're going to come up with an SN curve for a segment of fuel plus cladding, high burnup, and then you're going to separate the effects of the fuel from the -- just the cladding itself, so that to see if you -- the assumption that the fuel makes a big difference is just an assumption.

So you're going to have to -- is that what you're trying to sort out, to make sure that you could just use the cladding properties possibly?

MS. FLANAGAN: Yes, that's one of the aspects, and actually there's some static testing that would probably give more insight into the effect of the fuel itself. But yes, that's -- those are the two sides of the investigation.

CHAIR ARMIJO: Well, I could see where the fuel could have an effect, if it's bonded for example. But I'm not sure all the fuel behaves the same way. There will be some fuel that's got bonded areas, some fuel that doesn't. So your sampling is going to be critical, that you know what's inside the segment you're testing.

MS. FLANAGAN: Yes. Oak Ridge has also done some work to study simulated materials, and doing finite element analysis, to look at the effect of, for example, pellet-pellet interfaces, or the extent of the fuel cladding bond. So even if this sample size is very small and specialized, there's work to understand a larger segment from complimentary work.

MR. EINZIGER: Yes, a couple of things. I think that you have to go back to really why we're doing research, and we're not doing research to solve the problems. That's the applicant's job. We're doing research to find out if there's a problem, or if there's an acceptable way that we'll accept a solution from.

So this is part of the reason that we're testing the -- just the one fuel. You're right, it may be completely different from the BWR fuel. But if we find out that hey, this method is a good method, and it gives results that indicate that the fuel probably would be in good shape after a number of cycles that we think exceeds transportation, then somebody else DOE or the applicant, if they're using a different type, are going to have to come up and develop that for that particular type of cladding.

Also, this was, as Michelle indicated, there was two purposes. One was to look at the interaction of the cladding with the fuel, which was the static part, and we found out that there are some things that we have to take into account in the modeling.

For instance, the few samples that we have been able to fracture always occurred at the pellet-pellet interface, which indicates there's something going on with the stresses in the cladding that weren't taken into account just by -- when we were looking at it.

MEMBER SKILLMAN: Thank you.

CHAIR ARMIJO: Thank you.

MS. FLANAGAN: So the two pictures here show the apparatus that was developed, and this was taken before the device went in-cell. So in order to make suer that the device was actually going to produce some valid, a valid result, there was a lot of benchmarking that took place out of cell with surrogate materials.

The surrogate materials that were used were either stainless steel cladding with aluminum pellets, sometimes a single rod and then sometimes segments of pellets to simulate pellet-pellet interfaces. And then some zirconium cladding was also tested.

But the main purpose was just to test out this device that's first of a kind, subjecting the rod to a pure bending moment, and I say "pure bending" because the sample is loaded into the apparatus in this orientation. Right now we're looking down from above on the device, and this is a side view where the sample is shown here, and the sample can move laterally, and bending is induced by these --

CHAIR ARMIJO: Is it like four-point bending or two-point? Four-point bending? Okay.

MS. FLANAGAN: It folds along a length, a span, in order to induce the bending. So there's not four points, but it would produce the same type of effect, and because the sample can move horizontally, there's no load as the bending --

CHAIR ARMIJO: No axial load?

MR. RAYNAUD: There's no axial, right certainly.

CHAIR ARMIJO: Got you, yes, yes.

MS. FLANAGAN: There's no axial load as the sample is bent.

MEMBER RICCARDELLA: But it's held ridges, like fixed-fixed bending, like that?

MS. FLANAGAN: There's bearings that all of the sample ends can move this way.

MEMBER RICCARDELLA: Yes, I understand

that.

MS. FLANAGAN: But other ways --

MEMBER RICCARDELLA: How is bending imposed?

MR. RAYNAUD: Essentially, the sample is encased on these grips in a way that allows it to move actually if need be. But there's sufficient gripping of the sample that when you pull here, these arms move out.

MEMBER RICCARDELLA: Yes, okay.

MR. RAYNAUD: And the sample is then bent this way and then you push in. These arms move in and then you bend it the other way. So we have full reverse bending of the sample.

MEMBER RICCARDELLA: And with the grips, you're simulated and fixed-fixed end condition, but one of them's on a roller base?

MR. RAYNAUD: That's exactly right, yes. That's correct.

MEMBER RICCARDELLA: It's really hard to understand that. It would be nice to have a diagram.

MS. FLANAGAN: I know.

MR. RAYNAUD: It's a very bulky apparatus, and unfortunately there's not a very good view port for the sample.

MEMBER RICCARDELLA: And is the load with those actuators, is it like pushing -- those actuators are pushing or rotating?

MS. FLANAGAN: They are pushing and pulling.

MEMBER RICCARDELLA: Okay, got it.

MS. FLANAGAN: And these were chosen because of their high frequency capability. So the tests that we conduct are five parts of cyclic loading.

MR. LEE: And this is in the hot cell too?

MS. FLANAGAN: Yes. On the next slide, I'll show that.

MEMBER RICCARDELLA: Initially, it wasn't in the hot cell.

MR. LEE: It's always in the hot cell.

CHAIR ARMIJO: So you've done tests with stainless steels and aluminum pellets and --

MS. FLANAGAN: Yes, and for the stainless steel samples, we calibrated the bending moment, made sure that it was matching known fatigue properties of stainless steel and known stress-strain response, so that we were certain that every -- I mean this is a very complicated device, and we wanted to make sure that as we were loading it --

MEMBER RICCARDELLA: Did you strain

gauge the sample?

MS. FLANAGAN: Oh, there's another thing I wanted to point out. Here, there's three LVDTs that are actually touching the surface of the cladding, and the curvature of the sample is measured directly on the sample by interpreting the displacement of each of those LVDTs.

So one of the benefits of that is that it allows us to know precisely the displacement of the sample. It's not interpreted from the displacement up here, going through this whole system and then assumed -- there's no assumptions being made about the displacement.

It's actually measured directly on the sample through radiation-hardened LVDTs.

CHAIR ARMIJO: What's the upper limit on the strain you're going to put on in these tests, well below the elastic limit or --

MS. FLANAGAN: Yes.

CHAIR ARMIJO: Or higher or what?

MS. FLANAGAN: Well I mean for the static testing, we ran the samples to failure. So they definitely exceeded the yield stress and got to plastic deformation. For the cyclic tests, we were originally scaling the cyclic loads to portions of the yield stress.

But actually the yield stress is still much higher than anything. But we were more interested in the very low loading.

MR. RAYNAUD: It's high cycle fatigue.

CHAIR ARMIJO: High cycle fatigue.

MS. FLANAGAN: Yes. So we actually tested at relatively low loads, relative to the yield stress, and the cyclic testing is completed in a load control mode. So load is fixed and then displacement is measured.

MEMBER REMPE: What do you mean by "rad-hardened LVDTs"? What was changed from a normal one? Did you get them from Halden or what did you do?

MS. FLANAGAN: No. They were -- I don't know what's difference. I just know that that caused a couple of months of delay when we had to do it.

(Simultaneous speaking.)

MR. RAYNAUD: I can answer that question.

MS. FLANAGAN: Oh, okay.

MR. RAYNAUD: In some less expensive LVDTs, some components are made of some polymers or materials that are more susceptible to radiation damage over time. So we had to ensure that everything that went into the equipment, including the load cells, I mean we had to spend, you know, quite a bit of additional money to make sure that every component was not susceptible to --

MEMBER REMPE: Why didn't you just go get them from Halden?

MR. RAYNAUD: From Halden?

MEMBER REMPE: Yes.

MR. RAYNAUD: I don't think they sell this kind of --

MEMBER REMPE: They sell LVDTs they use in pile.

MR. RAYNAUD: But don't have their own special design for --

MEMBER REMPE: Yes.

MR. RAYNAUD: They have axial LVDTs that are specially made for their fuel testing.

MEMBER REMPE: They use copper nickel wire and other things. But I mean we don't have to give the details, but I'm just surprised. So you went to an American vendor and they had to do something special --

MR. RAYNAUD: I'm not sure. It must have been an American vendor.

MEMBER BALLINGER: But those polyamide-insulated LVDTs, you can get them from Schaevitz.

MEMBER REMPE: Yes, but they're very large in diameter. The small standard --

MEMBER BALLINGER: Yes actually --

CHAIR ARMIJO: We probably shouldn't be designing --

(Simultaneous speaking.)

CHAIR ARMIJO: We shouldn't be designing your test facilities. That's beyond our scope. But the fact is you've got this thing. It's working on unirradiated materials, and now it's in a hot cell?

MS. FLANAGAN: Right. So this slide just summarizes the work that was done, to make sure that the calibration and benchmarks was something that we were comfortable with out of cell, and then a radiated test matrix was designed. The cladding material that we had available or the fuel material that we had available is Zircaloy.

The burnup is about 65 gigawatt-days per ton, and the hydrogen content ranged from 350 to 750 weight PPM, and that's as a function of the axial height of -- on the, from where the sample was taken. Most of the samples are in the 500 weight PPM range, although there is some variability.

We conducted -- the plan, the matrix is to have five repeat tests, and nine different tests of varying stress levels to look at for deep strength. So that's the testing matrix. The status of the program is that this equipment has been installed in-cell.

It was installed earlier this year. These are some pictures of them loading the device down into the hot zone. This plate that is -- everything is mounted on is extremely heavy. It's quite large, and there was a lot of sophisticated manipulations that had to be made, to actually get it in there.

But it was installed earlier this year, and so far the static testing phase is complete and we're in the middle of the cyclic testing.

MR. RAYNAUD: Just to be clear, it was installed in 2013.

MS. FLANAGAN: Oh yes, sorry.

MR. RAYNAUD: In the late summer or some time in the summer.

CHAIR ARMIJO: Okay.

MS. FLANAGAN: Yes, thank you. I forgot the year.

CHAIR ARMIJO: Now all these were refabricated from full-length rods?

MS. FLANAGAN: Yes.

CHAIR ARMIJO: And that was done at Oak Ridge or--?

MS. FLANAGAN: Yes. Oak Ridge has the ability to accept full length rods, and these rods, I think, were somewhat segmented before they arrived. But the segments were chosen by our program, and we selected exact locations on the rod, and they cut the samples there and prepared them.

So to summarize the conclusions just from this research program, a unique and novel testing equipment, piece of equipment has been developed, and it's going to measure first of a kind parameters of high burnup fuel rods.

This equipment has been extensively tested and demonstrates intended functionality with surrogate materials, and we've made the first static tests and are continuing with cyclic testing.

A final report that will capture all of the test results is expected to be published later this year, and we -- because of the unique and new measurements, we do plan a number of conference papers to really share the results of this work, either through Oak Ridge or NMSS or Research, but sharing the results will be important.

And the work is part of an NMSS User Need. So NMSS is the User and they will be utilizing this in future work that they do.

CHAIR ARMIJO: Yes. One of the things that I worry about on refabricated fuel rods is that the handling and the cutting and -- can, you know, can shake things up mechanically. But also, you also lose all the fission gases and everything else. Did you repressurize them? Are they pressurized, or are they just -- after, there's just seals.

MS. FLANAGAN: They're not even sealed. They're just segments cut from a rod.

CHAIR ARMIJO: Oh they're just cut?

MS. FLANAGAN: Yes.

CHAIR ARMIJO: Okay.

MS. FLANAGAN: And the sample length is six inches, and the gauge section is two inches. So there's two inches on either side that's part of the grip system, or four -- two inches on each side? Total of four inches.

CHAIR ARMIJO: I wouldn't expect that the internal pressure would have much influence on very small cyclic loading, but have you --

MS. FLANAGAN: We've begun to think about that, but I think at this point that's a much more complicated question to answer. So once we actually have the answer for that, we could consider that, see what impact that might have, and see if it's on the order of magnitude that would be significant here.

MEMBER REMPE: We might do the assessment analytically, to see what impact --

CHAIR ARMIJO: Yes. That's what I was

thinking, yes, whether it -- I wouldn't think so, because your strains are going to be -- your displacements are going to be small and the strains are going to be small.

MR. RAYNAUD: Yes, but wouldn't that in effect affect perhaps the interference between the clad and the pellet? You know, if you pressurize it you might --

CHAIR ARMIJO: Yes, yes, it would, but to me, the most thing is that when that fuel is bonded, if you have bonded fuel, it really makes a difference.

Unless it's in the cutting and the handling, you somehow break those bonds in the fabrication, and then you wind up with variability in your test results that could be caused by the way the sample was prepared.

(Simultaneous speaking.)

MS. FLANAGAN: There's a lot of visual examination that's completed after the test, and then also before the test to look, and there hasn't been any indication of damage on the sample that we expect to be coming from the cutting.

CHAIR ARMIJO: Yes. Good.

MEMBER REMPE: So somehow with those examinations, you can see it's still bonded?

MS. FLANAGAN: Oh sorry. I mean on the cladding surface. But there's -- the cladding outer surface.

MEMBER REMPE: There's nothing you can do to check if it's still bonded?

MS. FLANAGAN: There's definitely examinations that we can do, and right now, we're reserving the decisions until after we have some of the test results, to determine where are the areas of largest interest, because those types of examinations are very expensive. So we want to make sure that we're looking at the right section.

So in some cases, that might be near the fracture. In some cases it might be near the end section, where we expect the rod to be intact. So all of that would be decided after the test results are complete, so we know that we're looking at the most interesting spots or welds, so we can make an informed decision about where to look.

CHAIR ARMIJO: I think this is very interesting, but do you know if anyone has ever done this before, tried to do cyclic fatigue tests on actual fuel rods, irradiated fuel rods? I had --

MS. FLANAGAN: My understanding is that it has not been done, and before we started this work, one of the first tasks at Oak Ridge was to do a review of existing -- I mean we started this project with just the objective.

We had no testing device. We had no idea of how to design a testing device that would do this, and so there first test was to look for equipment that could be on the market, that would make this type of measurement, and it was concluded that there was nothing like this. So that's why an R&D effort was designed, just to develop the test device and the methodology.

So there is some work on fatigue properties of cladding itself, some even of high burnup. But to our knowledge, there's no information on fuel and cladding as a system under fatigue conditions.

MEMBER RICCARDELLA: And the fact that somebody mentioned that the failures all seem to happen at the interface between two pellets indicates there definitely is -- there definitely is an effect.

CHAIR ARMIJO: Yes, with stress concentrations and things like that.

MEMBER SCHULTZ: Michelle, do you have pre-test analytical predictions that have been made?

MS. FLANAGAN: There are some that we made just from cladding mechanical properties, but and then some predictions about -- that simulate a combination of the cladding of the fuel. But that was just to make sure that we were designing a test device that would be strong enough. But we don't really make any conclusions about those.

MR. RAYNAUD: The predictions that were made were mainly -- mainly had to do with where the stresses were going to localize, to make sure that we weren't failing to sample an area that we didn't want. We didn't -- at least not that I know of, we didn't make any predictions of what the expected life would be.

I think that was a big unknown because the high burnup fuel, we didn't know if there would be, you know, defects, local defects in the fuel rods somewhere. You can have very stochastic effects in the failures of high burnup fuel. So we didn't even try to speculate.

MEMBER SCHULTZ: Is there any European experience in terms of cyclic fatigue from transportation, that would suggest this is an area we really need to focus on for transportation, cyclic fatigue?

MS. FLANAGAN: To my knowledge, not for high burnup fuel, and that's where the focus of this, is to understand whether high burnup fuel portends vulnerability, and I don't think many countries have started to transfer high burnup fuel.

MEMBER SCHULTZ: And have analytical sensitivity studies been done that demonstrate the effects or something like that that we need to be in tune with?

MS. FLANAGAN: In terms of the fuel itself or the whole system cask and transport?

MEMBER SCHULTZ: Well, I'm just thinking of the fuel itself. Well, within the cask of course.

MS. FLANAGAN: Not that I'm aware of, but maybe Bob is going to answer.

MR. EINZIGER: This is sort of a nascent area. The regulations require that the fuel essentially remain intact under normal conditions of transport, and there's two things that are defined as normal conditions of transport. That's the vibration and the one foot drop, and not much fuel has been transported and actually looked at per se.

It's either, if it's in the -- in France, a lot of it's going to the reprocessing plants, where it's being transported under much higher temperature conditions, and that's one thing Michelle didn't mention.

These tests are being done at room temperature, and of course as you go to higher temperatures, you recover more of the ductility, and so things should be better.

We're sort of trying to -- we're feeling our way on this one. The Japanese have done a little of vibration testing, but they were mainly looking at seals on casks. We haven't found very much on the vibration testing, and it's a matter of seeing like we never really expected a particular location for failures.

When they did the first test after the static test, they were down in the elastic zone, well down. We got a failure at an impulse that was -- so we never expected the failure. So we're learning as we go along, and one thing I want to mention, this is an easy test to build a cheap piece of apparatus and get data out that's not good.

It's a hard test to do and build there apparatus to get data out that's really good, and Michelle and Pat and Gordon and the people at Oak Ridge have spent a lot of time each step of the way, making sure that the data they got out was really the data they thought they had, and that went to both analysis and development of the grip, so it was -- they knew what the forces.

So this was not a cheap test, but we were confident in the data.

MEMBER SCHULTZ: Thank you.

CHAIR ARMIJO: Okay. Well look. This is very interesting, but I think we have a lot of projects that we'd like to hear about. So I think we have to move on.

Consequences of Failed Fuel in Transportation

MS. FLANAGAN: Okay. So the next program that I'll talk about, it's hard to say whether it's related, but really it assumes that the properties of high burnup fuel are difficult to quantify, and there's the possibility that during long-term storage or during transportation, the question is asked what if the fuel does fracture and we have some reconfiguration within a transportation or storage cask? What would the consequences be?

So this program assumed there was -- it did not consider specific modeling of fuel and known mechanical properties. Rather, it assumed that reconfiguration was possible, and then assessed the four technical disciplines: criticality, shielding, containment and thermal.

There was a number of specifically realizable scenarios that were analyzed, but there was no -- like I said, there was no -- there was no study about which of these scenarios was basically possible with, for example, a finite element analysis, looking at mechanical properties and expected loads, then a comparison, and then a demonstration that these scenarios would actually take place.

So it was just assuming that they would, and then looking at the consequences. There was three groups of fuel configuration that were considered. The groups were cladding failure, rod assembly deformation without cladding failure, and then changes to assembly axial alignment within the cask and without cladding failure.

Within the cladding failure category, both breached spent fuel rods, so small pinhole fractures, and damaged spent fuel rods were considered. Damaged spent fuel rods spanned the range of a couple of fuel rods falling to the bottom to just rubbelized fuel.

Within the fuel rod assembly deformation category, both side drop and end drop configurations were model, and then the difference -- the side drop, simulations pictured all of the rods clumping together. In the end drop, some bird cage geometry was considered to look at, cladding fuel rods moving away from each other.

And generic PWR, PWR transportation and storage cask models were used that had been developed from previous studies, and they were adapted for use in this study.

So the status of this project is that the analysis has been completed for both BWR and PWR transportation and storage cask models, in the areas of criticality, shielding, containment and thermal.

A final NUREG CR was delivered to NRC back in August, and this NUREG CR is currently under review in the User office, which is NMSS, and we expect that the publication will be later this year.

And we've discussed with the NMSS staff that they may discuss the results and implications at the regulatory information conference this year, as part of their presentations. So that's all I have for this topic. I mean I'm just presenting the status of where we're at.

Ductile to Brittle Transition Temperature

So I'll go ahead and move onto another research project. This research project is complete. This is work that was conducted at Argonne National Lab, and in the tests that Argonne conducted, they were reoriented hydride.

So they were taking high burnup fuel and pre-hydrided fuel that was -- where the hydrides were formed in a circumferential direction, and then they subjected them to temperature and pressure conditions and that reoriented the hydrides in the radial orientation, and then did a number of ring compression tests to evaluate the ductility of the reoriented samples.

Let's see. I'll guess I move on. So in this slide, I'll just say the conclusions that were reached in this program, although I will point out that this work has been published as an original research article in the *Journal of Nuclear Materials*, and if you have interest, I think it's a very good article that summarizes much more than I'm going to show here.

Two of the important conclusions were that pre-hydrided cladding was a poor surrogate for high burnup cladding materials, with respect to the effects of simulated dry storage conditions, and that's because the distribution of the hydrides across the cladding thickness actually plays a role in the mechanical properties.

So when you pre-hydrided the material, it did not simulate the actual morphology that you would find in a high burnup sample, and this was important, because you know, obviously pre-hydrided materials are much cheaper to work with. So the testing programs that are exclusively pre-hydrided can be misleading. So this was an important conclusion.

Another conclusion was related to a parameter called the radial-hydride continuity factor.

So this was a parameter that Argonne identified would indicate the extent of the connection between radial-hydrides, and that they found was correlated well to the ductile to brittle transition temperature.

CHAIR ARMIJO: What's the definition of this radial-hydride continuity factor? What does it represent?

MS. FLANAGAN: It's the ratio between the cladding thickness -- or not the cladding thickness, because it's not considering the oxide layer. But the cladding thickness minus the oxide layer, in the ratio with the longest, continuous radial-hydride. Is that what you would say Harold?

CHAIR ARMIJO: So short radial-hydrides that were not connected would have --

MR. SCOTT: The idea was there was a certain degree. In other words, if you look like 15 degree angle, can you reach another radial-hydride? So if I have a radial-hydride that goes halfway through, and it can't jump to another one, then it has a low continuity factor if there are lots of hydrides.

