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NUCLEAR REGULATORY COMMISSION

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ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

(ACRS)

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THERMAL-HYDRAULIC PHENOMENA SUBCOMMITTEE

MATERIAL, METALLURGY, AND REACTOR FUELS SUBCOMMITTEE

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JOINT MEETING: REVIEW OF THERMAL CONDUCTIVITY DEGRADATION

+ + + + +

WEDNESDAY

FEBRUARY 20, 2013

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ROCKVILLE, MARYLAND

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OPEN SESSION

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

COMMITTEE MEMBERS:

SANJOY BANERJEE, Subcommittee Chairman
J. SAM ARMIJO, Member
MICHAEL L. CORRADINI, Member*
JOY REMPE, Member
STEPHEN P. SCHULTZ, Member
WILLIAM J. SHACK, Member
GRAHAM B. WALLIS, Consultant

NRC STAFF PRESENT:

MARK L. BANKS, Designated Federal Official
WEIDONG WANG, Designated Federal Official
PAUL CLIFFORD, NRR
JENNIFER GALL, NRR
CHRIS JACKSON, NRR
ANTHONY MENDIOLA, NRR
BENJAMIN T. PARKS, NRR
CHRIS VAN WERT, NRO

ALSO PRESENT:

KEN GEELHOOD, PNNL

*Present via telephone

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Adjourn

P R O C E E D I N G S

8:31 a.m.

Opening Remarks

CHAIRMAN BANERJEE: The meeting will now come to order. You all ready? Okay. This is a meeting of the Joint ACRS Subcommittee on Thermohydraulics Phenomena, and Materials Metallurgy and Reactor Fuels, standing Subcommittees of the Advisory Committee on Reactor Safeguards.

I'm Sanjoy Banerjee, chairman of the Thermohydraulic Phenomena Subcommittee. ACRS members in attendance are Sam Armijo, Stephen Schultz, Joy Rempe, Bill Shack and Mike Corradini is on the phone. Our ACRS consultant, former ACRS chairman, Dr. Graham Wallis, is also present.

Mark Banks and Weidong Wang of the ACRS staff are the Designated Federal Officials for this meeting. In this meeting, the joint Subcommittees will review and discuss the thermal conductivity degradation TCD issue, how TCD impacts legacy fuel, mechanical design codes and how TCD effects on safety analysis will be the main subjects.

We will hear presentations from the NRC. We have received no written comments or requests for time to make oral statements from members of the public regarding today's meeting. For some items on the agenda, the presentations will be closed in order to discuss information that is proprietary to the fuel vendors and licensees, pursuant to 5 U.S.C. 552(b)(C)(4). Attendance at these portions of the meeting dealing with such information will be limited to the NRC staff and its consultants, and to those individuals and organizations who have entered into an appropriate confidentiality agreement with them.

Consequently, we will need to confirm that we have only eligible observers and participants in the room for the closed portions. The joint Subcommittee will gather information, analyze relevant issues and facts, and formulate proposed positions and actions, as appropriate, for deliberation by the full Committee.

The rules for participation in today's meeting have been announced as part of the notice of this meeting previously published in the *Federal Register*. A transcript of the meeting is being kept and will be made available as stated in the *Federal Register* notice.

Therefore, we request that participants in this meeting use the microphones located throughout the meeting room when addressing the joint

Subcommittee. The participants should first identify themselves and speak with sufficient clarity and volume so that they may be readily heard.

Okay. We'll now proceed with the meeting. Just to inform the joint Subcommittees, this is primarily an informational meeting. We can, of course, discuss it at the end and decide what we want to do.

But at the moment, no letter will be required. This is an evolving matter, and at some point, of course, the staff will come to us with a, probably with a request for a letter. But that's in the future.

So with that, I'm going to turn it over to -- I think it's -- is it going to be Chris Jackson or is going to be you, Paul. Okay, hi Chris.

<u>Introduction</u>

MR. JACKSON: Good morning. Thank you very much. First of all, I want to thank the ACRS for the opportunity to give you a briefing. It's my understanding that we haven't given you a briefing on this topic since last spring, so it's timely.

I want to reiterate, we're not requesting a letter. This is an informational briefing, but we hope we have a frank and open discussion. As you all know, all vendors have taken some action to address the TCD issues. The actions vary among vendors, and we haven't come to a conclusion one way or the other yet.

The estimated effects on TCD also vary quite a bit. In some cases, it's limited or no effect; in other cases, it's quite high, 200 or 300 degrees. We've received 50 to 60 reports already, so we've made quite a bit of progress. But we continue to work. With that, I'll turn it over to the staff, and thank you for the opportunity to brief you.

CHAIRMAN BANERJEE: Thank you, Chris. Is that Paul now?

MR. JACKSON: Yes.

CHAIRMAN BANERJEE: All right. Go ahead.

Overview of TCD Issue

MR. CLIFFORD: Okay, good morning. The purpose of today's briefing is to provide a status report on TCD. I will begin by introducing the cause and effect of the degradation and thermal conductivity, and provide a time line illustrating the availability of data in the approval of the current fuel performance models.

Ken Geelhood from PNNL will provide the second presentation. He will describe the algorithms used in the fuel thermal solution, their calibration and validation and the supporting empirical database in more detail.

In the third presentation, I will describe the impact of TCD on each of the fuel performance codes, along with the short-term and long-term corrective actions.

Ben Parks from the Reactor Systems Branch will provide the fourth presentation, where he will describe the impact of TCD on downstream safety analysis, and the steps taken by the staff to address this issue, and in the last presentation, I will address the root cause and corrective actions.

Irradiation damage, the build up of fission products, pellet cracking, changes in grain structure, changes in velocity all affect the transfer to the fuel pellets.

Legacy fuel performance codes do not include a reduction in thermal conductivity with increasing exposure, because earlier test data was inconclusive at the time that these codes were approved.

At the beginning of 1990's, measurements collected at the Halden research reactor through their instrumented fuel assemblies have provided sufficient evidence to demonstrate the fuel thermal conductivity is in fact a real issue that needs to be addressed.

MEMBER ARMIJO: Paul, before you go further, help me understand the second bullet. The legacy fuel rod codes didn't explicitly include a thermal conductivity degradation effect.

But if the codes were calibrated against high burnup fuel data, let's say fission gas release data or cladding, diametrical change or something like that, it's buried in there.

The effects are in the, in the really to get into the codes in some way, although they don't know what part of the fission gas release resulted due to thermal conductivity degradation, what it could do to telecracking and relocation and all of those other things.

So to a certain extent, it seems to me that if the fuel codes were calibrated against, you know, quality high burnup data, the effect is in there somewhere, but it's not explicit and what's missing?

MR. CLIFFORD: Well, the short answer is that there are integral tests that are needed to calibrate kind of the overall effects and the feedback effects within the fuel rod. As you mentioned, fission gas release. Yes, there's always been -- I shouldn't say "always been." There has been a good amount of fission gas release data at high burnup fuel.

So you could tune your model so that the fission gas release was correct. So that piece of the equation was okay. But your fuel temperature would have been artificially low, and that would have impacted other calculations in the performance.

MEMBER ARMIJO: So until you could separate the TCD effect by itself, right, you really --

MR. CLIFFORD: That's an artificially high fission gas release model, based on the actual temperatures that were being predicted. We'll get into that in a little detail in the second presentation, when we talk about the calibration of each of the models. Okay.

MEMBER SCHULTZ: That's how you would expect it to result, that you'd have a conservative prediction of fission gas release if the model or temperature was incorrect?

MR. CLIFFORD: Because you were tuning it. You're forcing, you are forcing the algorithm to match the data.

MEMBER SCHULTZ: Right.

MR. GEELHOOD: Because the inputs to like a fission gas release model, like the diffusivity of gas within the grain, isn't something that's readily measured. So a lot of times that's something that needs to be tuned, and so if your model's under breaking temperature, then your diffusivity would be tuned artificially higher.

MEMBER REMPE: But other phenomenon like the stored energy in the fuel, among other things, would be gone, right?

MR. CLIFFORD: Yes.

MEMBER REMPE: So that's --

MR. CLIFFORD: It would affect multiple things. It would affect cladding strain. It would affect stored energy, it would affect other things, and we'll get into that.

MEMBER SCHULTZ: So some things could be correct, but it would be by happenstance, and therefore you need to adjust it to understand the influence of different parameters that would be characterized in the model.

MR. CLIFFORD: Correct, and further in the presentations, you'll see where vendors have looked at each calculation and found that some remained conservative, in spite of TCD, while other ones needed augmentation factors. That will be clear.