CHAIR ARMIJO: You're trying to assess just how radial is radial?

MR. SCOTT: Yes, and that's --

CHAIR ARMIJO: It's kind of hard to do.

(Simultaneous speaking.)

MR. SCOTT: --important then, because Zirc-2, Zirc-4 behave differently.

MS. FLANAGAN: Yes, and as Harold mentioned, that was another important conclusion, is that there was -- because this factor played a big role in the ductile to brittle transition temperature and it was different, depending on the cladding and the heat treatment and the hydrogen content, that it's very material-specific, and it's not something that's just a function of the hydrogen content. It's also a function of what alloy you're talking about.

And then this work is also being conducted now under a DOE program. So DOE has continued the same test methods and apparatus, and they now fund the work. So this -- with respect to NRC's funding of this, we are now complete with this research project.

CHAIR ARMIJO: Okay.

MEMBER SCHULTZ: Michelle, could we back up a minute to the conclusions of the last presentation? You indicated that there's no draft information available on the NUREG CR related to the consequence assessment of fuel failure on spent nuclear fuel dry storage transportation packages, and that they evaluated criticality, shielding, containment, thermal evaluations.

Again, we've had a consequence assessment. This last year, the staff presented results about transportation accidents or spent fuel canisters, which demonstrated the consequences were extremely benign, and presented that to us. If there's any different results that are being presented in this NUREG that's under review, they're significantly different, because you're looking at high burnup fuel.

I would suggest that we need to know about that now, and if they are significantly different, I wouldn't think that the regulatory information conference is the time to drop it out and say oh, we found something significantly different than what we found last year.

MR. LEE: This was asked by NMSS. So the staff did present you the other results and knows everything about this study. So there shouldn't be any divergence in it.

CHAIR ARMIJO: Well, let me ask you. Did you find any big surprises?

MR. EINZIGER: These two things are really not related. The other study, the sister project, was to look at what could be the consequences of an accident, based on looking at the conditions of the accident. This particular study is saying okay, we don't know whether an accident can cause these fuel redistributions or can't.

We're going to assume, and we're going to look at the consequences of that. That's not to imply that these conditions are actually going to happen, because the sister study is showing in all likelihood that they're not going to happen.

We're just looking at if you can't show analytically, because you don't have the mechanical properties of the cladding, which the next study was looking at, what the configuration is going to be the configuration is not going to be, and you go to a worse case, is there an issue, and this study is showing that there probably isn't.

MEMBER SCHULTZ: Okay, thank you. Pardon the interruption, but I needed to clarify that. Thank you.

MR. LEE: Meraj, you wanted to say something?

MR. RAHIMI: Just I wanted to elaborate. When we set out the high burnup issue, we wanted to go two routes, you know. One is the testing; the other one did a consequence analysis, and it's true.

The consequence analysis is that given that there's the base configuration, the fuel has reconfigured inside the cask, the separate study that you are mentioning too, that's about the probability the cask is involved in an accident, and you know, the containment is leak-tight, can water get in.

But here it's assuming, according to regulatory conditions, 71.55, assuming there is a water moderator inside the cask, if the fuel reconfigures, what is the consequence? Is there a criticality? What is the K effect as constant of reconfiguration? That was on the criticality.

So from given an accident, given there is a water intrusion, now if you don't know about the mechanical properties of the fuel cladding, high burnup cladding, and assuming this thing reconfigures, do you still need the regulatory safety requirement? I mean that's what we're trying to show, that even if all these things happen, do we still meet the 71.55, the criticality safety requirement? So that's how we approached it.

MEMBER SCHULTZ: And again, if you have found that we do not, then you need to know that now. It's a significant issue. We don't want to have a discussion about that at the regulatory information conference.

MR. RAHIMI: Yes, yes. We are going -- right now, we are trying to get the results, you know, from the research and actually we are having a meeting and we're putting out the strategy on licensing high burnup casks, both storage and transportation.

So we'll be more than happy how this result plays into the strategy, the licensing strategy that we're putting out.

MEMBER SCHULTZ: High burnup fuel has been loaded into casks.

MR. RAHIMI: They have, but they have not been renewed. They have not been transported. Those fuel have been in storage, high burnup. We have not issued licenses or certificates yet, for those casks that have been loaded with high burnup fuel, the high payload casks.

But we've got right now two or three renewal application for those high burnup fuels in storage, and we've got two or three applications for transporting those high burnup fuels. So all these results are going to feed into our licensing strategy.

CHAIR ARMIJO: Well, I think it's a topic that the ACRS -- if there is something controversial coming out of this.

MEMBER SCHULTZ: And I don't know.

CHAIR ARMIJO: I don't know either. So that the --

MEMBER SCHULTZ: I get a little nervous when we say we've tried to identify if there is a possibility of a configuration, where we would load it with water, the canister would have a criticality potential.

CHAIR ARMIJO: Right, and there is ways that you can configure stuff, if you work hard enough, to make, to create problems that won't happen in reality.

That's of course a concern. And so, you know, I think as early as you can, the staff should talk to the ACRS with the results on this one, because we sure wouldn't want to be learning about the results --

Well maybe we've got to make a request right now. Let's get, you know, the findings, your conclusions and findings before the RIC. We will not try to publish ahead of you. We sure want to know. Richard, that's a request to you and your manager.

MR. LEE: I think that's -- the User office has to be involved with this.

CHAIR ARMIJO: No, I'm making the request of the NRC staff.

(Simultaneous speaking.)

CHAIR ARMIJO: Because if you found

something very interesting. If you have confirmed that there's likelihood that there's no problem, the consequences are no problem, that's great to know. If you found something yes, under these conditions, we could have a criticality and they're not so --

MR. LEE: I just wanted to let you know that this -- the likelihood is a very, very small probability.

CHAIR ARMIJO: I know.

MR. LEE: But 10 C.F.R. 71.55, as Meraj mentioned, requires you to have water ingress into this containment canister, in order to do --

CHAIR ARMIJO: It's the same sort of situation we've gotten into with expedited fuel transport. Likelihood is very low; consequences can be very high. But it turned out that they weren't. The final risk is extremely low.

So I think it would, you know, at least for this Subcommittee, I'm requesting that the staff please provide us with their findings from this study.

MR. LEE: You have seen the EPRI study back in December 2006 --

CHAIR ARMIJO: My memory doesn't go back that far.

MR. LEE: But they have published, the industry has published. So EPRI has studied this issue as well, and back about maybe five, six, seven years ago, NMSS has also did a smaller study. But this is a much more comprehensive study. All four items, as Michelle mentioned.

And just remember this also, making an assumption about misloading. So you have sufficient excessive activity in order to create criticality. So you have additional of just the loading. You have misloading in the cask. So there are many assumptions in this.

CHAIR ARMIJO: Well it's, you know, we've just gone through a process where we've evaluated, you know, the regulatory analysis, have used so many conservative assumptions it creates a problem which is really not real, and I'm getting the impression that that's --

(Simultaneous speaking.)

MR. RAYNAUD: --the results, and our User office will make use of it, as you mentioned, about these so-called strategy.

CHAIR ARMIJO: Yes. Well, I think we're going to have some problems. But again, I'm repeating the request, and Zena, if you'd follow up with that. Let's move on.

Extended Storage of High Burnup Fuel

MR. RAYNAUD: First of all, forgive me for coughing and so on, but I'm fighting a cold --

CHAIR ARMIJO: No, you're given.

MR. RAYNAUD: And I got something there for a minute. So the next topic has to do with extended storage and the cladding stress that can develop during extended storage.

The issue that we're trying to tackle here is that there's a possibility that during extended storage stresses, sufficient stresses could develop in the cladding, to lead to either creep failure or a delayed hydride cracking type of failure.

To know if that will or will not happen, we need to determine what the stresses are going to be in the cladding over the period of extended storage. Some of the proposed sources of stress that we are looking to evaluate are plenum gas pressure and the fuel pellet swelling due to helium decay and the damage that it causes in the fuel pellet.

This is part of the NMSS User Need 2011-002, and the three main items in the scope of this particular task are to determine first the evolution of stress and the cladding as a result of only changes in rod internal pressure. Then we will look at the extent of pellet swelling over the time of extended storage, and combine then those two sources of stress to determine whether we might have any creep failures or sufficient stresses to cause delayed hydride cracking.

The first two phases, which have to do with rod internal pressure and then determining how much pellet swelling will occur are completed, and I will talk about those in just a second. The third phase of the program is still in progress.

This slide essentially shows a summary of the results of calculating the cladding stress over a very long period. You can see here it goes way beyond the postulated period of extended storage. We went out to 2,000 years, and we're looking at the cladding stress as a result of increases -- increasing gas pressure in the rod, due to simply decay of fission products.

So mainly what we're talking about is additional helium, as well as some others, but helium is the dominant gas here. We used origin calculations to determine what the gas production would be over the period of time, and then because we don't know how much of that gas will be actually released from the pellets to the void volume on the rod, we did the two bounding conditions.

Either none of it is released or all of it is released, and so here the stresses are shown in the hoop, axial and radial direction for both the case for where none of the gas is released to the plenum and the router to the void volume, and where all of it is released.

What you can see is that even when all the gas is released, which is the "worse case scenario" for this particular assumption, the stresses still decrease over time and relatively rapidly in the first 100 or so years, and that is mainly because of the temperature decrease in the canister, and you're not producing enough gas overcome the pressure decrease related to the temperature decrease in the canister.

So the conclusion was that gas production alone is not going to be enough to cause significant stresses in the fuel rod, that would cause concern. The next phase --

MEMBER RYAN: Is that a fairly rapid decrease?

MR. RAYNAUD: In the gas pressure?

MEMBER RYAN: Yes.

MR. RAYNAUD: Yes. You can see here, I mean of course the scale goes very far, but it happens in the first, you know, decade you already have a significant decrease, sort of how it was when it was first --

MEMBER RYAN: Other aspects of the storage system are okay in the first ten years, and expect nothing, you know, really improving the overall profile by having the gas pressure. Have you looked at that kind of time-dependent dynamics?

MR. RAYNAUD: You mean how the temperature changes in the system?

MEMBER RYAN: Well, the whole system changes, not just temperature, but what reacts to that, what does the metal do, what's corrosion doing, is it coming in? You know, there's a lot of phenomenon and factors that impact the system behavior. We're just trying to get a little bit more in-depth and a feel for that.

MR. RAYNAUD: The answer to your question is no. Here we're really focused only on one fuel rod essentially. You know, there's a very wide range of what the fuel rods might look like when you put them in the canister initially.

So I did so some studies looking at typical power histories and typical burnups, and sort of I did this analysis for the worse case scenarios that I came up with, with the smallest void volumes and the highest rod internal pressures that you would obtain from normal variation from the sort of standard power histories found in the industry. But beyond that, no, we're not looking at any other sensitivities that you're mentioning.

MEMBER RYAN: Thank you.

MR. RAYNAUD: The second phase of the program was to look at the impact of fuel pellet swelling on stresses, and the first step in that is to determine how much swelling is going to occur over a long period of storage.

So I pulled a large literature survey to look at studies of fuel pellet swelling over time. Many of these studies are performed with -- it's accelerated aging. So they'll build pellets with plutonium-238, for example, with strong alpha emitters, or americium and so on.

And they measure the swelling of these pellets over time. There's a lot of studies out there, and they all agree on this, that swelling will saturate over time, and the saturation values are typically between .03 percent and .45 percent. This is lattice swelling.

So you have to multiply that by three to get the volume increase. So one to one and a half percent volume increase roughly would be the saturation values. Some of the studies already provided correlations to fit their data. Those that didn't, I fitted the data based on accepted equations in the literature, and I then proceeded to get -- take an average of all of those to get what I will call my best estimate swelling, for what that's worth.

Then I also took the bounding curve, and we will do the stress analyses for both the best estimate and the bounding cases.

CHAIR ARMIJO: So you'll start out with some sort of available free volume in the rod, where -- which whether it can accommodate this one percent of swelling and stresses?

MR. RAYNAUD: Like my strategy is to use the FRAPCON fuel performance code, which I'm in the process of modifying, to try to make it do these poster radiation calculations, and so you model the steady state of radiation first, and again I'm taking the worst case scenario that I could find.

So I'm using a pretty aggressive power history, which would give me a lot of gas in the rod. So pretty high pressures, and small volumes. So I'm taking the rods that have the highest pressures to begin with and some of the smallest void volumes that are available, and then I will add to that the swelling of the pellet and see what stresses are calculated in the cladding.

MEMBER RYAN: Patrick have you formulated

-- is this formulation study in a report yet?

MR. RAYNAUD: Not yet. I've written a couple of, you know, two-page progress reports for NMSS, but it's only internal. I mean I will produce something when it's all done, to summarize it.

MEMBER RYAN: My eyes aren't good enough to catch up.

MR. RAYNAUD: Yes, I'm sorry. I realized that.

Okay. Well, I hope so. For now, this is just to show that really there's a lot of literature, and in fact here is only shown what I consider valid data for this study. There's a lot of studies that are just plutonium and americium.

I threw that out, because americium, you know, we're talking 20-40 percent americium. That's not typically what you're going to see. So I tried to keep only UO2 and uranium-plutonium mixtures.

MEMBER REMPE: So this morning, they talked about incomplete drawing, and so in your worse case or one of your sensitivities, are you going to look at the presence of moisture and net effects, any effects it might have on the cladding?

MR. RAYNAUD: That is not planned. I mean if the cladding is breached, which is not the assumption here, and there's moisture in the canister, then oxidation of the fuel will lead to a lot more swelling than we're talking about here is my guess. So that's not part of the scope of this work.

CHAIR ARMIJO: Well just as a ballpark, one percent volumetric strain, accommodating that doesn't seem like a great challenge, unless the cladding is extremely brittle.

MR. RAYNAUD: Intuitively, I would perhaps agree with you. But I don't think we can say for sure. I mean there is some voiding --

CHAIR ARMIJO: You've got to do the analysis. All I'm just saying, I'm just -- if it was -- if your analysis had shown up, it would get up to 5, 10 percent, I'd say well, it's getting pretty -- it's pretty bad news. But --

MR. RAYNAUD: I mean, you know, here it's volume that really what we're looking is probably radial stresses are going to be the worse, and I mean circumferential stresses. So radial expansion of the pellet.

CHAIR ARMIJO: And this happens very, very slowly.

MR. RAYNAUD: It does.

CHAIR ARMIJO: So it's not like kind of a loading that would initiate and propagate a crack, unless you have a flaw already there. So yes. Anyone, you'll finish it up this year? You'll finish that up?

MR. RAYNAUD: Yes, hopefully very early in the year. The spring is planned. Some of the FRAPCON work is proving a little bit more difficult than initially foreseen, but I'm working through that.

CHAIR ARMIJO: Okay.

Fuel Performance Codes: FRAPCON AND FRAPTRAN

MR. RAYNAUD: Then I'm going to continue on. Can we kind of switch to a different topic? We've been talking a lot about spent fuel up until now.

Now, I'm going to talk to you about our fuel performance codes, FRAPCON and FRAPTRAN. For each code, I'm going to go through sort of the current state of affairs and what we plan to do in the next couple of years.

So FRAPCON is the first code that I'm going to talk about. It's our steady state fuel performance code. Our current version, which I believe was issued in late 2010 perhaps is 3.4(a), and we are about to release the next version of the code, which we've been working on under a contract with Pacific Northwest National Lab for the last three years, and that will be FRAPCON 3.5, and some of the improvements or additions to the code that we made are listed here.

We are updating all our creep models and hydrogen pickup models. There's been a lot of Halden data recently on creep, so all that data was used to update our codes. Hydrogen pickup mainly as a result of whatever's published in the literature, and we make sure that our models keep up with the new data.

We've added the capability to have variable axial node lengths, which was not the case before, and we can now do some zoning in the fuel enrichment, the Gadolinia concentration, whether you have a central hole in the pellets or not. The central hole is mainly to simulate Halden tests or VVER fuel.

However, enrichment and Gadolinia, zoning, that's something that's more and more common in the industry. It has been for a while actually, but I think our code was lagging a little bit in that area. We're limited in the number of axial modes and time steps we could model. We still have a fixed maximum number, but that's been greatly increased, and we'll move to dynamic arrays in the very near future.

We've added pellet chamfers to the geometry of the pellet. We have also looked at our correlations for fuel-specific heat and high stress cladding creep and made some small changes to those. I already mentioned, sorry for the duplication, the revised hydrogen pickup models.

Then we had a peer review this year, and a lot of items were identified by our users as small bugs or easy additions or fixes to make to the code. So we tried to process those as quickly as possible, and we are --

We just implemented what I call a FRAPCON to FRAPCON restart capability, meaning when we tried to model refabricated rods in the past, you had to only model that segment for the base radiation as well. We did not have the capability to stop -- model the base radiation, and then take only a subset of that fuel rod and continue on with a test program of sorts. So now the code will be able to do that.

That's mainly to be able to model experimental test programs, such as Halden and what's been doing -- been happening under SCIP also.

CHAIR ARMIJO: I guess I don't appreciate that, what you're saying there.

MR. RAYNAUD: Yes.

CHAIR ARMIJO: Why can't you do that with FRAPCON as it currently stands? You take a full length rod that you've modeled and you know its characteristics, and then you pull out a segment and then you're going to put it, let's say, in Studsvik or Halden and cook it and do something else. What were you missing?

MR. RAYNAUD: We were missing -- essentially when you do that, you refabricate your rod and you lose your gas and you put a new gas composition in.

CHAIR ARMIJO: Presumably to match the thermal properties of the gas that you lost, right?

MR. RAYNAUD: No. It's often just helium.

CHAIR ARMIJO: Well, they can put in argon.

MR. RAYNAUD: They can put in anything, you're correct. But a lot of times they put in --

CHAIR ARMIJO: Helium, okay.

MR. RAYNAUD: Okay, and we did not have that capability to change the gas composition. So we had to get around that by tricking the code into doing things that it really wasn't designed to do. So now we won't have to do that anymore, and it will probably yield more reliable results.

CHAIR ARMIJO: Okay, okay.

MR. SCOTT: I have a question. A minor detail, but the first rod did not have a hole in it. But if you drill a thermocouple hole, you'd have to model that, right?

MR. RAYNAUD: Yes. So in the past, when we had to model a rod only, that you know, of course there had been a base irradiation on that rod, on a full-length rod somewhere, that was taken from a full-length rod.

Well, we knew the base irradiation of that full-length rod, but we only modeled a piece of that full-length rod with the plenum volume that was that of the refabricated rod.

So there was some inconsistencies, so we didn't have a choice. But there were some limits to what we could do.

MEMBER REMPE: I don't know if this is the best place to ask it, but I was reading some of the information that was given to us ahead of time, and there were some comments from the peer review committee. The folks from IRSN talked about their volition of what they had done with FRAPCON.

How does that work with your international collaborators? If they come up with some special version, are they required to give you the source codings? So if you want to put it in the official NRC-sponsored version you can do that, or how does this collaboration work?

MR. RAYNAUD: I think that it's a good question. I think this is a good place to talk about it. They are not required to give us their developments.

But most of our users are open with that and are willing to. So of course we have our own verification and validation procedures, so we have to make sure that what they've done, you know, is acceptable to us.

And but we have incorporated some things from our users, and I think we'll actually increase that, because the community has been very active in the last couple of years. It was very obvious at the last peer review meeting that we had that they've developed a lot of interesting models that I think we can benefit from, and that we don't really have necessarily the resources to develop ourselves sometimes.

So we'll definitely increase that, looking at other people's codes and incorporating that into our version.

MEMBER REMPE: Because we do share the source coding with them?

MR. RAYNAUD: Yes.

MEMBER REMPE: So it seems like when I was looking at some of the things they were talking about, it wasn't just IRSN. So I'm glad to hear you're doing that. Thanks.

MR. RAYNAUD: Yes. Some of the major accomplishments is we developed a statistical tool to run many iterations of FRAPCON and then do some statistical processing of the results, to look at sensitivities from the inputs to the outputs. NRR has used that extensively in their licensing. We use it for power uprates, and I believe you've heard of that from Paul Clifford at NRR over the years.

We have now the SNAP plugin, which is what is used for TRACE and MELCOR, that is operational with the FRAPCON 3.4, and that we'll adapt for FRAPCON 3.5, and although that's not currently what we're using, we expect that in the future, SNAP would be the tool to best make the codes talk to each other, between TRACE and FRAPCON or FRAPTRAN.

Right now, we do it by our own means via Excel. But SNAP is where we should be going.

MEMBER SCHULTZ: Patrick, before you leave it, just for clarification. The update to the cladding creep models and hydrogen pickup, that's an update to models. That's not an addition of any models?

MR. RAYNAUD: Correct.

MEMBER SCHULTZ: Okay, so they've been changed. The other question is with regard to pellet chamfers, is that a modification that affects the pellet stress analysis, or is it just volume, rod volume?

MR. RAYNAUD: It's mostly rod volume.

MEMBER SCHULTZ: Analysis related to the --

MR. RAYNAUD: It's only a radial calculation.

MEMBER SCHULTZ: --pellet cladding interaction has not been modified?

MR. RAYNAUD: It has not.

CHAIR ARMIJO: So you can't -- with FRAPCON, can you model localized cladding strain, let's say at pellet interfaces? You cannot.

MR. RAYNAUD: We cannot. This code is 1-1/2 D. So basically just do a one-dimensional radial calculation from the center pellet to the core, and then in terms of axial transfer, there's no axial heat transfer, but there is gas communication that is assumed.

CHAIR ARMIJO: Okay.

MR. RAYNAUD: So that's why we don't capture pellet to pellet interfaces and so on. So it's really only a rod volume issue. It could have an impact, and I'm sure somebody could think of a very odd case, where the outer surface of the pellet is what drives the axial elongation of the stack, and in that case you might have an impact on chamfer. But it wouldn't be very physical. But mathematically, that could have an impact.

CHAIR ARMIJO: Yes, you could it.

MR. RAYNAUD: Okay. So our future plans in the next two or three years, we're going to go through a major effort to modernize the language of the code. So you know, from a person who's just a User not a developer, hopefully you would see no difference in the predictions. That's how you know you've succeeded.

But right now, the language of the code is quite archaic, in old FORTRAN, and it's proving to really hinder our development efforts. We've reached that point where some of the old structures are so complex and embedded into each other that future code development is being more and more difficult.

So we're going to put a lot of effort into modernizing the language of our code. We're going to reincorporate the ability to model spent fuel, which is called FRAPCON DATING. A DATING sim module is compatible with an older, much older version of FRAPCON, but that compatibility was not carried forward for reasons that I don't know.

And we also, actually importing from ISRN, they developed an auto-validation tool for FRAPCON that will run all the cases for you, compare with older versions or with external data, and actually spit out a report. So it's very nice and we have it for FRAPCON. We hope to maybe make it work for FRAPTRAN as well in the future. So that's an example of where we communicate with our users.

And we -- we think there's some improvement that could be made in fission gas release, gamma heating and in very rare cases where FRAPCON does not converge, we could try to implement some automatic time stepping and time step reductions to make the code converge, as well as another big phase of the code development would be better integration with thermal hydraulics and neutronics codes, TRACE and PARCS for NRC.

And that version, I would hope to release it in 2016 some time, and because of the major changes in the writing of the code, we'll probably go from 3 point something to 4.0 at that point.

Now I'll talk about FRAPTRAN, which is our transient fuel performance code.

CHAIR ARMIJO: Pat?

MR. RAYNAUD: Yes.

CHAIR ARMIJO: Before you go, you know, in the past, the ACRS has recommended more than once that FRAPCON develop a PCI capability to model the strains and the stresses of pellet interfaces in a volume PCI transfer, and you're going to hear it again in the research report, because I think it's --

And I don't know. It may not be possible, because of what you just mentioned. It's 1-1/2 D type of code. But how difficult, assuming your management chose, you know, said hey, we really should do this? Is it really fundamentally not possible to do that with FRAPCON?

MR. RAYNAUD: I'd be hesitant to say it's impossible.

CHAIR ARMIJO: No. I know nothing's impossible. But I mean it is really impractical? Do you have to do maybe a totally different type of code?

MR. RAYNAUD: We would completely have to rewrite the code if we want to go to 2D or 3D and capture a missing pellet or a pellet-pellet interface. That would not be possible with FRAPCON.

However, there are some more simple models maybe that just have to do with the chemical species and the stress, and you know, how fast you're ramping up and down, pre-conditioning, deconditioning and the fuel rods, those sort of things.

CHAIR ARMIJO: No, I'm thinking just mechanical, just purely mechanical.

(Simultaneous speaking.)

MR. RAYNAUD: We already do that.

CHAIR ARMIJO: The gases, of course, can affect the temperatures and temperatures affect the mechanical. But the correlations that we've been seeing, in looking at the skip data, is strained. You can model the strain at pellet interface or even pellets just on the cladding. You can model PCI --

MR. RAYNAUD: We already do that on our 1D basis. The stresses and strains are an important part of this thermal-mechanical modeling of fuel also.

MEMBER SCHULTZ: Right. But if you're not modeling the chamfer and the strain analysis, then you're missing the reason why the chamfers were put in place.

MR. RAYNAUD: Right, yes. We're not capturing the concentrations. So we wouldn't do a good job probably in predicting this.

MEMBER SCHULTZ: So maybe it's within the code or maybe there's already an appropriate interface with 2D codes that can be validated and demonstrated.

MR. RAYNAUD: There is a finite element module that was incorporated into the code years ago, developed by an external organization actually, and we seldom use it because for one, it hasn't -- we try to maintain it with the rest of the code, but it's kind of a black box, and it really increases our computational time by a factor of ten or more.

And so we haven't put a lot of effort into it. So I think the code might have the capability, but it would still assume, you know, axisymmetric pellet and

--

CHAIR ARMIJO: Sort of a patch type of thing here, is it? It doesn't go -- it doesn't change it to a 2D model or --

MR. RAYNAUD: No. It's not a proper 2D model.

CHAIR ARMIJO: Okay, okay.

MR. RAYNAUD: So I'm not sure I've answered your question very well but --

CHAIR ARMIJO: No. I just gave you a heads up, that's all.

MR. RAYNAUD: There are some serious limitations that would need to be overcome to capture the stress concentrations and so on. So now getting back to FRAPTRAN or transience fuel performance code, 1.4 is the current verison and we're about to release 1.5.

A lot of the changes we've made match what we've done in FRAPCON. So we've increased our arrays for a number of nodes and time steps. We've added the pellet chamfers. We've improved our LOCA modeling capabilities to better match what is done in experimental programs like Halden. So you have an external plenum that is say at room temperature, in addition to the plenum that is at the top of the fuel rod.

We can do double-sided oxidation, which was not the case previously, and we've done some improvements to the thermal hydraulic models. Mostly actually, mainly we've assessed our current models and we haven't made the improvements yet. But we've assessed where the improvements are needed, and that would come in the future.

Then we try to respond to our User group feedback by fixing bugs and making small enhancements where we can. The other major accomplishments are -- on FRAPCON, I'm sorry, that should have been deleted from here. It was on the previous code. But we did also adapt SNAP for FRAPTRAN, not just FRAPCON.

I think a big step in FRAPTRAN is in the future development, again with a big modernization of the programming languages. We want to develop a statistical pool for FRAPTRAN, which we currently only have for the steady state code and also an auto-validation tool.

We're going to take a very close look at our thermal hydraulic and reflood models because right now, they're rather simplistic and some of the complex phenomena that occur or that are predicted to occur, for example, by TRACE during a reflood scenario, flow reversals and such, cannot be modeled in FRAPTRAN.

So it would be nice to have that capability, to just be able to take TRACE output and feed it right into FRAPTRAN, without having to toy with it to make it compatible. This 2.0 version will also hopefully be released in 2016 some time.

That was it for the fuel performance codes. If you don't have any more questions on that, I'll continue.

MEMBER SCHULTZ: So you mentioned improvements to the models, both FRAPCON and FRAPTRAN, and some of it was in response to User group requests or models that they might have put together?

MR. RAYNAUD: Yes.

MEMBER SCHULTZ: The piece that of course goes along with that is recalibration, revalidation of the models and I guess I would just want to be sure that in fact that is a key piece that's clear moving forward.

One of the -- one of the nice features of the FRAPCON program have been that the code has been, I guess I would say relatively well-controlled, and that the validation and benchmarking to the data set, as it has improved, has gone along hand in hand with the model development.

I get a little nervous when I hear that users are saying oh, I've got a new model and I want to get it into the code, and I think it's better, and then you have to ask why. Is that because it matches your data set, and if so, are you going to give us that data set and combine it with the code model data set that we can use?

Those are questions I would hope that you would hold in mind before you leap to making improvements that are suggested by the users.

MR. RAYNAUD: And we do, and I appreciate your comment. Most of what we take from the users is not so much fitting coefficients to better tune to this data set that they have or so on.

Usually, we prefer to take new capabilities. For example, if somebody at MIT developed a compliant pellet model, and so we'll take a close look at that and see, because here, if they have some validation of the mechanics, the equations that feed into it and so on, you know, it's a true capability that we currently don't have. We have a rigid pellet model.

So that's a real addition to the code. If somebody comes and say oh hey, I have these couple of data points over here. I, you know, tuned this little coefficient to really hit those two data points, that's probably not something we're going to consider quite as the same priority, I would say.

And regardless, we always make sure that whatever changes we make are consistent with the database that we have and the validation cases that we've had for a long time, and that we've built the code up on year after year. So we wouldn't want to have a huge departure from what we know is well-validated already.

MEMBER SCHULTZ: Sounds like you're maintaining the right approach. Thanks.

MR. RAYNAUD: Thank you. We're scheduled for a break here, but we're a little bit early. So I'm happy to continue.

CHAIR ARMIJO: No. I think you were supposed to get 2:50, aren't we? 2:50.

(Simultaneous speaking.)

CHAIR ARMIJO: Well, if you can --

MR. RAYNAUD: I'm happy to continue.

CHAIR ARMIJO: Yes. Let's try and get at one more section or possibly two, but let's try one more. I'm going to try and hold to the agenda and break at 2:50.

The Studsvik Cladding Integrity Program

MR. RAYNAUD: This next phase of the presentation has to do with the Studsvik Cladding Integrity Program, and there are two topics really, the past and present and the SKIP program has been largely focused on pellet cladding interaction, and in the future we foresee that the focus of the program will be on loss of coolant accident.

So there have been three phases of the SKIP program. SKIP-1 was from 2004 to 2009, and the focus of that program was pellet cladding interaction from the point of view of cladding properties mainly. A lot of the investigations that were done were on cladding.

Then in the second phase, to 2009 to 2014, which is about to end in June, there was still a focus on pellet cladding interaction, but this time looking much more at what the influence the pellet properties were on the pellet cladding interaction.

SKIP-3, which is only a proposal at this point, kind of switches from PCI to LOCA, and the major focus of the program, I would guess at least 80 percent of it would be loss of coolant accident, and a large portion of that would be fuel dispersal actually. The PCI portion of SKIP-3 would only be to try and finish up what wasn't quite finished in SKIP-1 and -2, and hopefully tie up loose ends and remaining issues with PCI.

So in SKIP-1 and -2, we briefed this Subcommittee in June of 2013, and to talk about the SKIP results that were relevant to PCI due to stress corrosion cracking during AOOs and PWRs. A lot of what was shown there is also applicable to BWRs.

What we described was that overall, PCI/CC was, with the way things are currently operated, a low probability, low consequence event, and that it was currently being managed quite successfully by utilities.

That said, SKIP was doing a lot of research. They had an enormous database of power ramp tests and were doing a lot of investigations on select samples that they were power ramp testing, and a lot of separate effects testing and modeling to try to obtain a better handle on how to come up with a PCI criterion.

Despite all the research that has gone on, it seems to be a very complex phenomenon and, you know, every different pellet design or fuel design seems to bring in a slightly different behavior. So despite all the research that has gone on, it's been very difficult to get a handle on some kind of universal PCI criterion.

So the bottom line is we still don't have that, sort of a consensus that all the SKIP people agreed on. We will continue to follow the SKIP research on PCI, and if anything definitive or something sufficient that we think we can develop a criterion with comes out of it, we will definitely incorporate that into our fuel performance codes.

CHAIR ARMIJO: Yes. Well Patrick, we've been looking at the SKIP data. I've asked Dana to look at it and I've looked at it too, and as soon as I have some time, we'll wrap up what we've been finding, and basically it's a strain criteria is all you need.

There isn't as much scatter as you might suggest, if you filter out a bunch of stuff that are oddball kinds of things. Not industrial designs, and so -- and there clearly is a threshold power criterion, that if they're below a certain threshold there is no PCI risk.

I do agree it's being successfully managed. The only thing I worry about is AOOs that have certain characteristics that haven't been analyzed, and that could lead to not just one or two rods but many, many, many rods failing, and it would be a surprise.

In the BWRs, it's handled primarily by the barrier cladding, the zirconium line cladding. BWRs, it's a more forgiving system, but that's where we ask -- we've been following up to look at PWR PCI characteristics. It's very similar to what's going on in BWRs. Very little strains can cause PCI, and there's a lot of data, and it can happen in very short times, minutes as opposed to hours.

So we're working on that. We'll be providing that to the staff as soon as we've finished our analysis. But you know I agree. It's -- as far as normal operation, we're in good shape. We get surprises due to missing pellet surface, but that's not what I'm worried about. That's a manufacturing problem.

But in the event that we had an AOO of more than a few couple of minutes, that took PWR fuel up into power levels of 14, 15 kilowatts per foot, even for that short time you could fail a lot of fuel. That's a concern, and if you have a strain criteria that says we'll never, you know, we'll never reach that strain level, then you're okay.

So anyway, that's -- we may comment on that in the research report.

MR. RAYNAUD: Okay. Well, I would look forward to that and I appreciate your comments.

CHAIR ARMIJO: Yes.

MR. RAYNAUD: I think --

CHAIR ARMIJO: Well, we see --

MR. RAYNAUD: I agree with you that lower limits or, you know, thresholds can be derived from the data available. I think what I meant to say is sort of a universal.

My goal ultimately would be to have a more mechanistic criteria, not just a threshold but something more comprehensive and mechanistic that would tell me, you know, is it going to fail or not, based on more than just crossing a threshold.

That's, I think, what I was trying to point out here, that due to that kind of thing is --

CHAIR ARMIJO: That's very design-dependent. That's very design-dependent.

MR. RAYNAUD: Absolutely.

CHAIR ARMIJO: Okay.

MR. RAYNAUD: So the SKIP-3 program will focus mainly on fuel dispersal during LOCA. Some of the proposal highlights are to test siblings rods in the Halden reactor and at Studsvik and the hot cell in the apparatus that NRC developed which, you know, Studsvik might iterate on that apparatus and change it a little bit.

But essentially it's a benchmark. The Halden and Studsvik tests, compare them to one another. Make sure that the results that are obtained are consistent, and that's because that question has been raised by the international community as one of the major things that need to be resolved, to move forward in fuel dispersal LOCA research.

There would be quite a bit of integral LOCA testing at Studsvik in the hot cells, as well as a variety of separate effects tests that would be proposed to hone on the thresholds that lead to very fine fuel fragmentation and axial relocation and dispersal.

There would be also separate effect testing to investigate the role of the fuel microstructure on fragmentation, and also a lot of ceramography of the pellets, to correlate the effect to the state of the fuel before the transient.

Another aspect of LOCA research was not fuel dispersal, and actually it's not really -- potentially LOCA but other transients as well, where you might overheat the fuel and experience some DNB for some period of time, but not necessarily failed fuel, because you recover quickly.

And then looking at the impact of those types of transients on the cladding properties down the road. They would also look at axially loading LOCA samples in addition to the normal heating up with the pressure inside the rod, to see what impact on cladding failure that might have.

The PCI aspect of SKIP-3 would be mainly to do some separate effects tests, to investigate the effects of slow ramp rates on the benefits of that to mitigate PCI, and then also propose some slow ramps in pile.

So we've been very actively reviewing the SKIP-3 proposal, mainly because we want to ensure that the proposal addresses as many of our needs as possible when it comes to LOCA and fuel dispersal research, and we think that it would be a very valuable --

It has the potential to be a very valuable program, and a very good way to leverage our resources to obtain a large amount of data. So we're still evaluating the proposals and we'll see where that ends up later this year.

CHAIR ARMIJO: So NRC has not made a decision yet whether it will be -- join the SKIP-3 program or not?

MR. LEE: We intend to join.

CHAIR ARMIJO: You intend to join.

MR. RAYNAUD: That is it for SKIP.

CHAIR ARMIJO: Okay. Well then the next one would be Michelle, would be the next one. Why don't we take a break now, and come back in 15 minutes. So that would be 2:55, 2:55. Okay. Take a break.

(Whereupon, the above-entitled matter briefly went off the record.)

Experimental Research on Fuel Fragmentation

CHAIR ARMIJO: Okay, Michelle. You're on.

MS. FLANAGAN: Okay. The next couple of topics are going to go pretty quickly, because we've already presented this information to the Subcommittee just a month ago. So I'm only including them just to recap, because it's a major part of our research activities for the last two years.

I like this slide because it shows how the different parts of our research plan are related. So when we came to the ACRS in December, we presented -- I presented our experimental efforts.

So these were efforts to understand which conditions would result in fuel fragmentation, relocation and dispersal, and this is focused on experimental programs, interpretation of the post-irradiation examinations, and conclusions that we could draw with the available data.

That is combined with a significant analytical effort, which Patrick presented, that looked at when the conditions that we saw caused for this temperature, when those conditions were met.

The combination of these two efforts would produce a quantity of fuel dispersal, an estimate of quantity of fuel dispersal, which could be used to assess the consequences, for example, what the impact on peak cladding temperature would be if there was fuel dispersal, whether there could be flow blockage, and all of that work is still ahead of us.

But no matter what, we have to have a recommendation on this subject, or the status of the subject, included in the final rule package that goes to the Commission for the ECCS rulemaking. So when we submitted the proposal rule to the -- sorry, to the Commission, they said we also noted that this work was ongoing, and that we were not concluded the need for regulation at that point.

The Commission included in their SRM that they would like us to decide whether it needed to be included in ECCS rule in 50.46 or not, and if it did need to be included, that we needed to actually have that recommendation by the time that we issued the final ruling. So we will have progress and a regulatory recommendation of some sort noted in the final rule.

MEMBER SKILLMAN: Michelle, let me ask this. I suspect you answered this a month ago, but I just don't remember it. How are the TMI-2 lessons learned factored into this discussion?

MS. FLANAGAN: I want to say that they're not related, but that's only because the experiments or part of the experiment to operate were separate effects types of experiments, and TMI proceeded past the conditions that we're looking at here. This is a design basis LOCA scenario, and TMI proceeded past that.

So there's no direct use of the observations of TMI in this prediction of field dispersal. However, if we go into the consequence analysis and utilize our severe accident MELCOR code, all of the TMI results are integrated into the phenomena that are modeled there.

So in that way, we could say that there's lessons learned, considered in the consequence assessment. But I wouldn't say it's a very direct part of the research for fuel dispersal.

MR. LEE: Richard Lee. I did ask Dana Powers about at the TMI there was some fuel transfer from the primary system through the cooling system.

MEMBER SKILLMAN: So there was some. Indeed there was. There was a lot.

MR. LEE: Yes, and I said did that pose any problem that arise from it? He didn't remember there was anything that they have to take additional precaution. But the whole system was cleaned up and then -- and as you know the situation now, it's --

MEMBER SKILLMAN: Well, other than not being able to get into the building, there was no big problem.

MR. LEE: Correct, that's right. So it's a cleanup problem, not a -- I mean definitely.

MEMBER SKILLMAN: You couldn't respond during the accident. Actually, I'm not asking the question so much out of the TMI-2 orientation, but Sam's question about AOOs that could be slow-moving, and that could damage a lot of clad under the right circumstances.

Particularly with the PWR with pumps running, you can transport a lot of fuel pellets and a lot of shards very, very quickly, because the water's really whistling through that core. So if there is a scenario where there's major clad damage because of an AOO like Sam's talking about, there could be a consequence that is stunning.

MR. LEE: If we want to look at any of the consequence, we can definitely use a MELCOR code to do the analysis. For example, depends on the dispersal particle size, which is a regular one, and Dana told me that there is very extensive literature out there that correlate all these, how these irregular-shaped particles will form the debris bed that as it progress.

Suppose it cannot be carried by the steam? Based on the terminal velocity it will settle down, and you can form a bed and trap at certain locations in the core. So one can look at the accident, for example, when they do the fuel dispersal, they will find out where the location, axial and rate of leave where the material comes out.

Then we can look at the distribution and see what particle debris bed formation all over the core can be estimated, and then we'll take that as initial conditions and we can do the MELCOR calculation starting with these debris beds, they are located in different areas, and model it and see how the entire system will calculate predicted by MELCOR, including the one that trapped inside the core, which will be evaluated with cooling and blockages.

The product can transfer into the sum and example, then we can look at what got transported, and you can look at subsequent consequence.

MEMBER SKILLMAN: I understand what you've said, but just let me say quickly that in a PWR, you're running solid, except for your pressurizer level, and if your pumps are running, whatever material got lose in your core is now in your steam generators and your cold legs. It's the bottom reactor vessel, and to the extent that it might transport through the surge line it's there too.

And so the AOOs that Dr. Armijo was talking about, under the right circumstances, can create a radiological nightmare that we really haven't seen since TMI-2, and that's my point.

CHAIR ARMIJO: But they wouldn't fragment the fuel. The kind of things I worry about, just from -- would cause cladding cracks but it won't.

MEMBER SKILLMAN: It's an AOO, not a LOCA.

MS. FLANAGAN: I want to point out that the experimental efforts that we've focused on all simulate conditions of a LOCA.

So they simulate the very high temperatures of a LOCA and the very large ballooning strains, and we've seen that those are actually really important aspects of the conditions that we see. You do need that significant strain, and you do need those significant temperatures.

So when we've defined some of the conditions that are needed to start this phenomenon, a logical question would be do you see those conditions in other situations outside of a LOCA. So we've started to ask that question, but the conditions that are required to start this phenomenon are quite significant, and they might not be something you'd see in an AOO. But we will look at that after we're --

CHAIR ARMIJO: As part of your consequences analysis, what Dick is saying is any of that stuff that gets out there, if those pumps are running, it's going to be all over the place.

MEMBER SKILLMAN: Single pellet and Avogadro's number, if multiplied at 2 and whammo! There are enough atoms everywhere that you can't get near the thing. I mean it's really serious.