CHAIRMAN BANERJEE: I guess the questions that you're facing are arising from three previous letters we wrote, in which -- which OPP was that? Which said that in spite of the fact that you show temperatures to the TCD might be incorrect, the fission gas release was okay. It was tuned, based on data.

I mean that was the impression we had. I think this was the cause of this questioning. What we are seeking at some point you will give us is confirmation that the fission gas release, based on the legacy codes, was okay. Okay. Let's move on.

MR. CLIFFORD: Okay. This slide illustrates the degradation of fuel thermal conductivity, and in the next presentation, we'll get into much more detail and show you the algorithm there used to solve fuel thermal conductivity and the temperature and burnup effects.

They're kind of semi-empirical correlations, in that it's a mathematical form that we -

CONSULTANT WALLIS: Because I realize there are different models which give somewhat different results. This is an atypical result.

MR. CLIFFORD: This is the model --

CONSULTANT WALLIS: It's FRAPCON, this is FABCON.

MR. CLIFFORD: This is FRAPCON. But for instance Halden has a model that's similar, and other vendors may have similar models.

MEMBER CORRADINI: Can I ask a question about the models? Are we on Slide 4?

MR. CLIFFORD: Yes.

MEMBER CORRADINI: Okay. So let's just take one of these curves that are just a correlation. Is the correlation approach with data to get the median or the mean, and then develop a 1, 2 or 3-sigma, or is the approach to get the lowest thermal conductivity of the data?

I'm trying to understand this, relative to other correlations that I've used. So if this is not the appropriate time, when you get to it, I'd like to know how you correlated.

MR. GEELHOOD: I mean the quick answer is these are best estimate models, but we'll talk more about how uncertainties are applied maybe a little bit later.

MEMBER CORRADINI: Okay. Okay, thank you.

MR. CLIFFORD: Okay, on Slide 5. This is an important slide, because it illustrates the evolution of the Halden fuel temperature database. Each symbol represents in the reactor, online, center line temperature measurements taken over a period of time in the Halden reactor for multiple fuel rod segments within their instrumented test rates.

CONSULTANT WALLIS: Does the X axis mean anything?

MR. CLIFFORD: The X axis is the date of the publication of the report.

CONSULTANT WALLIS: Does that mean anything, in terms of interpreting the data?

MR. CLIFFORD: What I'm trying to get --

CONSULTANT WALLIS: Does it get better with time or something? I mean does time matter?

MR. GEELHOOD: You get access to more data as time progresses, and so you know, in 1980, we only had temperature gauge --

CONSULTANT WALLIS: But we should believe IFA 681 more than Slide 1-3?

MR. GEELHOOD: Not necessarily, but more data's available to validate models later, at a later date.

MEMBER CORRADINI: If I might just ask, however, ask a question. Also as these tests progress, these are different burnups right? So there's kind of like another axis here that as time progresses, you guys are doing different burnup amounts?

MR. CLIFFORD: Correct, and that's the key point I'm trying to make here.

MEMBER CORRADINI: Right. That's what I thought.

MR. CLIFFORD: So high burnup data wasn't available prior to 1990. The highest was 432, which is up to 40 gigawatt days.

So models tuned before that time were tuned to the data that was available, and as time went on in the 1990's, all the programs took on higher burnup fuel rod segments, and was able to collect data that was then used to tune more recent codes.

If I add to the X axis, here, I'm adding, this is Slide 6. This is the approval date of each of the current fuel rod performance codes.

MEMBER ARMIJO: Oh, that's good.

MR. CLIFFORD: So this really illustrates what data was available when each code was approved. So just as an example, if you look at GSTRM, which was the legacy GE code, when it was approved, there was very little data. There was no high burnup data available to validate connectivity models within --

There was maybe fission gas release data available, and maybe it was tuned correctly for that. But no integral center line fuel temperature measurements which could have been used to validate the fuel temperature predictions.

MEMBER ARMIJO: I believe at that time, GE had its own proprietary rigs at Halden, measuring temperatures. But most of the data was empirically fitted to right from measurements of actual fuel rods.

MR. CLIFFORD: The only data I'm showing here, this is the $U0_2$ and gad rods from Halden that are publicly available, that have been used to tune FRAPCON.

MEMBER REMPE: What kind of fuels? What bender fuels? Are they a mixture? There's all this proprietary stuff from various vendors, and then the community test --

MR. CLIFFORD: Yes.

MEMBER REMPE: Are these foreign fuel tests?