MR. RAYNAUD: I think we don't disagree with you, but really all of our research is focused, and it's missing in the title. But we're talking about LOCA fuel fragmentation, relocation and dispersal, and there potentially are, as you've mentioned, some other events that could led to fuel fragmentation, relocation and dispersal.

But we have not focused our research on that. We've barely begun to think about that in all honesty. It's been brought up, but to date, none of what we're going to talk about here considers that there's still liquid water in the core. I mean during reflood yes, but that's much slower velocities of the coolant. We don't have the reactor coolant pumps running and so on.

So we have not looked into the aspects that you're talking about, which is non-LOCA fuel dispersal.

MEMBER SKILLMAN: Okay, thank you. Fair enough.

MS. FLANAGAN: So I won't revisit this, the information that was presented in these two, in the top fuel conference and then at the ACRS. But the references are here, just to remind. But there is information available that can be referenced, if it's of interest, to look further into this topic, and it's all captured in these two references.

This slide just summarizes the very high level of the conclusions of the experimental effort, and that was that we completed a detailed assessment of PIE results, and from Halden and Studsvik, and that information was used to develop a proposal for what conditions are actually driving this phenomenon.

The proposal was used to define thresholds for when we would see this phenomenon and when we would not, and the idea was that with those thresholds, an analytical effort could be started that would actually be able to quantify fuel dispersal. Patrick will speak about that in a second.

The work that we're focused on with the experimental research was either -- was mostly through Halden and Studsvik. The Studsvik work was a bilateral effort that NRC initiated, and the Halden work is a multi-party program.

So we don't have another bilateral program planned for the future, but we do have a number of collaborative efforts that are on this topic that we plan to be engaged in.

One of them is the working group on fuel safety under the OECD nuclear energy agency, has proposed a CAPS on this project. CAPS is --

MR. LEE: Right there, CSNI activity proposal sheet. I always have a hard time remembering that.

MS. FLANAGAN: Oh yes, I wrote it. I'm glad I remembered that.

MR. LEE: --I don't remember.

MS. FLANAGAN: Yes. There are studies proposed by the CSNI Group on specific issues that they believe are of great importance, and they bring together experts to write a summary report. So there's no experiments that are connected, but there's experts reviewing the data and making some conclusions about it.

So they've determined that this topic should be a CAPS. It has been approved by the CSNI board and we fully intend to participate and probably will be very active in the writing of that and the meetings that are associated with that, and that will keep us engaged with the other international organizations that are considering this same issue, what their conclusions are, and where they expect the research to be needed.

We also are planning to continue with the Halden next phase of the program, which should include at least another LOCA test if not two or three, and we will continue to follow the examinations that are planned for the tests that have been completed most recently.

Halden has also proposed a new structure for some of their projects. So this particular subject of fuel dispersal has a lot of attention from the members, and they thought that a LOCA expert advisory group could be formed, with some of the more active members, to help direct LOCA tests.

So they proposed that, and it was discussed at the most recent Halden program group meeting. We're not really sure what the logistics of it will be and how often it will be held, or really what it would look like.

But we definitely are interested in being involved in that, because it could bring together some of the world's best experts in this issue, to help decide what tests are needed, what are the most important aspects that still need to be understood, and how can we conduct experiments to resolve those.

MEMBER SCHULTZ: Michelle, so that time frame, the 2015, 2015 to 2017 time frame, doesn't quite mesh with the delivery date that you have for the Commission paper.

MS. FLANAGAN: Yes.

MEMBER SCHULTZ: Is that a problem or is that -- is this going to be what you would consider confirmatory research?

MS. FLANAGAN: The Halden program, which operates in three-year phases, and so this is the time period of their next three-year phase, and the LOCA program and tests are just one aspect of that.

MEMBER SCHULTZ: Okay.

MS. FLANAGAN: That will be performed in the earlier phase. But also, to some extent we do consider the future work as confirmatory. I mean we have the ability today to make very conservative assumptions about this phenomena and make progress and regulatory recommendations that are very conservative and generally informed by a lot of data.

But the work that's going to be continued at Halden and in the SKIP-3 proposal would be confirmatory and also a finer understanding of the threshold. So where we might conservatively assume 10 gigawatt day range or 10 gigawatt days lower than the most observed test, the additional research will allow us to have a much more precise understanding of that threshold, and be more of a best estimate understanding. So --

MEMBER SCHULTZ: Thank you. I see how it fits together. Thank you.

MS. FLANAGAN: Okay.

Analytical Research on Fuel Fragmentation

MR. RAYNAUD: The next phase of the research on fuel fragmentation, relocation and dispersal is an analytical research phase, and I presented some of this at TOPFUEL in September in Charlotte, and we talked to you in December.

But to summarize, we have a three phase approach with the experimental research that Michelle just described, which gives us the conditions for fuel dispersal, and then the next phase is to determine when those conditions are met in a core and for a given scenario, and how many fuel rods are going to meet those conditions and thus be able to determine how many fuel rods rupture and how much fuel is expelled from those fuel rods.

In the third phase, which has not been done and is looking to the future, would be a consequence analysis. Once we know how much fuel is predicted to be dispersed during a LOCA, we can then analyze the consequences of that event.

So if we focus on the analytical research, we use what we think is a pretty near approach to core-wide LOCA modeling. It's certainly a higher level of detail than what's found in the literature, whereby we model each assembly individually and in some cases we even go to subassembly a little of detail.

The aim of this study is really to just determine how much fuel is dispersed and characterize when, during the transient it's dispersed, in what location in the core, and what that fuel might look like in terms of the fragment size distribution. We developed a scheme using the NRC codes FRAPCON, TRACE and FRAPTRAN. They kind of all link to each other.

FRAPCON provides the initial conditions and fuel rods that are burnup-dependent. That's fed into TRACE, which then calculates the thermal hydraulic conditions of the transient, which are applied as boundary conditions in FRAPTRAN, to get the detailed fuel rod thermal mechanical response during the transient.

That is -- the behavior of the fuel rod is then compared with the experimental thresholds that Michelle talked about, to determine where the conditions for a fuel rod rupture first of all, but then for fine fragment fuel dispersal are met, and then we calculate how much of that is expelled into the core.

So these kinds of calculations, it takes quite a bit of time to set up the models. But then once the models are set up, the whole scheme can run in less than a week on just the desktop computer or something like that. So we've completed some analyses already.

In terms of PWRs, the first study we ever did was a four-loop Westinghouse designed plant. We ran a large break LOCA, double-ended guillotine break of the cold leg at middle of cycle, and we did three variants of the scenario, ideal plant response where all systems are available.

Lost off site power, where a system response is delayed because of the loss of off site power and they start up the emergency diesel generators, and then one where only one train of CCS was operable.

Predictions showed that the only case where we had fuel dispersal was when only one train of ECCS was operable, and that was less than ten kilograms of fine fuel particle dispersed. We then proceeded to look at a CE plant, and we're pretty far along, but we haven't completed the analyses quite yet.

We performed some calculations on a GE BWR/4 for large break and small break LOCA, beginning, middle and end of cycle, and what we found there is that the peak cladding temperatures were effectively too low to produce fuel rod ruptures, and so we had no fuel dispersal.

We plan future analyses for PWRs. We want to look at a B&W plant and then Westinghouse two loop and three loop. And for BWRs, because we believe that the 5's and 6's, BWR/5's and/6 will behave better than the BWR/4, we will do analyses for BWR/2 and BWR/3. These studies maybe won't give us the ultimate answer for every plant.

Every time you analyze a different plant or a slightly different scenario, you're going to have a different answer. But it will hopefully give us an order of magnitude of the phenomenon, that we can then proceed to analyze in terms of the consequences, and that's really where we're headed here, to see how significant of a safety issue this might be.

MEMBER SKILLMAN: When you spoke about the results from the Westinghouse four-looper, you said less than ten kilograms of fuel dispersal. In your judgment, is that a large number or a small number?

MR. RAYNAUD: Well, I think this came up in December. I think from a radiological perspective it's enormous.

MEMBER SKILLMAN: It's a large number.

MR. RAYNAUD: From a thermal hydraulic impact perspective, I think that amount of fuel spread into the whole core, and it's very coolable because it's very small particles that will be rewetted very easily. I think from a coolability perspective, it's not insurmountable.

Again, this is just based on my scientific engineering judgment. I don't have any calculations to back that yet. We're looking at that in the future doing consequence analysis. I think the radiological impact was much larger, and it's not something that I'm an expert on, so --

MR. LEE: I think in the radiological, it would be more of the operational issues. It's not the outside release that I can imagine, because outside criteria assume a very source, much larger than this.

I cannot foresee such a dispersal can cause a siting dose limit to be violated, okay, because the siting dose include a very large early in vessel release, which is huge. We're talking about core melt accident. This cannot be done closed down coming from this.

MEMBER SKILLMAN: Thank you.

MR. LEE: Okay. But plant operation probably is a problem.

Accident Tolerant Fuels/Emerging Fuels Research

MR. RAYNAUD: So that concludes our briefing on dispersal, fuel dispersal. The next topic, unless you have more questions on fuel dispersal, is accident-tolerant fuels, and what I'm going to do is give a very brief overview of some of the DOE industry activities in this area, and most of the material that I'm going to present is taken from DOE briefings. It's not our product from research.

We have been monitoring DOE industry activities related to accident-tolerant fuels. It's been a pretty open information exchange. We've been invited to briefings by DOE. DOE has come to NRC to brief us, and this is just to stay in form in anticipation of in the future, at some point, the potential licensing of some accident tolerant fuel design.

It's helpful for NRC to just be aware of what is being done. It can help us prepare for any regulatory research that we might need to perform ahead of such a licensing, and to date we've only been observers. DOE is asking for more feedback, but still we are only observers to this point.

So DOE has a very aggressive program, part of which was already in place, but which accelerated with the events at Fukushima, to put in a leak test assembly or a leak test rod of accident tolerant fuel in a U.S. commercial reactor by 2022. Some irradiations of candidate materials are to begin this year.

So we'll continue to monitor those activities and we'll then take appropriate action, if needed, in terms of regulatory research if that comes up. So the next three slides are from DOE briefings, and just summarize their activities.

As I mentioned, DOE, this was -- they were already developing some next generation light water reactor fuels with what they called enhanced performance.

So they wanted to go to higher burnup, better reliability and get a higher power density. Then after Fukushima, Congress directed DOE to really focus their efforts on accident tolerant fuels. So they started implemented their program mainly with the National Labs, industry partners and some universities in the U.S., and there are very large collaborations in place and quite a bit of funding to develop accident-tolerant fuels.

The way that accident tolerant fuels are defined are a light water reactor system that should tolerate loss of active cooling for a significant period of time.

That's open to interpretation, but basically the systems should tolerate loss of active cooling for a considerably longer period of time than current fuel design, and of course, still be able to maintain the current performance of fuels during normal operation.

So there's a pretty strict development envelope, where you have to take into account not only what the current reactor fuels look like. It has to be backwards compatible and work in the current reactors.

You have to look at the impact on the fuel cycle, on the safety for the regulatory framework, and also one big aspect of all of this is the economic aspect. I think one thing that they still struggle with right now is the cost of these accident-tolerant fuels, and it needs to be something viable for industry to ever adopt it.

Here's a time line that leads to the 2022 insertion of leak test assembly or a leak test rod into a U.S. reactor. You can see that from 2012 to 2015, it's mainly studies of a variety of advanced concepts, and then a down-selection should be performed some time in 2016, based on laboratory research as well as some tested radiations in HIFER and ATR, I believe maybe even Halden in Norway.

Once the down-selection is performed in 2016, they plan to run some steady state radiation tests long term, as well as some separate effects tests for accident conditions such as LOCA and transient tests IMPAL (phonetic), in a test reactor of sorts.

During this time, they will also have to develop a field performance grid to be able to submit it to NRC, to make a case for the insertion of these leak test rods and leak test assemblies. So it's a very aggressive and ambitious schedule, and for now, we're just observers. I expect that they will engage with NRC in a more formal manner as they progress towards licensing.

Here are a few of the candidate materials that are being discussed. Some of the materials mainly have an emphasis on more benign scheme reaction, which would result in much less hydrogen being produced, and you wouldn't have -- they were very concerned with the hydrogen explosions that occurred at Fukushima obviously, and so that's one thing that they're looking to avoid.

So looking at advanced deals, what they call the FeCrAl alloys, iron, chromium, aluminum, steels; refractory metals, such as molybdenum, ceramic claddings like silicon carbide. They're also looking at doping current zirconium or other types of alloys, and they are trying to coat zirconium alloys with ceramics, or encase a very thin zirconium tube in a silicon carbide sleeve.

So this may not be an exhaustive list, but those are the more recent ones that were presented in the fall, when DOE came to brief us on this topic. Then they also have pre-advanced concepts for the fuel pellet itself, not just the cladding.

They're looking at higher density fuels, metallic fuels as well as uranium nitride, uranium carbide, uranium silicide, to get to higher thermal connectivities and higher fissile content.

In some cases, some of these designs, you have less room for the fuel. So then you have to increase your fissile content somehow or you won't be able to achieve criticality.

In other cases, you might have a cladding that consumes more neutrons that zirconium does, or just the fact that you want to make it economically viable and you need to achieve much, much higher burnups, and so you need more fissile content to begin with.

Off site fuels with additives are also being looked at, as well as TRISO or BISO microencapsulated fuels. So TRISO particles encapsulated, silicon carbide pellet and then put into a cladding form.

So each of these concepts have pros and cons, and they're all being evaluated comprehensively against the operating and design envelope, and you know, what can you gain for -- at what expense, I guess?

So we're looking forward to the down-selection process and finding out what happens there, and maybe at that point there will be time for us to see if we need to do any research, in view of licensing.

MEMBER RYAN: I'm curious, Patrick, about the question at the end of higher burnup. You kind of lose something when we get too far up in burnup. Could you discuss that a little bit more please.

MR. RAYNAUD: Well, I'm not sure what you lose. I mean from a purely economic point of view, if it's a once-through fuel cycle and you're not going to reprocess, I think, and I've never been in the industry, so perhaps I don't have a full picture of this, that you know, if you can leave the fuel longer in your reactor, as long as it performs in a satisfactory manner and doesn't fail, that may be a good thing.

If someone has insight on that, I'd be happy to hear about it. So you know, I don't see any downside, other than the performance could be great, and you obviously have to ensure that that's not the case.

MEMBER RYAN: Of course, the challenge is is that performance going to be nice, load downward performance you can predict and react to, as opposed to it's fractured. It's a mess, so --

MR. RAYNAUD: Yes, yes. I mean clearly, there will be probably some degradation mechanisms that we maybe don't even know about yet, and especially with some of these more exotic materials. So I think --

MEMBER RYAN: So you still see a range of potentially significant challenges on the high burnup end?

MR. RAYNAUD: Yes.

MEMBER RYAN: From lots of points of view?

MR. RAYNAUD: I see very significant challenges with many of these designs, just because of the current reactors and the current regulatory structures, and some of these materials are radically different from what we have experienced in the operating commercial fleet. So I think licensing is going to be a challenge, no doubt.

MEMBER RYAN: Thank you.

MEMBER SCHULTZ: You mentioned compatibility as one of the five features, as well as fuel cycle, just as an example in terms of enrichment limits and so forth that you mentioned. High reactivity loading may be required in order to be at all compatible with what can be achieved with clad fuel.

MR. RAYNAUD: Correct. I mean the whole fuel cycle infrastructure was designed for a certain envelope of enrichment levels that may need to be exceeded in some cases here.

So there's a big impact on the country's infrastructure and, you know, the economic viability of these fuels still has to be proven, because unless Congress or the NRC puts in requirements, if it's not economically viable, I doubt that many facilities will pick it up.

MR. LEE: And the enrichment is still limited to five percent at this time.

MR. RAYNAUD: Yes.

MR. LEE: If you go beyond that --

MEMBER SCHULTZ: Right.

MR. LEE: All those plants have to retool their production line, and ACI (phonetic) is going to have a much more critical review of the greater than five percent enrichment. I'm sure of that, from the criticality point of view and everything.

So I don't know what SMR is entailed, because if they run very long through cycles, they will have a lot of challenging core design that we have to validate. So we don't know what will be coming down the pipelines in five-ten years.

MR. RAYNAUD: And all this said, I think DOE is very conscious of these potential major hurdles that we're talking about, and they're not operating in a vacuum.

So they -- I think in their down-selection process, they're going to take all that into consideration, and maybe go for a more smaller incremental step, rather than a revolutionary, huge change.

MEMBER SCHULTZ: But it seems to me that

perhaps the problem is overly constrained. To say we have to -- and in addition to being a robust safety case for a new fuel design, wanting to get into a new realm of safety design. Get rid of the zircaloy, and hydrogen production issues.

They've also added another constraint. They say it has to be compatible with current fuel. Why is that? If we're building SMRs, why don't we develop a design that would be used and useful in an SMR, first of a kind? The first loading would be of this new fuel design, not to backfit it so that it could be put into --

MEMBER REMPE: Wouldn't that slow down deployment of SMRs, if you have to get a fuel, a new fuel qualified?

MEMBER SCHULTZ: I'm not -- I'm not saying you can't build an SMR until you have a new fuel design. Make it so it can be used in an SMR that is newly designed under DOE funding.

CHAIR ARMIJO: One of the arguments for the SMRs is probably let's -- it doesn't need fuel as much as a big one.

MEMBER SCHULTZ: That's true.

CHAIR ARMIJO: So you know, it's kind of a -- it's a very difficult problem.

MEMBER SCHULTZ: At least to figure out.

CHAIR ARMIJO: These are new -- these are materials where we have essentially no experience in -- as far as chemistry, the compatibility of the fuel and the new cladding, whether it's ceramic or molybdenum or iron chromium, aluminum, and then the coolant chemistry.

Even if it wasn't accident tolerant, these materials, to be fielded as a new fuel assembly, it's a huge effort. It's a huge effort, just to meet the current regulatory requirements, performance requirements. So it's a tough job. I think DOE had better be talking big money.

MR. RAYNAUD: I believe they're spending around $30 million a year.

CHAIR ARMIJO: How much?

MR. RAYNAUD: It's either ten a year over three years, or 30 per year, million dollars. I know that's a big difference, but we're talking tens of millions of dollars annually.

MEMBER SCHULTZ: It's a drop in the bucket of fuel development.

MEMBER REMPE: No, but in your discussions with them, are you talking about the whole system analysis very much and the whole plant response during an accident? Not just the fuel performance but control materials and how they would behave, and how the operator should respond?

MR. RAYNAUD: No, we haven't got to that point.

MEMBER REMPE: That might be an interesting thing to be thinking about too.

MR. RAYNAUD: One thing that DOE has been talking about is there's accident-tolerant fuel, and then you can make an accident-tolerant reactor. Well, that's a whole different ball game and, you know, a reactor's much larger, as we all know, and maybe much more complex than just the fuel.

MEMBER REMPE: If you just improve the fuel and the control materials stay the same. I'm not sure -- I think it's a question that ought to be answered with the MELCOR analysis.

MR. RAYNAUD: Oh you mean in terms of everything else that can melt, yes. Yes, I agree.

CHAIR ARMIJO: W.R., Look at the massive that's just channels. I think it's huge.

MR. RAYNAUD: They have talked about carbide channels.

CHAIR ARMIJO: Well.

MR. RAYNAUD: Anyway.

CHAIR ARMIJO: Well, it's interesting.

It's good that you're going to stay on top of it. But it's a tough -- it's going to be a tough project.

MR. RAYNAUD: Well like I say, for now we're just observing and listening and, you know, providing minimal feedback within the boundaries that we're allowed to operate in as a regulator, and we're waiting to see where it goes before we engage in anything more substantial in terms of the research.

MR. LEE: And within Research, I mean within NRC itself, we have a so-called Fuel Technical Advisory Group that consists of all the major offices like NMSS, NRO, us. So all these subjects are put on the table to discuss, so other offices know what is going on, because we burn such a fuel in the reactor, the NMSS needs to know what is coming out from the reactor.

CHAIR ARMIJO: Yes, right.

MR. LEE: Ultimately to their -- become their responsibility --

CHAIR ARMIJO: Yes. If you're worried about these potentially embrittled zirconium clad fuel transportation, I think silicon carbide would be more of a challenge, you know. So it's the whole system is affected, and I think NRC could help frame the whole system problem better.

I don't think it's been analyzed from the standpoint of the entire core, the entire system, the entire fuel cycle. It's more than 10 million bucks a year.

MR. LEE: I believe that for the silicon carbide fuel, I believe Oak Ridge has done some analysis using MELCOR. It's just switch out the silicon, changing to zirconium cladding to silicon carbide, and they changed that and did some analysis on that. We also asked Dana Powers to write an opinion papers on silicon carbide, what does it meant from the melting and fission products.

That paper was written, and we have given that to DOE, and it raised a lot of questions related to severe accident response, which they have to answer and they have to acknowledge that this is really not safe at the end of the day.

CHAIR ARMIJO: Okay. Thanks, Patrick. We have one more, I believe.

MR. RAYNAUD: Our last topic, I guess.

CHAIR ARMIJO: Michelle.

Accident Tolerant Fuels: Overview

MS. FLANAGAN: Yes. So this is just one slide, and we have spent the last couple of meetings discussing focus areas for the last two years, and we wanted to conclude the presentation with some thoughts about potential focus areas for the next two years and beyond.

So we got together as a group and thought about where we'll need to increase our efforts in the future, and we came up with five different areas that we wanted to mention. One has already been brought up in a couple of ways, and that's small modular reactors. Fuel licensing and analysis needs may require us to increase our focus in this area.

A lot of the small module reactors are proposing very similar fuel to what is currently being used, but there are aspects of our field performance codes that might need to be updated, aspects of the dimensions in these cores that might need to be analyzed.

So there's new work that we should be coming up to speed on in the area of small module reactors, to prepare for fuel licensing and analysis needs.

Spent fuel storage and transportation, as well as ultimate disposal solutions is obviously something that's still ahead of us, and could result in a couple of new topics. The need for more localized, dynamic and synergistic picture of the core to handle new fuel requirements and operating practices. So this is a result of the fact that our embrittlement, our understanding of embrittlement now shows us that high burnup fuel could actually be worse than low burnup hot fuel.

So our LOCA methodologies have focused on the hot rod, in demonstrating acceptable behavior and remaining below the criteria. Now we need to also look at high burnup rods and the whole core must be understood, to assess whether each rod is below its respective embrittlement limit.

The same is true for RIA. The same thing could be said of fuel dispersal. We need to have while one aspect of the fuel rod is decreasing, the decay heat and stored energy is decreasing, the consequences for fuel dispersal embrittlement are increasing, and so we need to actually look at the entire core, in order to assess those aspects.

Our code capabilities are currently very focused on the old way of doing things and old priorities. So with new priorities, we need to have new tools that can handle these questions.

There's a growing industry use of statistical analysis, and we have to come up to meet that, and be able to assess and replicate the trends of the industry, and the last point gets to a little bit of where we started with Joy, your question about our shrinking budgets and how we plan to accommodate that.

We envision relying, increasing reliance on our international collaborations, to work together with partners to complete work, to exchange information and better leverage our resources. Not only are the budgets continuing to be a challenge, but also the research questions that we have are very complex, and in some cases require very expensive testing, and it's not something that any country or organization is able to complete on its own.

So in the future, we see a lot of potential for increasing our connections with international organizations and sharing -- to leverage our resources. I'll say that.

MEMBER REMPE: So I have a question about -- and it's not just in your area, but in other areas too on how does NRC decide they have enough data? If someone's getting ready to start a new experimental program or qualify fuel or the high burnup demo, for example, and they know that they've come to NRC for a licensing case.

So NRC needs to give them advice on how much, the density of data. It's like with the fuel qualifications. How do you decide how much data you need?

Do you just say okay one sensor for

temperature, for pressure and moisture, water level, in the case of the high burnup demo, or do you say a lot of, you know, I want temperature at a density of every ten inches or something like that? What's the guidance you guys rely on to decide whatever they do will be adequate data when they're done?

MR. RAYNAUD: I think -- this is not going to answer your question, but I think NRO would be much better suited than us in Research to respond to that. Ultimately, it's their decision.

MEMBER REMPE: For licensing?

MR. RAYNAUD: For licensing, yes, of fuel. When it comes to code development, we take whatever data is available, and then we quantify, in our models, the uncertainty and the bias of those models. So we may not have much data, but we can still use that with a larger uncertainty essentially.

MEMBER REMPE: So with FRAPCON, if you're going to put a new model in, when do you decide well, I have enough data if someone were going to propose a new test? Do you just say well get what you can and I'll put it in, or do you try and say well, I'd like the data or something?

I just am wondering, because this has come up a lot in other areas too that I've worked in, and what should be sufficient data and how much is really needed. Is it just the engineer involved at the time, there's no official guidance? Or it depends on the application and there's not a good answer?

MR. RAYNAUD: I don't know of guidance for code development kind of stuff that would address that. I think if it's data that we already have a database for, we have data point and when we see how it matches up and if we need, you know, we'll see how that impacts the model, how well -- how good it fits, and if it doesn't, you know, can we treat it?

Is there a reason for that and if there isn't. If we need to incorporate it in our database because there's no reason not to, then we might have to retune our model slightly and want to have a different uncertainty and bias to our model.

If it's a completely new phenomenon and we only have one data point for it, I think we would wait to have more. We're not going to immediately jump and do something in our code when we're really not sure yet where this might take us. But in terms of licensing, I don't think -- I can't answer the question. I doubt Michelle could either.

MR. LEE: From licensing point of view is obviously the plants are operating, so it should be adequate. So all the new, so-called new data used for validation in the code is our prediction uncertainties, will reduce the uncertainty of that predictions, of whatever the parameters that we are looking at. So that's how we view it.

If a program propose to us to address certain uncertainties in certain area that we think that is well-quantified, it will be less value to us. For example, if I'm going to look at the early in-vessel melt progression, you know, candling (phonetic) and all these things, I will be less interested in that type of experiment.

If I go to a mold late vessel degradation, I will be more interested in that area. But remember, severe accident progression is not homogeneous. It's very complicated, so you really need to say that we can live with the uncertainty good enough for licensing, and we really don't have to go through exclusion details to find out what happens and down to very, very detailed level, because some experiments are not useful for us.

For example, let's take the PHEBUS program, okay. They finished the test and they will cut it and they do all these micrograph examinations and look at all these details, how the uranium oxide behaved and what temperature it reached. When they give us those data, we couldn't use it because our code doesn't use any of these information whatsoever.

So we find those type of analyses really have no relevancy to our licensing framework, in supporting our code that used for confirmatories. So it depends on what people propose, in terms of what the would like to do in terms of experiments, and what type of post-examination they would like to conduct.

So we will comment -- our comment will be based on how useful it is for our code development, or quantified uncertainty in reducing it. That's how we evaluate the proposal that come in to us. Some of them refuse to participate.

For example, they do a lot of containment analysis during CFD and all these things, and they tell us they're going to study iodine. But there's no radiation source in there; there's nothing in there to do anything. So what am I going to use the results for?

Give me false sense, giving me wrong model, because it has nothing to do with iodine behavior absent of the radiation field. So we refused to participate, and we've been asked multi-times, repeatedly, our management, including Brian Sharon, now the chairman of CSNI, right.

So it's no longer looking for U.S. interest.

He's looking for CSNI interest, so he kept asking can we do this. I said no, because it has no value to us, so we said no. There are some other programs pushed by Switzerland, and we also say no too, because it doesn't do anything for us and we just turn it down.

MEMBER REMPE: Let me give an example then. If there's something with high burnup cladding, if they give you -- and this is a theoretical example. But if they gave you an example of a test they're going to do with high burnup cladding, as long as the data were comparable to what you got from regular cladding, you'd say that's sufficient, and you wouldn't be asking for more?

MS. FLANAGAN: This is theoretically?

MR. RAYNAUD: I think we'd look at the conditions of the test, to make sure that we agree that it was done in the proper conditions, that the data that was produced was QA'd properly, and that there's no atypicalities or significant atypicalities, and then I would imagine that if all that seems acceptable, that we would consider that data as acceptable data and work from there.

MEMBER REMPE: Okay. I just was curious. Thanks.

CHAIR ARMIJO: Yes, okay. Are there any

comments from people in the audience?

(No response.)

CHAIR ARMIJO: Okay. Is there anyone on the bridge line? Is the bridge line open?

MS. ABDULLAHI: Yes, it's been opened.

CHAIR ARMIJO: Nobody's on the bridge line? Okay. Any further comments or questions from the members? Pete.

Committee Comments

MEMBER RICCARDELLA: I would just reiterate Steve's comment, about whether or not there's a surprise waiting with some of the research material on the -- what is it? There's a scenario for the fuel transport task that they're working on. I think you identified that, Steve. That could be a very uncomfortable issue if that were to be revealed at RIC, when we really haven't had a chance to talk it through.

CHAIR ARMIJO: I appreciate that. Steve.

MEMBER SCHULTZ: Yes. I would iterate that as well. I'm just looking at the backup slides, which are titled "Consequence Assessment of Fuel Failure on the Safety of Spent Nuclear Fuel Dry Storage and Transportation Packages."

So the write-up indicates that very sophisticated calculations are being done, and they're being done, it would appear, on potentially piles of fuel pellets and different configurations that may happen in some sort of accident configuration, and if we're not first evaluating whether we can get to those configurations before we analyze what the consequences might be, I think we're looking at it in the wrong way.

If it is a problem, then we have -- and it's being identified because of analyses that's already been done, then it's important that we begin to address it soon, sooner than later.

CHAIR ARMIJO: Okay. Ron.

MEMBER BALLINGER: I don't have anything to add.

CHAIR ARMIJO: Mike?

MEMBER RYAN: I'd like to compliment the presentations today. You went through a lot of depth and shared, I think, a lot of your strategies and thinking behind the work you've been doing. I think that in part will maybe address some of the comments Steve made that, you know, you haven't closed off any avenue.

But by the same token, it's expensive and you don't have all the money on the planet. So you're not going to get to look at every avenue. So at some point you're going to bring things to closure or put things aside for the moment that may ultimately be important or may not be.

So I would just urge you to continue that questioning attitude, in spite of the fact you might be pressured about schedule and costs, as we always are. But don't give up that inquisitive nature, and make sure that there's not an important stone that's left, you know, unexamined.

There will be lots of ones that are not important and you can set aside. But there will be a few that will be important, and it sounds like you've got the questioning approach to continue to find those and deal with those appropriately. So thank you for your presentations today.

MR. LEE: Thank you.

CHAIR ARMIJO: Joy.

MEMBER REMPE: I also wanted to thank you for spending the time to go through this, as well as the guys who were here this morning. We didn't thank them as much we should have.

CHAIR ARMIJO: Yes, we should have. But Ron was chairing that one.

MEMBER REMPE: It was Ron.

MEMBER BALLINGER: I thanked them in the beginning, ahead of time.

MEMBER REMPE: Well you never know if they really what they should be doing. But I thought it was actually a good idea for you guys to have done this, and I was talking to Richard earlier today about, that I wish I had done something like this with the severe accident research.

CHAIR ARMIJO: Yes. I think we could have all.

MEMBER REMPE: So the comment's mainly for ACRS, that I think this is a better way of doing this biannual thing, and hopefully we'll start doing this more often. Actually, I asked Richard to have some of the staff come talk to us later about some of the findings that I've been reading about.

And I think it's just a better way to do this review, rather than throwing a stone over the wall. So I hope we do that.

MR. LEE: Even in this briefing, we really did not cover the results of all these programs.

CHAIR ARMIJO: I understand, yes.

MR. LEE: Because 20 minutes is not enough.

(Simultaneous speaking.)

CHAIR ARMIJO: It's impossible, right. Right, it's impossible.

MR. LEE: We could only give a very brief status.

MEMBER SCHULTZ: But I agree. Really, thank you for the presentations, because it is clearly a very comprehensive and very well-developed research program.

CHAIR ARMIJO: Well, it makes it a lot easier for us to do a fair job of writing the research report.

MR. LEE: And as I told you, there is a Technical Advisory Group that, you know, different office chairs different year. It would meet like every three months quarterly, to go through all the fuel-related issues. We have a tech group for that. We have a Neutronics Criticality Tech Group, which includes all the offices, that address criticality issues related to spent fuel pool degradations and volume degradation and all those things and others.

In the severe accident area, we couldn't find too many people, because we don't -- because we are too busy right now with the Fukushima stuff. Coming back to the things that you all said, and I spoke to User group or the User office, they will put the study in context on the entire plant, as Meraj briefly discussed this morning, so you have understanding how that fit into the entire picture.

It's not just a study stand by itself, and

I'm sure not just this committee, the Commissioners are interested in that study, because more than a year ago, when NMSS presented a budget to the Commission, Magwood, Commissioner Magwood asked specifically about that study, and I told him that when the study is done, we will brief up and down, whatever you want me to do.

CHAIR ARMIJO: Yes, yes.

MR. LEE: But it need to be put in context why NMSS commissioned this study, and it just happened that Oak Ridge is the one who do the analysis, and it was a convenient contracting instrument. That's why it end up in Michelle's contract.

(Simultaneous speaking.)

MR. LEE: So another different contract.

MS. FLANAGAN: Right. So we presented the part that our group is responsible for, but it's really part of a much bigger picture, which we didn't have the, you know, wasn't designed to be presented here, and it really needs to be seen in that context before, I think, some of the discussion that we had --

MR. LEE: And the same thing with extended storage too, with talk about cladding stresses. Only one little piece of the extended storage thing that NMSS, Bob Einziger and company addressing. So I think you heard some of that this morning, right.

MEMBER REMPE: Yes.

CHAIR ARMIJO: Well, I'd like to add my thanks. I appreciate you for a very well-prepared presentations. Good discussions. Unfortunately for the people in the fuel business, light water reactor fuel is doing just fine. It works beautifully, it's efficient, it doesn't fail very often, and like we're paid to worry about things that might happen that are credible, not incredible.

I think the staff is working on the right things. So I really have nothing, other than my BCI issue, but I'll have that for a long time. But I think you've got a good program, and you know, I think we're -- unfortunately, I think the United States has a huge problem in the lack of facilities to do normal fuel development, fuel testing, fuel irradiations, things like that.

So I think it makes everything so expensive that you have to go -- it takes too long also to go to other countries to get your fuel irradiated and run programs. But we're stuck.

MR. LEE: And we are also keeping track of other country activities. For example, IRSN and CEA more closely, and CEA do a lot of fuel development work for Ariba.

CHAIR ARMIJO: Yes.

MR. LEE: So they will -- and then they do a lot of fact analysis for them too, and ISRN is connected with that. So when we talk to ISRN, we'd like to find out what's going on with that aspect of it.

CHAIR ARMIJO: Yes. Well, I think --

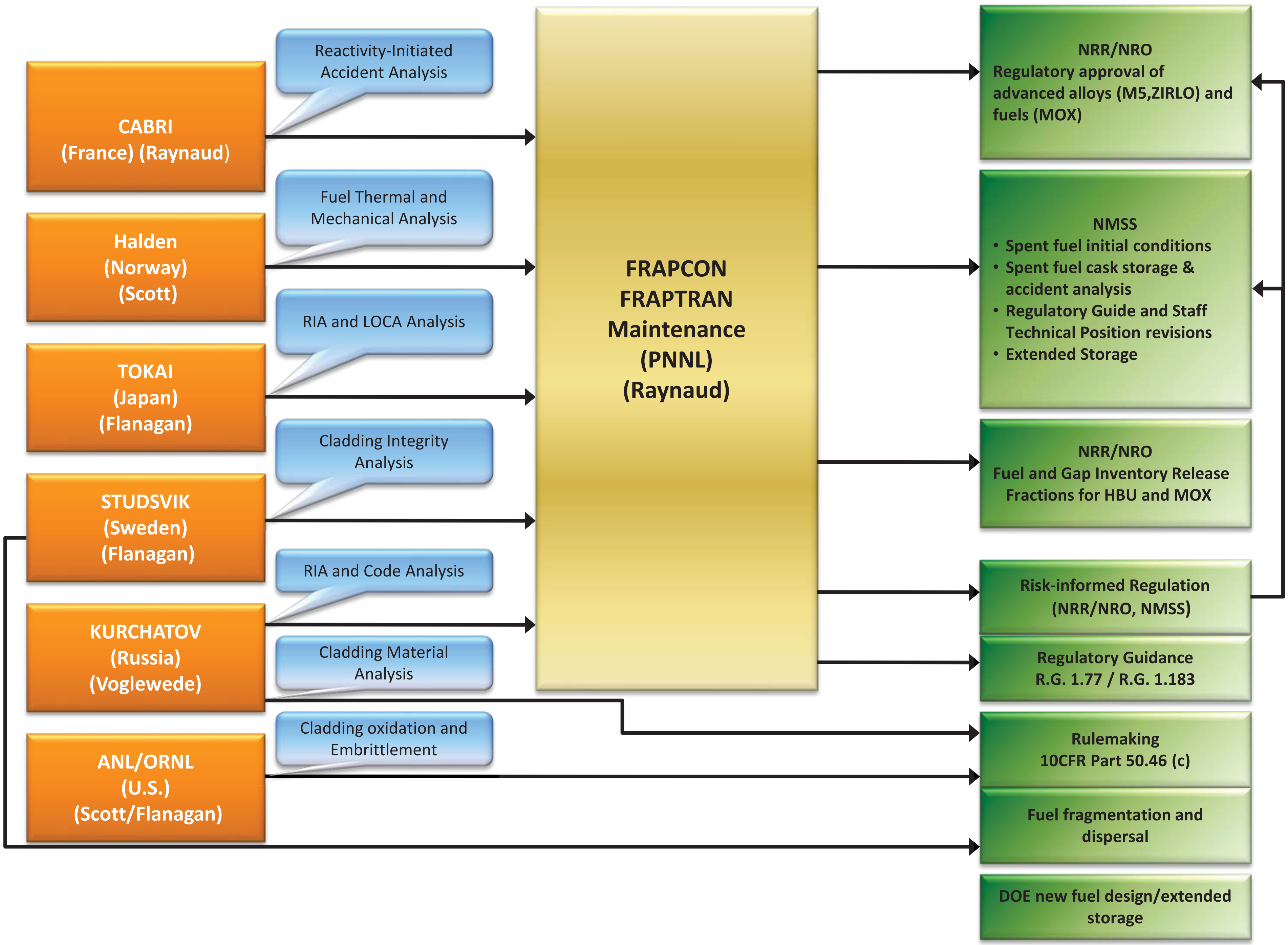
MR. LEE: Also we're going to be ramp up our engagement with Japan, to be closely connected with JEA and JNES, which will be by the end -- later part of this year become the regulatory agency, research arm of the agency. That's what we think.

CHAIR ARMIJO: Yes, yes. Okay. Well, with that, I'd like to thank everybody.

MR. LEE: In your committee report, you can say "transfer more money to other two divisions."

CHAIR ARMIJO: Okay. Thank you very much. We're adjourned.

(Whereupon, at 3:56 p.m., the meeting was concluded.)



CABRI (France) (Raynaud)
Halden (Norway) (Scott)
TOKAI (Japan) (Flanagan)
STUDSVIK (Sweden) (Flanagan)
KURCHATOV (Russia) (Voglewede)
ANL/ORNL (U.S.) (Scott/Flanagan)
Reactivity-Initiated Accident Analysis
Fuel Thermal and Mechanical Analysis
RIA and LOCA Analysis
Cladding Integrity Analysis
RIA and Code Analysis
Cladding Material Analysis
Cladding oxidation and Embrittlement
FRAPCON FRAPTRAN Maintenance (PNNL) (Raynaud)
NRR/NRO Regulatory approval of advanced alloys (M5,ZIRLO) and fuels (MOX)
NMSS
• Spent fuel initial conditions
• Spent fuel cask storage & accident analysis
• Regulatory Guide and Staff Technical Position revisions
• Extended Storage
NRR/NRO Fuel and Gap Inventory Release Fractions for HBU and MOX
Risk-informed Regulation (NRR/NRO, NMSS)
Regulatory Guidance R.G. 1.77 / R.G. 1.183
Rulemaking 10CFR Part 50.46 (c)
Fuel fragmentation and dispersal
DOE new fuel design/extended storage

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Biannual ACRS Review of Research Fuels Programs

Briefing provided by staff in RES/ DSA/FSCB
January 14, 2014

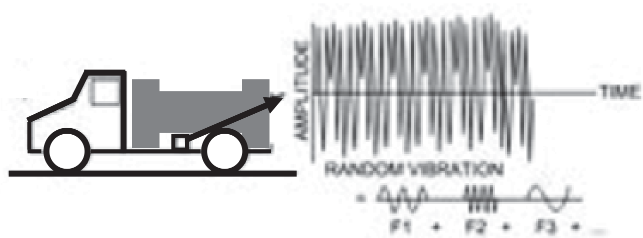
Presentation Overview

- High Burnup Spent Fuel Fatigue Testing for Transportation Applications
- Consequence Assessment of Fuel Failure on the Safety of Spent Nuclear Fuel Dry Storage and Transportation Packages
- Extended Storage of High Burnup Fuel: Cladding Stress Analysis
- Fuel Performance Codes FRAPCON and FRAPTRAN
- The Studsvik Cladding Integrity Program: PCI (past and present) and LOCA (future)
- Experimental Research on Fuel Fragmentation, Relocation and Dispersal
- Analytical Research on Fuel Fragmentation, Relocation and Dispersal
- Accident Tolerant Fuels: Overview of DOE and Industry Activities
- Emerging Fuels Research

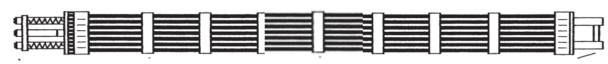
High Burnup Spent Fuel Fatigue Testing for Transportation Applications (1/6)

Motivation: Vibration normally incident to transport must be analyzed for fuel in transportation casks.

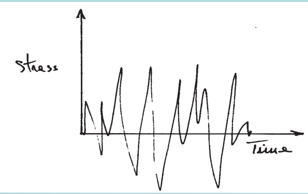
A transportation cask will experience some level of oscillation due to normal conditions of transport.



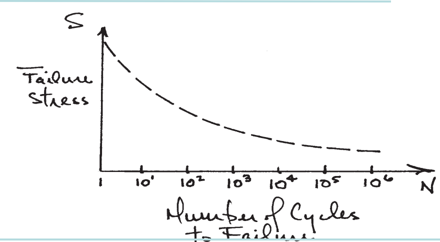
That oscillation will be transmitted in some way to the contents of the cask, the fuel elements.



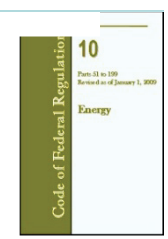
The oscillation transmitted to the fuel elements will result in local stresses



The fuel cladding has the potential for fatigue failure if a large number of cycles are seen during transport, even if the maximum stresses seen by the cladding are far below the yield stress of the material. High burnup material in particular may be highly brittle. In addition, it is not clear how the ceramic fuel will effect the potential for cladding failure.



Current regulation state: "Evaluation of each package design under normal conditions of transport must include a determination of the effect on that design of the conditions and tests specified in this section" 10 CFR71.71(c)(5) specifies the condition: "*Vibration.* Vibration normally incident to transport."



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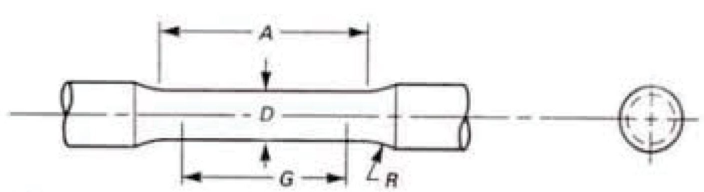
High Burnup Spent Fuel Fatigue Testing for Transportation Applications (2/6)

Objective of research program: Investigate a number of important attributes of the fuel/clad system. These attributes include (but are not limited to):

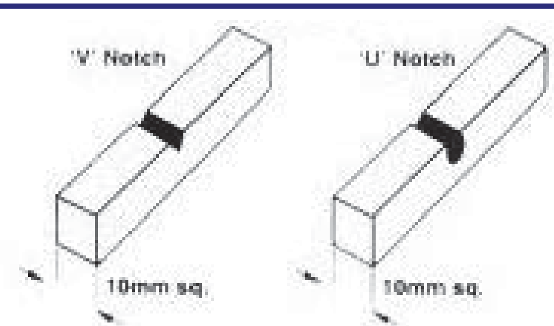
- The bending stiffness of fuel rods while taking into account the presence of fuel inside the cladding, particularly when fuel is bonded to the cladding at high burnup.
- The number of cycles to failure for high burnup fuel rods at a range of stress levels

Challenges: There were a number of unique challenges to meeting the objective.

- The objective of this testing program is to measure properties of **high burnup, irradiated fuel rods**. Normal vibration testing devices utilize **reduced gauge sections** or **pre-notched samples** to prevent failure in the grip section and ensure meaningful data. Neither of these testing approaches was acceptable to measure the failure behavior of high burnup, irradiated fuel rods to obtain meaningful indication of failure conditions during transportation. We also do not have the ability to weld local **strain gauges or utilize laser readings** on high burnup material in-cell. Finally, hot-cell space and time is extremely costly, as is testing material. The **size of the testing device, sample size and test duration all had to be kept to a minimum**. Therefore, an entirely new fatigue testing device had to be developed for this project.



reduced gauge section

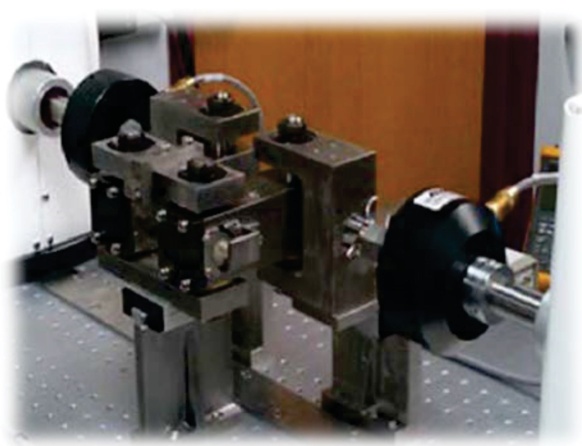


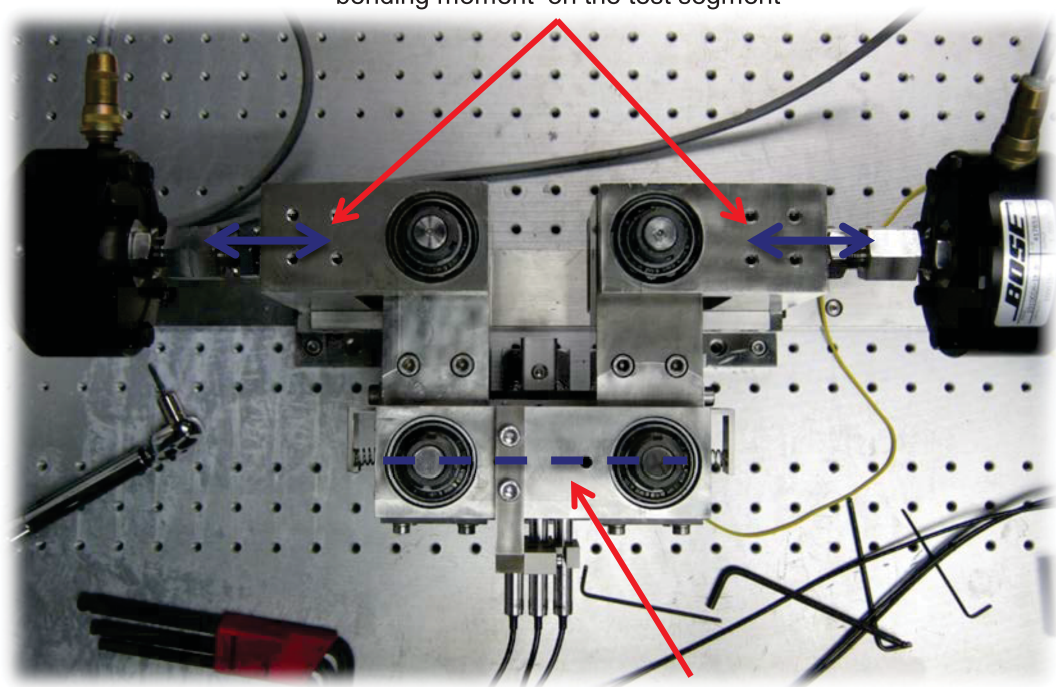
pre-notched sample

High Burnup Spent Fuel Fatigue Testing for Transportation Applications (3/6)

Testing equipment: A reversible pure bending test system was developed by Oak Ridge National Laboratory to support this NRC research project

- The test system can be used to test and characterize static bending stiffness as well as the vibration integrity of spent nuclear fuel. The reversible bending is conducted utilizing a U-frame setup with the push-pull force applied at the loading point. The deformation of the rod specimen is measured directly using three-point deflection, and therefore the curvature of deformed rod specimen can be easily estimated. The functionality of the test system has been demonstrated using surrogate rods in out-of-hot cell tests.





High Burnup Spent Fuel Fatigue Testing for Transportation Applications (4/6)

Calibration and Benchmarking: Equipment was extensively tested and demonstrates intended functionality with surrogate materials

- Multiple references summarize the calibration and benchmarking efforts using Stainless Steel cladding with Aluminum Oxide pellets as surrogate materials, some with epoxy to simulate fuel-cladding bonding effects
- Finite element analysis was used to investigate the expected influence of pellet-pellet interfaces and pellet-cladding bonding.

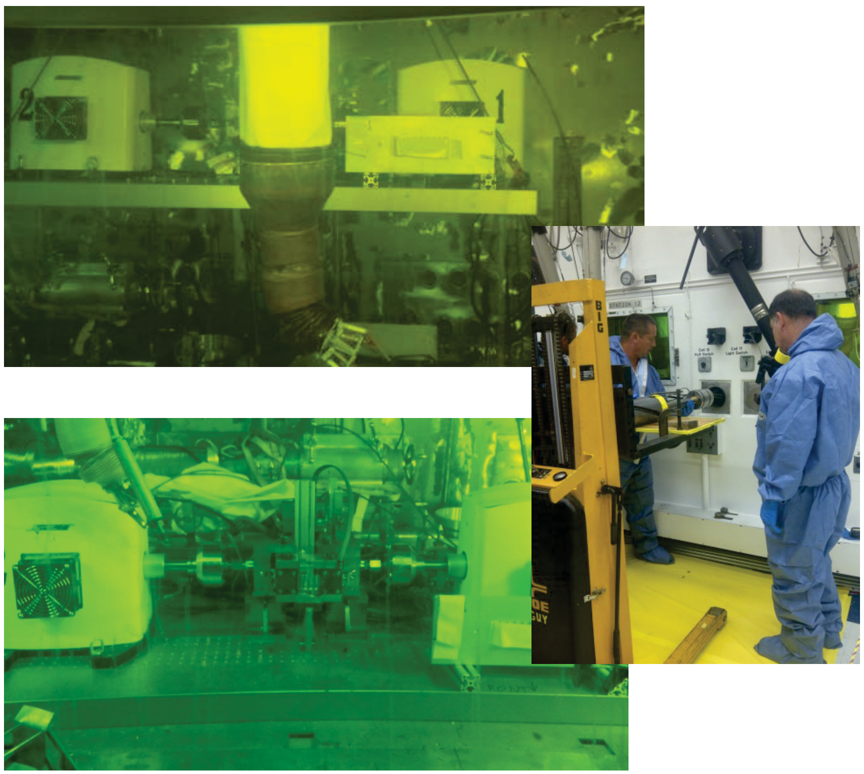
Irradiated testing: A test matrix was developed to measure important attributes of irradiated fuel.

- Cladding is Zircaloy
- Burnup is approximately 65 GWd/MTU
- Hydrogen content ranges from 350 – 750 wppm
- 5 repeat tests will measure static bending stiffness
- 9 tests at range of stress levels will measure fatigue strength

High Burnup Spent Fuel Fatigue Testing for Transportation Applications (5/6)

Status

Testing device has been installed in-cell



- First phase of irradiated testing (static testing) is complete.
  - 4 repeat tests show very consistent response under static loading
- Second Phase of irradiated testing (cyclic testing) is ongoing.
  - 4 tests to date, each conducted at different constant stress level, are consistent with an expected S-N curve

High Burnup Spent Fuel Fatigue Testing for Transportation Applications (6/6)

Conclusions and Remaining Work

- Unique and novel testing equipment has been developed to perform important measurements in-cell on as-irradiated, high burnup fueled rods
- Equipment has been extensively tested and demonstrates intended functionality with surrogate materials
- First of a kind measurements have been made of high burnup fuel to investigate critical questions on the response of high burnup fuel under transportation conditions
- Cyclic testing is expected to be completed within the first few months of CY 2014
- Final report capturing all test results will be published later this year
- We expect a number of conference papers to be prepared to share the results
- NMSS will use the results to make a determination on transportation of high burnup spent fuel.

Backup

Consequence Assessment of Fuel Failure on the Safety of Spent Nuclear Fuel Dry Storage and Transportation Packages (1/3)

Motivation: Limited data are available to distinctly characterize the cladding and fuel mechanical properties and aging phenomenon for long storage times and high fuel burnup. Recertification of dry storage casks and the growing population of high burnup fuel (> 45 GWd/MTU) prompted the need to assess the potential consequences of fuel failure during normal, off-normal, and accident conditions of spent fuel storage, and normal and accident conditions of transportation.

Scope: The report documents an evaluation of the impact of a wide range of postulated failed fuel configurations with respect to four technical disciplines.

- Criticality
- Shielding (dose rates)
- Containment
- Thermal

The report evaluated a wide range of physically realizable scenarios. However, there was no study or comparison of mechanical properties, finite element analysis stress distribution studies, or physical testing to evaluate the likelihood of each configuration.

Regulatory Application: The findings of this research effort are intended to inform the safety evaluation of SNF storage and transportation systems by identifying failed fuel configurations that would have the most significant safety concerns. Consequences of configuration changes in each technical discipline were assessed relative to the corresponding nominal intact configuration.

Consequence Assessment of Fuel Failure on the Safety of Spent Nuclear Fuel Dry Storage and Transportation Packages (2/3)

Three failed fuel configuration categories were considered. Configurations characterized by:

- Cladding failure
- Rod/assembly deformation without cladding failure
- Changes to assembly axial alignment without cladding failure.

Within configuration categories 1 and 2, multiple scenarios were identified:

- Cladding failure category
- Scenario 1(a)—breached spent fuel rods
- Scenario 1(b)—damaged spent fuel rods

Rod/assembly deformation category

- Scenario 2(a)—configurations associated with side drop
- Scenario 2(b)—configurations associated with end drop

Generic PWR and BWR transportation package / storage cask models used in previous studies were adapted for use in the analysis.

Consequence Assessment of Fuel Failure on the Safety of Spent Nuclear Fuel Dry Storage and Transportation Packages (3/3)

Status

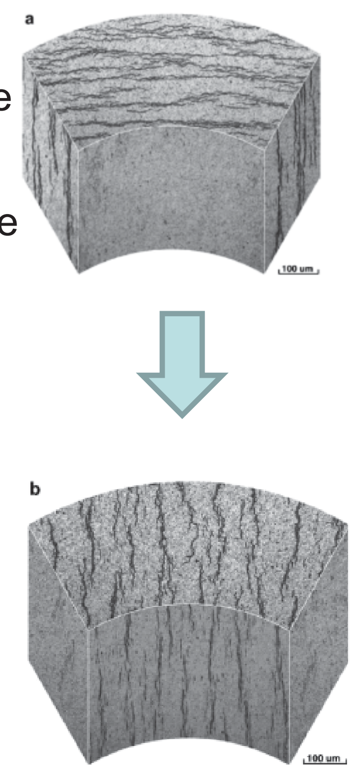
- Analysis was completed for generic PWR and BWR transportation package / storage cask models in the areas of criticality, shielding (dose rates), containment and thermal
- A final NUREG/CR was delivered to NRC by ORNL in August 2013.
- The NUREG/CR is currently under review in NMSS (the User Office),
- The NUREG/CR is expected to be published shortly.
- The staff intends to discuss the results and implications of this work at the Regulatory Information Conference later this year.

Backup

Ductile-to-Brittle Transition Temperature for High Burnup Zircaloy-4 and ZIRLO Cladding Alloys in Simulated Drying-Storage Conditions (1/2)

Motivation:

- Pre-storage drying transfer operations and early stage storage subject cladding to higher temperatures and much higher pressure-induced tensile stresses than experienced in-reactor or during pool storage.
- If these are high enough, then radial hydrides could precipitate during pre-storage operations and during dry-cask storage, resulting in a reduction in cladding ductility.
- Radial hydrides represent an additional embrittlement mechanism that can reduce cladding failure limits during storage as the cladding temperature decreases below a ductile-to-brittle transition temperature (DBTT). As such, the effects of radial hydrides must be included in structural analyses when the cladding temperature is below or marginally above the DBTT.



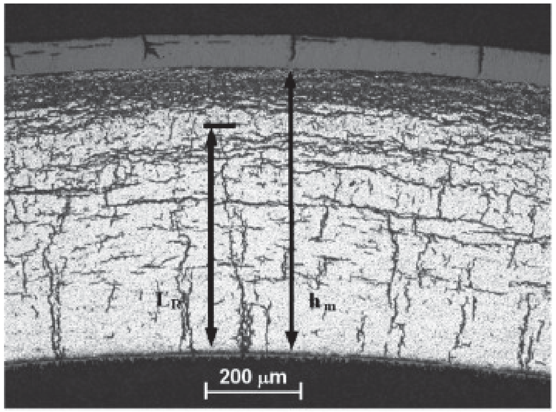
Experimental Method:

- A test procedure was developed at Argonne National Laboratory to simulate the effects of elevated temperatures, pressures and stresses during transfer-drying operations and early storage, as well as cooling slowly under decreasing pressures and stresses during both drying and storage.
- The procedure was applied to both non-irradiated/pre-hydrided (PH) and high-burnup Zircaloy-4 (Zry-4) and ZIRLO™
- The RCT was used as a ductility screening test and to simulate pinch-type loading that would occur during cask transport accidents.

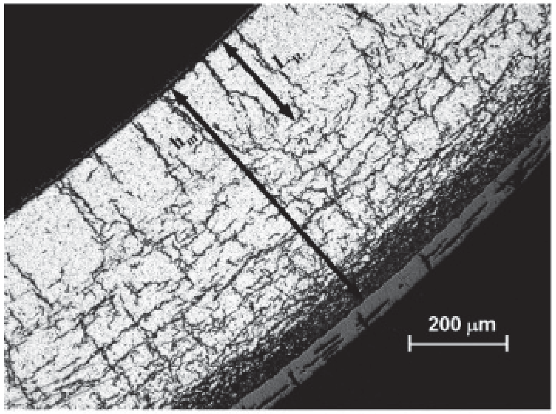
Ductile-to-Brittle Transition Temperature for High Burnup Zircaloy-4 and ZIRLO Cladding Alloys in Simulated Drying-Storage Conditions (2/2)

Conclusions and Future Work:

- It was observed that pre-hydrided cladding was a poor surrogate for high-burnup cladding with respect to the effects of simulated drying-storage conditions.
- A significant outcome of the research was the definition of metric for the correlation of radial hydride orientation with crack growth, the radial-hydride continuity factor (RHCF).
- The RHCF was observed to be correlated with the ductile-to-brittle transition temperature (DBTT), where a high RHCF resulted in an increase in the DBTT.
- RHCF and the DBTT were observed to be highly dependent on cladding material, irradiation conditions, and pre-drying distribution of hydrides across the cladding wall, as well as peak drying-storage hoop stress.
- Results have been published as an original research article, “Ductile-to-brittle transition temperature for high-burnup cladding alloys exposed to simulated drying-storage conditions,” in the Journal of Nuclear Materials*.
- DOE is conducting follow-on work investigating other cladding materials and hydrogen levels.



(a) Maximum RHCF (80%)



(b) Minimum RHCF (38%)

* M.C. Billone, T.A. Burtseva, R.E. Einziger, J. Nucl. Mater. 433 (2013) 431-448

Extended Storage of High Burnup Fuel: Cladding Stress Analysis (1/3)

Problem statement: are the stresses due to spent fuel evolution during extended storage sufficient to cause a cladding failure concern, either due to creep or to delayed hydride cracking?

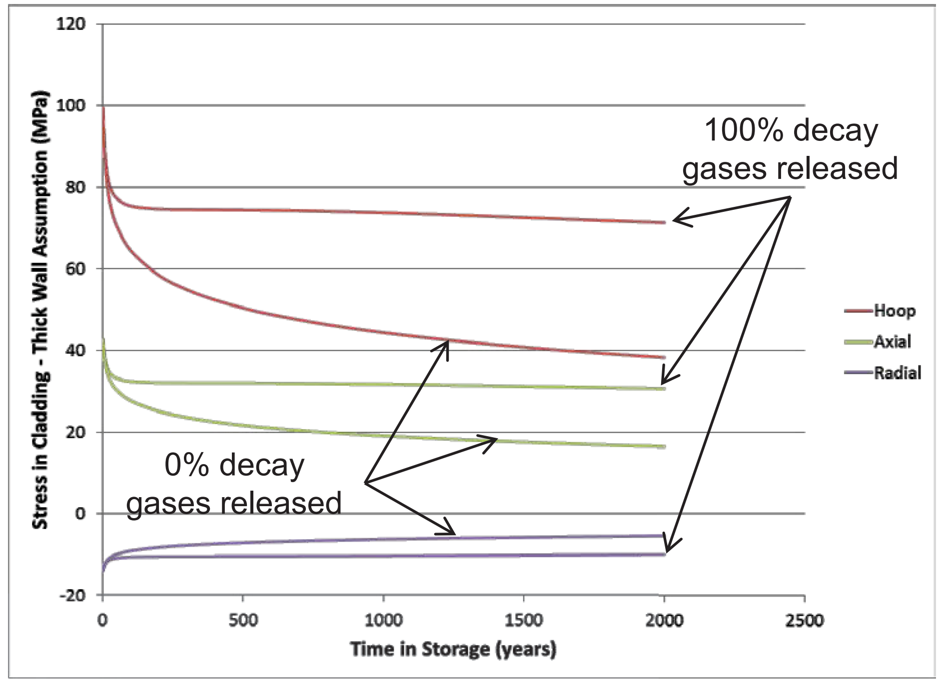
- Proposed sources of stress are plenum gas pressure, phase change of the hydrides upon cooling from drying temperatures, and swelling of the fuel due to a buildup of helium decay product (resulting in pellet-cladding mechanical interaction - PCMI).

- Subtask 4 of Task 7 under User Need NMSS 2011-002 has the following work scope:
  - Determine the cladding stress related to rod internal pressure changes over an extended storage period, based on gas production and release to the rod void volume (complete)
  - Determine the extent of fuel pellet swelling during extended storage (complete)
  - Combine the above sources of stress to calculate cladding stress and creep during extended storage (in progress)

Extended Storage of High Burnup Fuel: Cladding Stress Analysis (2/3)

Effects of decay gas production on rod internal pressure during extended storage times

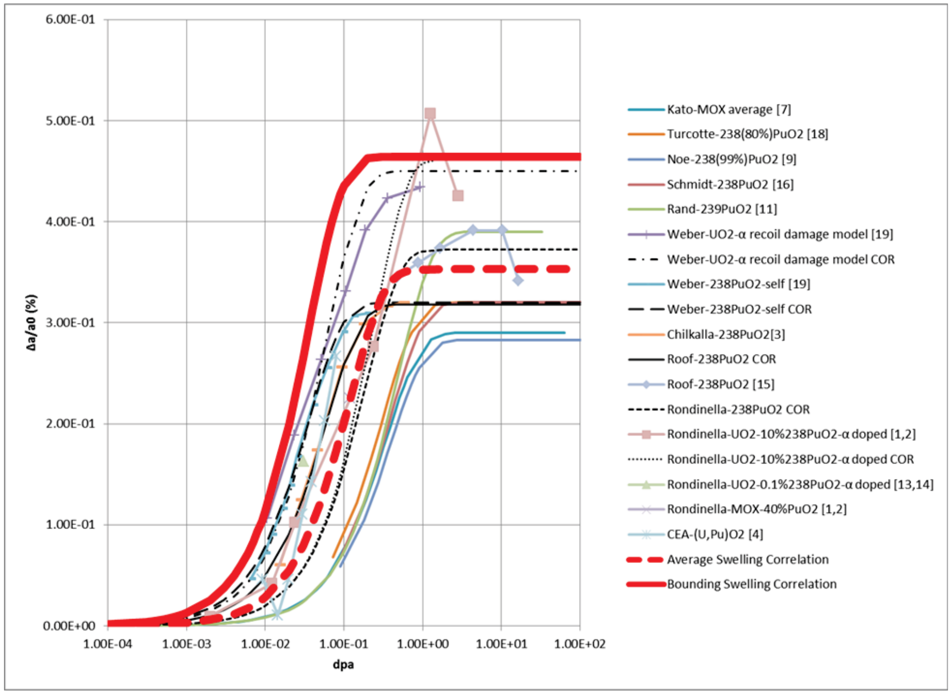
- Gas generation as a result of decay of fission products is not sufficient to increase the rod internal pressure, even if 100% of the decay gases are released to the rod void volume
- The initial calculation assumed the rod void volume is constant, but does take into account the decreasing temperature in the canister as a function of time during storage



Extended Storage of High Burnup Fuel: Cladding Stress Analysis (3/3)

Fuel pellet swelling as a result of helium production and damage accumulation during extended storage times

- Large literature survey performed
- Lattice swelling saturates around 1 dpa
  - It is estimated that spent fuel will accumulate between 0.1 and 5 dpa over a period of 100 years of storage
  - Lattice swelling saturation values vary between ~0.3 and ~0.45 (%Δa/a0)
- Best-estimate and bounding correlations for swelling have been developed
- FRAPCON fuel performance code is being modified to be able to simulate spent fuel evolution during extended storage, to obtain cladding stress and creep rates



Fuel Performance Codes FRAPCON and FRAPTRAN (1/4)

FRAPCON

- Current version is FRAPCON-3.4a
- FRAPCON-3.5 to be release in Q1-2014
  - Update to cladding creep models and hydrogen pickup models
  - Variable axial nodes and zoning for enrichment, Gadolinia, and central pellet hole
  - Expanded arrays for increased number of nodes and time steps
  - Addition of pellet chamfers
  - Investigation of correlations for fuel specific heat and high stress cladding creep
  - Revised hydrogen pickup models
  - Bug fixes and enhancements related to user group feedback
  - FRAPCON-to-FRAPCON restart and refabrication capability
- Other major accomplishments in current program
  - ARM FRAPCON statistical tool used extensively by NRR
  - SNAP plugin operational for version FRAPCON-3.4a, will be adapted for FRAPCON-3.5
  - Peer review

Fuel Performance Codes FRAPCON and FRAPTRAN (2/4)

FRAPCON

- Future development plans to be carried out over the next 2 to 3 years:
  - Major effort to modernize codes to enhance future development (Fortran 95, dynamic dimensioning, platform independence, etc…)
  - New capabilities: FRAPCON-DATING for spent fuel behavior, auto-validation tool, etc…
  - Prediction improvements: FGR, gamma heating, automatic time stepping to avoid non-convergence
  - Improved coupling with TRACE and coupling with PARCS
- FRAPCON-4.0 to be released in 2016
  - Major beta versions will be released to members of the user group

Fuel Performance Codes FRAPCON and FRAPTRAN (3/4)

FRAPTRAN

- Current version is FRAPTRAN-1.4
- FRAPTRAN-1.5 to be release in Q1-2014
  - Expanded arrays for increased number of nodes and time steps
  - Addition of pellet chamfers
  - Advanced LOCA modeling (external plenum, double sided oxidation, TH improvements)
  - Bug fixes and enhancements related to user group feedback
  - Review of ballooning models
- Other major accomplishments in current program
  - ARM FRAPCON statistical tool used extensively by NRR
  - SNAP plugin operational for version FRAPTRAN-1.4, will be adapted for FRAPTRAN-1.5
  - Peer review

Fuel Performance Codes FRAPCON and FRAPTRAN (4/4)

FRAPTRAN

- Future code development plan in place which accounts for NRC needs and user feedback
  - Major effort to modernize codes to enhance future development (Fortran 95, dynamic dimensioning, platform independence, etc…)
  - New capabilities: ARM FRAPTRAN, auto-validation tool, etc…
  - Prediction improvements: improved decay heat, improved transient TH and reflood models, improved fission product release model
  - Improved coupling with TRACE
- FRATRAN-2.0 to be released in 2016
  - Major beta versions will be released to members of the user group

The Studsvik Cladding Integrity Program: PCI (past and present) and LOCA (future) (1/2)

Three phases of the SCIP program

- SCIP-1 from 2004 to 2009: focus on PCI and cladding properties
- SCIP-2 from 2009 to 2014: focus on PCI and pellet properties
- SCIP-3 from 2014 to 2019: focus on LOCA and PCI remaining issues

SCIP PCI Research (SCIP-1 and SCIP-2)

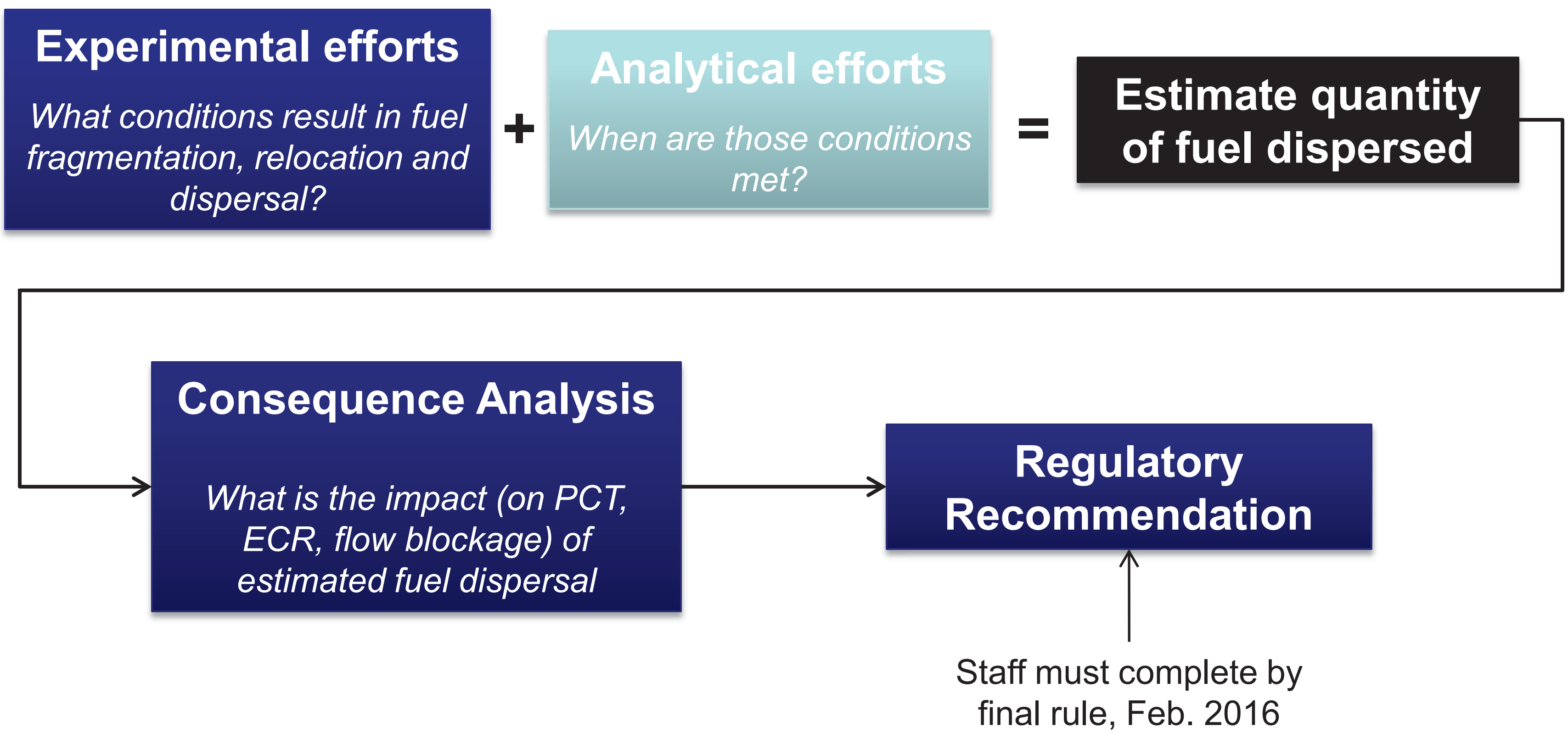
- ACRS briefing on June 17, 2013 described SCIP results relevant to PCI due to stress-corrosion cracking in PWRs, also applicable to BWRs:
  - PCI/SCC is a low probability, low consequence event, and is being managed successfully by utilities
  - The SCIP research and database includes 1119 power ramp tests (800 BWR, 213 PWR, 81 PHWR, and 25 unspecified), as well as separate effects testing and modeling
  - PCI is a complex phenomenon, and despite much research, a comprehensive mechanistic criterion has yet to be defined, largely because of the complexity of the phenomena at play, and the scatter in the available data
  - NRC/RES will continue to follow PCI research in SCIP-3 (small portion of the program), and participate in PCI modeling workshops with SCIP-3 to try to develop a PCI criterion for fuel performance codes

The Studsvik Cladding Integrity Program: PCI (past and present) and LOCA (future) (2/2)

SCIP LOCA Research (SCIP-3)

- Main focus of SCIP-3 is fuel dispersal during LOCA
- Proposal highlights:
  - Sister rod testing at Halden and Studsvik for benchmarking of past test results
  - Out-of-pile integral LOCA testing (similar to ANL and Studsvik NRC tests) and separate effects testing to determine fine fuel fragmentation burnup threshold and parameters influencing fine fragmentation, and to determine the cladding strain threshold for fuel axial mobility
  - Separate effects testing to investigate role of fuel microstructure for fragmentation
  - Effects of cladding overheating on post AOO cladding properties
  - Effects of axial load on LOCA cladding failure
- Small emphasis on PCI:
  - Effects of slow ramp rate will be investigated via separate effects tests, and in-pile ramp tests
- FSCB staff is reviewing the SCIP-3 proposal (which includes significant additional research on fuel fragmentation, relocation and dispersal) with a critical eye and intends to provide significant feedback (both written and during discussion at the next SCIP meeting in November) to help focus the intentions and value of this program

RES Fuel Fragmentation, Relocation and Dispersal Research Plan



Experimental Research on Fuel Fragmentation, Relocation and Dispersal (1/3)

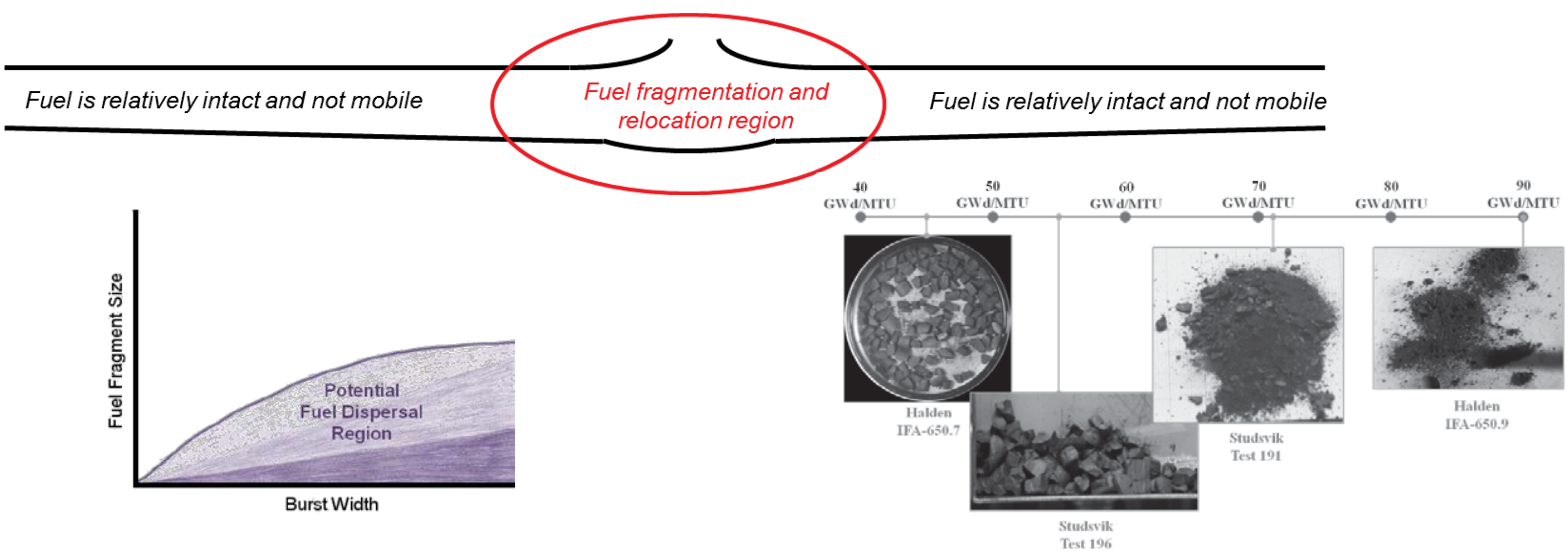
- Work presented at TOPFUEL conference and received positive feedback.
  - M. E. FLANAGAN, et al., “Fuel Fragmentation, Relocation and Dispersal under LOCA Conditions: Experimental Observations,” Proceedings of TOPFUEL 2013, Charlotte, NC, September 15-19, 2013, American Nuclear Society (2013), paper #8334.

- Presented results and conclusions to ACRS Fuel and Materials Subcommittee on December 4th, 2013

Experimental Research on Fuel Fragmentation, Relocation and Dispersal (2/3)

Conclusions of experimental research on fuel fragmentation, relocation and dispersal:

- 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.
- These threshold can be used in regulatory analysis to quantify fuel dispersal.



Experimental Research on Fuel Fragmentation, Relocation and Dispersal (3/3)

- Research staff plan to stay engaged in a number of ongoing international, collaborative experimental activities on fuel fragmentation, relocation and dispersal

  – WGFS CAPS Project:
    - OECD/NEA Working Group on Fuel Safety (WGFS) has drafted a CSNI Activity Proposal Sheet (CAPS) to provide a report which summarizes experimental findings and discusses the safety significance of fuel fragmentation, fuel relocation and fuel dispersal during a LOCA.
    - FSCB staff are developing comments and intend to recommend active participation in the report writing project.
    - The report is expected to largely overlap the work FSCB staff is already doing. We will complete our planned work independent of this effort, and we consider there will be significant value added by working with the WGFS to expand beyond our scope to the perspectives and conclusions of the international community.

  – Halden LOCA expert advisory group:
    - The HPG requested that Halden "form a 'LOCA expert advisory group' to facilitate deeper discussion on LOCA testing at Halden". We support the formation of such a expert group and intend to recommend Michelle to serve for NRC at the HPG meeting on Oct 8-9.

  – Halden 2015-2017 Program Proposal:
    - FSCB staff is reviewing the next Halden proposal (which also includes significant additional research on fuel fragmentation, relocation and dispersal) with a critical eye and intends to provide feedback at the country visit Oct 7th.

Analytical Research on Fuel Fragmentation, Relocation and Dispersal (1/3)

- Work presented at TOPFUEL conference and received positive feedback.
  - P. A. RAYNAUD, “Core-wide Estimates of Fuel Dispersal During a LOCA,” Proceedings of TOPFUEL 2013, Charlotte, NC, September 15-19, 2013, American Nuclear Society (2013), paper #7927
- Presented results and conclusions to ACRS Fuel and Materials Subcommittee on December 4th, 2013

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

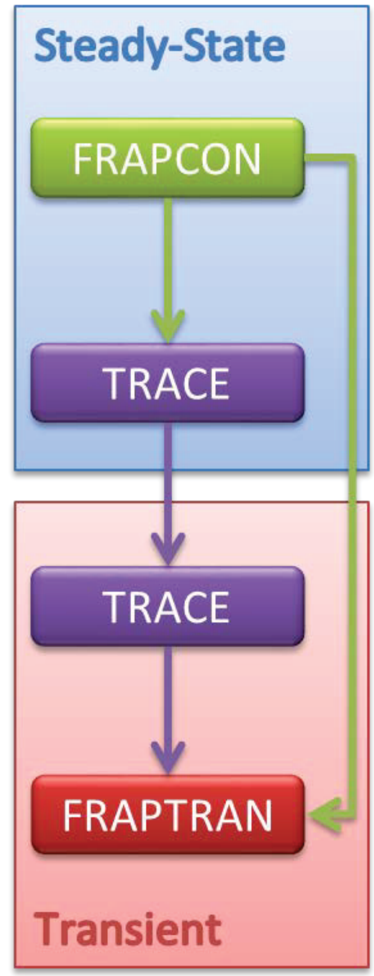
Analytical Research on Fuel Fragmentation, Relocation and Dispersal (2/3)

New approach to core-wide LOCA modeling

- Higher level of detail achieved for fuel rod thermal mechanical response
  - Each assembly modeled individually
- One of few published studies aimed at predicting amounts of fuel dispersal
- Timely predictions: calculation times under a week

Modeling strategy

- Steady-state fuel performance: FRAPCON
  - Initialization of fuel rod parameters for TRACE and FRAPTRAN
- Steady-state systems thermal hydraulics: TRACE
- Transient systems thermal hydraulics: TRACE
  - Initialization of TH boundary conditions for FRAPTRAN calculation
- Transient fuel performance: FRAPTRAN



Analytical Research on Fuel Fragmentation, Relocation and Dispersal (3/3)

Completed analyses

- PWR plants
  - 4-loop Westinghouse plant LB-LOCA (3 variants: ideal plant response, LOOP, 1 train of ECCS inoperable): less than 10kg of fine fuel dispersal for 1 ECCS case
  - 2x4 CE plant LB-LOCA 50% complete
- BWR plants
  - GE BWR/4 LB-LOCA and SB-LOCA: low PCT and no fuel rod ruptures

Future analyses

- PWR plants
  - 2x4 B&W plant LB-LOCA and SB-LOCA
  - Westinghouse 2-loop LB-LOCA
  - Westinghouse 3-loop LB-LOCA
- BWR plants
  - GE BWR/2
  - GE BWR/3

Accident Tolerant Fuels (ATF): Overview of DOE and Industry Activities (1/4)

- NRC monitors DOE and industry activities related to the development of ATF
  - Open information exchange to be able to provide regulatory feedback when it becomes necessary
  - Anticipation of potential regulatory research for the licensing of ATF
  - NRC has been an observer to date, but DOE recently asked for more feedback and involvement

- DOE has an aggressive research program aimed to insert LTRs or LTAs in a commercial reactor by 2022
  - Irradiations of candidate materials is to begin in ATR in 2014

- NRC RES will continue to actively engage with DOE and industry with regards to ATF development and licensing strategy

- NRC RES will engage in regulatory research if needed, after down-selection between the many ATF concepts has been performed

Accident Tolerant Fuels: Overview of DOE and Industry Activities (2/4) [From DOE briefing to NRC on November 21, 2013]

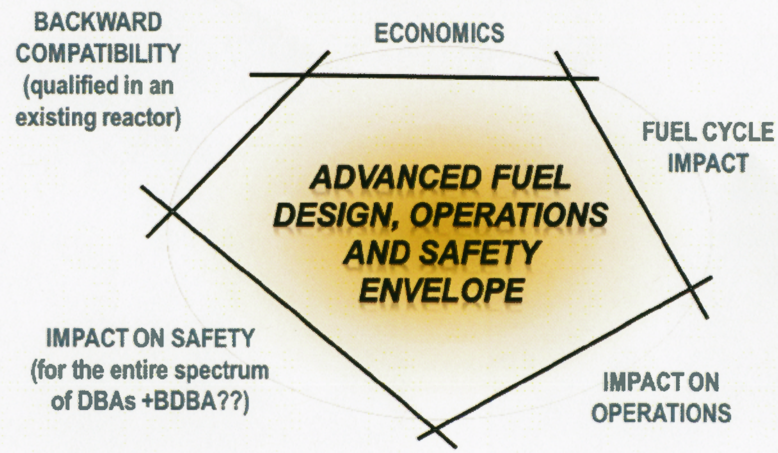
Accident Tolerant Fuel became a major focus area for DOE after Fukushima

- DOE's nuclear fuel R&D program was exploring the development of next generation of LWR fuels with enhanced performance.
  - Increased burnup – reduced waste volume
  - Increased reliability – reduced failures
  - Higher power density – power upgrades
- After the unfortunate events in Fukushima (March 2011), the U.S. Congress directed DOE to focus efforts on development of fuels with enhanced accident tolerance.
- Accident Tolerant Fuel development program is being implemented as a collaborative effort among National Laboratories, Industry and Universities within the U.S.
- Due to the nature of the problem, international collaborations are essential.

ATF for a LWR System Should Tolerate Loss of Active Cooling for A Significant Period of Time

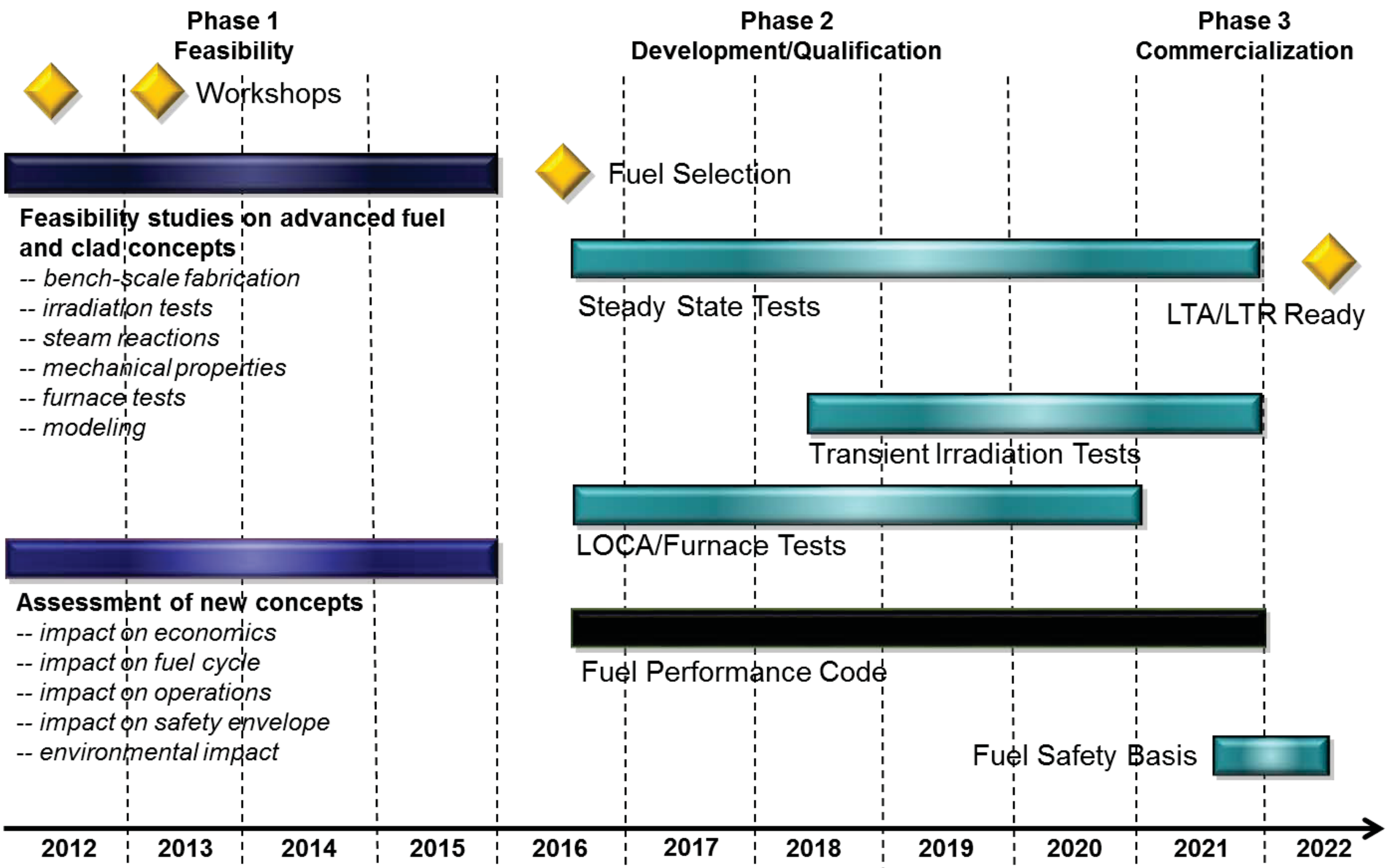
Fuels with enhanced accident tolerance *are those that, in comparison with the standard UO_2 – Zr system, can* tolerate loss of active cooling *in the core for a* considerably longer time period *(depending on the LWR system and accident scenario) while maintaining or improving the fuel performance during normal operations.*

New ATF Designs Must Meet the LWR Operations, Safety and Fuel Cycle Constraints



Accident Tolerant Fuels: Overview of DOE and Industry Activities (3/4) [From DOE briefing to NRC on November 21, 2013]

RD&D Strategy For Enhanced Accident Tolerant Fuels – 10 Year Goal



Accident Tolerant Fuels: Overview of DOE and Industry Activities (4/4) [From DOE briefing to NRC on November 21, 2013]

ATF program focus on cladding materials with more benign steam reaction

- **Advanced steels (e.g. FeCrAl)**
- **Refractory metals (e.g. Mo)**
- **Ceramic cladding (SiC)**
- **Innovative alloys with dopants**
- **Zircaloy with coating or sleeve**
  - SiC (INL research)
  - MAX-phase ceramics

New advanced fuel concepts also are being considered

- **Higher density fuels (metal, nitride, silicide) (some INL research)**
  - Higher thermal conductivity
  - Higher fissile density to compensate for neutronic inefficiency of some new clad concepts without increasing enrichment limits
- **Oxide fuels with additives**
- **Microencapsulated fuels**
  - TRISO or BISO fuel dispersed in a ceramic or metallic matrix

Each concept has some pros and cons across the spectrum of operating and transient conditions of interest. A systematic analytical and experimental evaluation is being performed during the feasibility studies.

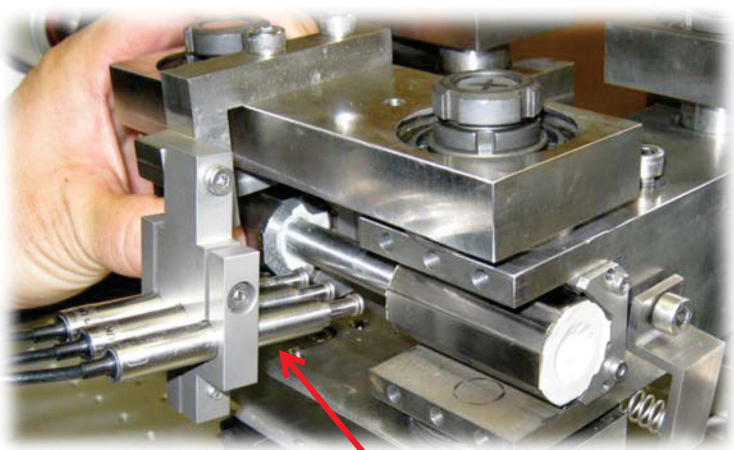
Emerging Fuels Research

In the future, the following areas stand out as likely to grow in importance and staff focus:

- Small Modular Reactors (SMR) fuel licensing and analysis needs
  - Developing an understanding of the potential neutronics, thermo-mechanical and accident behavior of nuclear fuel in SMRs.
  - Modifying current codes and methods to address these differences
  - Potentially developing new tools and methods to address issues particular to SMRs
- Spent fuel storage and transportation, as well as ultimate disposal solutions
  - High burnup issues
  - Advanced fuel cycle and fuel designs
  - Reprocessing and/or disposal
- The need for a more localized, dynamic and synergistic picture of the core to handle new fuel requirements and operating practices
  - LOCA requirements are moving towards hydrogen-based criteria, requiring for more detailed core modeling and analysis than the traditional “hot rod” focused analysis. Effective coupling between thermal-hydraulic and fuel performance codes is growing in importance.
  - RIA requirements are also hydrogen-based and dominated by localized effects. Effective coupling between neutronics and fuel performance codes is growing in importance.
- Increased focus on statistical analyses for fuel behavior during steady-state and transients
  - Move towards best-estimate calculations with uncertainty quantification, rather than bounding calculations with conservative assumptions
- Optimization of international collaborations to have better information exchange, better leverage of resources, and better input in international programs
  - Shrinking budgets and increasingly complex research programs

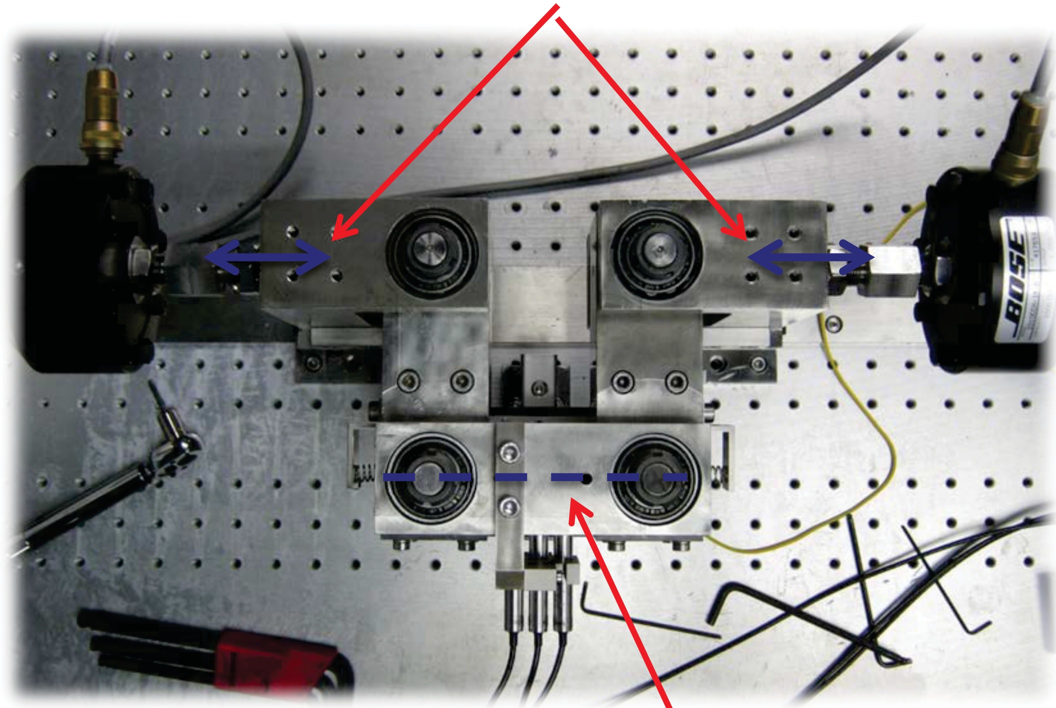
BACKUP SLIDES

Backup slides: *High Burnup Spent Fuel Fatigue Testing for Transportation Applications*



3 LVDTs measure the curvature of the sample along the gage section direction.

Push-pull force applied to U-Frame results in bending moment on the test segment



Location of test segment

Top Left: The grip sections have been uniquely designed to induce uniform bending moment (without local pinching loads) across the gauge sections

Bottom Left: The grip design provides for easy loading into the test device and enables frictionless grip in combination with roller bearing design

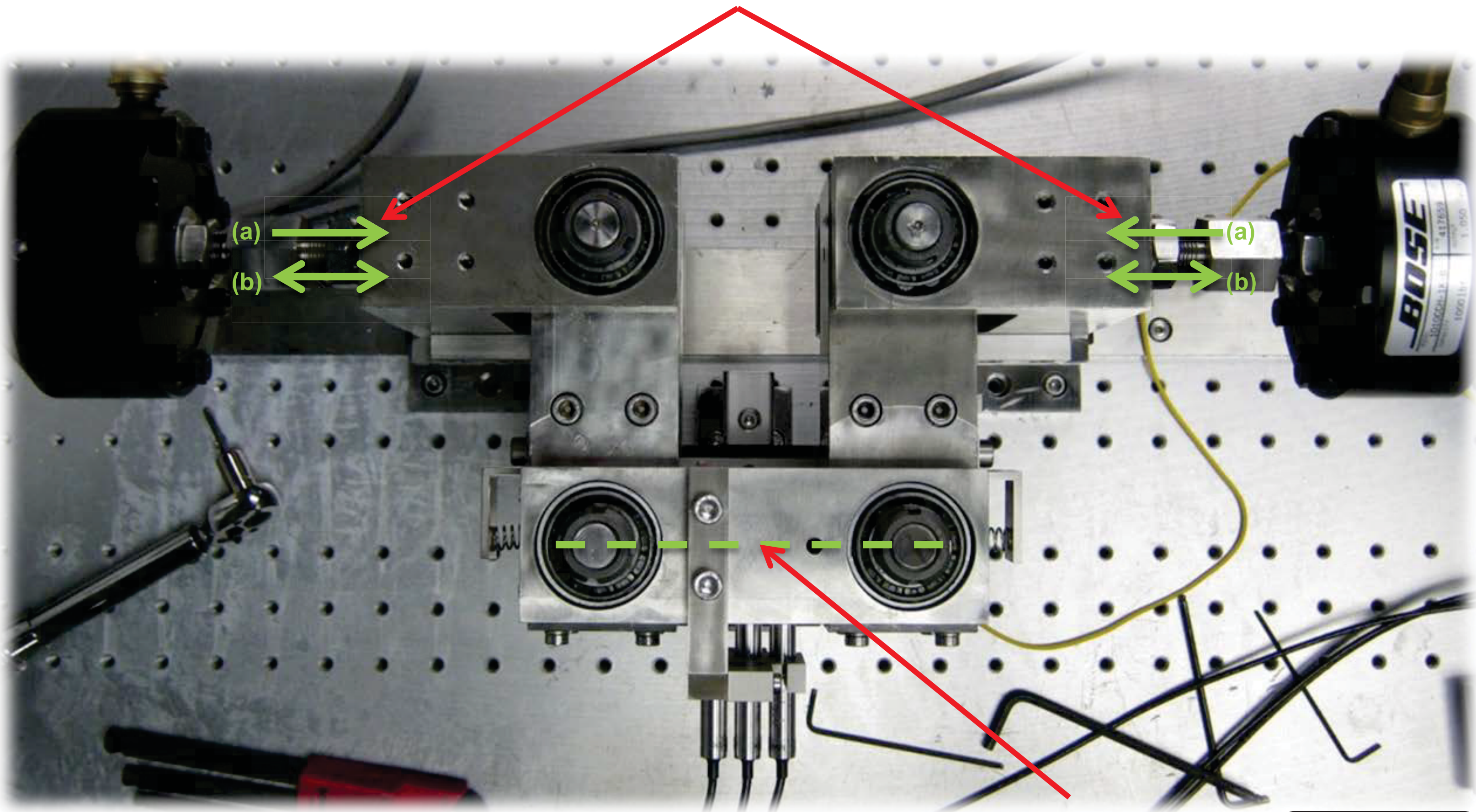
Right: Test device seen from above. Final design utilizes two electro-magnetic motors, a U-frame design and a horizontal setup, enabling pure reversible bending with versatility in input functions (frequency, magnitude etc) and frictionless operation.

Back

Backup slides: *High Burnup Spent Fuel Fatigue Testing for Transportation Applications*

(a) In static mode, the Bose linear motors operate in displacement control mode and apply quasi-static displacement to a maximum stroke of 12 mm in one direction. This displacement is translated to the test segment as a uniform static bending moment.

(b) In dynamic mode, the Bose linear motors operate in load control mode and they apply a set loading amplitude by applying displacement in two directions (+/- from the neutral test segment position). This loading is translated to the test segment as a reserve-bending cyclic bending moment.



Location of test segment

Back

Backup slides: *Consequence Assessment of Fuel Failure on the Safety of Spent Nuclear Fuel Dry Storage and Transportation Packages*

- Generic pressurized water reactor (PWR) transportation package/storage cask model
  - Representative of high-capacity-type casks/packages, referred to as generic burnup credit (GBC)-32
  - The PWR models contain 32 17 × 17 PWR fuel assemblies representative of a Westinghouse (W) optimized fuel assembly (OFA) design

- Generic boiling water reactor (BWR) transportation package/storage cask model
  - Representative of high-capacity-type casks/packages, referred to as generic burnup credit (GBC)-68
  - The BWR models contain 68 10 × 10 BWR fuel assemblies representative of a General Electric-14 (GE14) design.

- Different initial fuel enrichments (1.92 to 5.0 wt % 235U), burnups (0 to 70 GWd/MTU), and decay times (5 to 300 years) were considered in the analyses.

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Backup slides: *Consequence Assessment of Fuel Failure on the Safety of Spent Nuclear Fuel Dry Storage and Transportation Packages*

Codes and Methods

- Criticality:
  - The Scale code system was used to perform the keff and depletion calculations necessary for these analyses. All calculations used the 238-group neutron data library based on Evaluated Nuclear Data Files, Part B (ENDF/B)-VII.0, distributed with the Scale system.
  - The KENO V.a and KENO-VI Monte Carlo codes were used for keff calculations within the appropriate Criticality Safety Analysis Sequence-5 (CSAS5) and CSAS6 sequences. Both codes use Monte Carlo transport to solve the keff eigenvalue problem. KENO-VI uses a generalized geometry process and is used for the fuel pellet array configuration and some increased fuel rod pitch configurations. KENO V.a has a more restrictive geometry package but is significantly faster because of the simpler geometry treatment. KENO V.a is used for the majority of configurations considered in this analysis.
  - For calculations involving irradiated fuel compositions, the isotopic compositions were generated with the Standardized Analysis of Reactivity for Burnup Credit using Scale (STARBUCS) sequence . STARBUCS is a sequence to perform criticality calculations for spent fuel systems employing burnup credit. The STARBUCS sequence uses the Oak Ridge Isotope Generation and Depletion Code–Automatic Rapid Processing (ORIGEN-ARP) methodology to generate depleted fuel compositions and uses the compositions in a KENO model to calculate keff.

- Shielding:
  - The radiation source terms for the shielding analysis were determined with the depletion and decay capabilities of the Scale 6.1.2 code system, including Transport Rigor Implemented with Time-Dependent Operation for Neutronic depletion (TRITON), Oak Ridge Isotope Generation and Depletion Code–Automatic Rapid Processing (ORIGEN-ARP), and Oak Ridge Isotope Generation in Scale (ORIGEN-S). The neutron and gamma radiation source terms were calculated in the group structure of the Scale 27N-19G Evaluated Nuclear Data Files, Part B-VII.0 (ENDF/B-VII.0) shielding library.
  - The Scale 6.1.2 shielding analysis sequence Monaco with Automated Variance Reduction using Importance Calculations (MAVRIC) and the Scale 27N-19G ENDF/B-VII.0 shielding library were used to perform Monte Carlo transport and dose rate calculations. MAVRIC uses Denovo, a discrete ordinates code [30], to determine particle importance as a function of position and energy and uses Monaco to perform Monte Carlo transport calculations. Radiation transport optimization is accomplished by: (1) sampling more often source particles that have an ability to produce a significant dose rate value outside the source regions, and (2) reducing the variance of particle scores in the spatial region of interest. The MeshView utility in the Scale code system enables visualization of detailed radiation dose maps produced by MAVRIC.
  - The American National Standards Institute/American Nuclear Society Standard 6.1.1-1977 flux-to-dose-rate conversion factors were used in all dose rate calculations, as recommended in NUREG-1617 and NUREG-1536.

Backup slides: *Consequence Assessment of Fuel Failure on the Safety of Spent Nuclear Fuel Dry Storage and Transportation Packages*

Codes and Methods

- Containment:
  - The radionuclide activities of the W 17 × 17 OFA and GE14 assemblies were calculated with the depletion and decay capabilities of the Scale 6.1.1 code system [30], including Transport Rigor Implemented with Time-Dependent Operation for Neutronic depletion (TRITON) and Oak Ridge Isotope Generation in Scale (ORIGEN-S). The Scale 238-group Evaluated Nuclear Data Files, Part B-VII.0 (ENDF/B-VII.0) nuclear data library was used in the TRITON depletion calculations.
  - Analysis results are provided for releasable source term, the effective A2 value for the total source term, allowable radionuclide release rate, and allowable leakage rate at operating conditions for the GBC-32 and GBC-68 casks described in the shielding analysis section. The calculation methodology described in NUREG/CR-6487 and the containment acceptance criteria provided in 10 CFR Part 71 were used in this study.
- Thermal:
  - The thermal analysis used the Coolant Boiling in Rod Arrays—Spent Fuel Storage (COBRA-SFS) cycle 3 and the RADGEN cycle 3 computer codes. COBRA-SFS has been validated and used extensively to analyze SNF storage casks and transportation packages. The software was developed by Pacific Northwest National Laboratory (PNNL) and tailored specifically for transportation package/storage cask analysis. The code includes convection, conduction and thermal radiation heat transfer and can accommodate a range of environmental boundary conditions, fuel assemblies and transportation package/storage cask designs. View factor information for the assemblies, which is required by COBRA-SFS, is generated using the RADGEN code. The RADGEN code determines thermal radiation view factors analytically for each pin in an assembly as well as other cavity view factors.
  - Both the COBRA-SFS cycle 3 and RADGEN cycle 3 computer codes will be used "as-is". Code modifications were not included within the work scope. Any code deficiencies or limitations found during the conduct of this work are reported and discussed.

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