MR. GEELHOOD: So the NRC participates in the Halden program, and the program decides where they're going to get the fuel from. So most of these are probably from U.S. vendors.

MEMBER REMPE: And a mixture, and you don't see anything skewing, a vendor that has considerably different results versus another vendor?

MR. GEELHOOD: No, we don't see a lot of difference in, you know, pellet structure from one vendor to another, cladding, you know, the effect of cladding.

MEMBER REMPE: The fission gas release is individually tagged for each fuel rod. So you would notice that Fuel Rod A released gas, versus Fuel Rod B in a particular checkout?

MR. GEELHOOD: Yes, and the Halden test is not 100 percent prototypic of a PWR, and so it's really designed more to get one thing, in this case temperature, or they might want to get one thing like creep, knowing that the fission gas release that occurs, while it's important for the prediction for that test, may not be prototypic of the fission gas release that you get in a commercial plant.

MEMBER REMPE: And furthermore, these fuel rods would have shortened the gap between the fuel and the cladding to get thermal conductivity better?

MR. GEELHOOD: They may do different things like that, or they have gas flow rates and so they can vary the gas in the gap, to change the temperature of the rod. So they can do a lot of those kind of tests, because they're looking at one particular thing, and maybe for one test they're not as interested in gas release.

MEMBER REMPE: Okay. So that's something to keep in mind, when we look at FRAPCON results, compared to what you're doing to the vendors in the future for EPUs, is that it's a good benchmark. But there are some things in the FRAPCON code that may --

MR. GEELHOOD: And you'll see in a minute. But the Halden test is not the only place we get things for FRAPCON. We also, you know, our gas release models are tuned more from other test data and commercial rods, because we -- because that's something that's easy to get during a post-radiation examination, is to get that gas release puncture data.

So we can tune to a more prototypic set of gas release data, whereas with temperature, you can't measure it anywhere outside the Halden reactor. So to validate our temperature models, we use Halden.

MEMBER REMPE: But it's an in-state, or you actually take a rod and puncture it and put it in a furnace and do it as a function of time, or you just get the end state?

MR. GEELHOOD: Well yes. So we get one

point for that, because you know, you take it out and you puncture it and find out how much gas has been released. Halden has the capability to measure online pressure, but it's not always the best way to really figure out what the gas release is, because sometimes the puncture data doesn't necessarily match the online pressure.

MEMBER CORRADINI: If I might follow on Joy's question, just so I understand. So when you do this separate test for puncturing to get the integral amount of gas, when you do a back correlation of it, is the assumption that the gas is sitting in the gap, or how -- and this is not the right time to get to that?

I guess Joy probably knows much more than I do on this, but where do you think the gas is, now that you have an integral measurement?

MEMBER REMPE: It's the gap.

MR. GEELHOOD: The gas in this case is in the gap. There's a lot of gas still in the fuel, and it is possible to probe fuel and figure out where the gas is in the fuel. But the gas we care about for fission gas release is gas in the gap. So you just puncture it and you --

MEMBER CORRADINI: Okay. But the

assumption is whatever -- the assumption is whatever you do in the volumetric current, the integral measurement, it's coming from the gap, not from any sort of diffusion out of the fuel?

MR. GEELHOOD: No, because diffusion kind of turns off at room temperature, and even 200 degrees. So whatever you get in the hot cell is just going to be what was in the gap when it was in the reactor.

MEMBER CORRADINI: Okay. So the puncture test is done at low temperature. I guess I missed that. I'm sorry.

MR. GEELHOOD: Yes, it's done in the hot cell and so, you know, probably higher than room temperature because of decay heat, but not that much higher.

MEMBER CORRADINI: Okay, thank you.

CHAIRMAN BANERJEE: Well, before you move from the slide, would it be helpful to know where FRAPCON comes there roughly?

MR. GEELHOOD: Well, there's different versions of FRAPCON. So FRAPCON --

CHAIRMAN BANERJEE: I'm thinking the latest or greatest version.

MR. GEELHOOD: The last release came out

in, I've got it right here, 2011, and so --

MR. CLIFFORD: But the thermal conductivity model was updated in 3-3.

MR. GEELHOOD: Yes, which was like 2,000 --

CHAIRMAN BANERJEE: Is that next time?

MR. GEELHOOD: Yes, probably. So FRAPCON is an evolving thing. New versions come out, and so when Paul does reviews of vendor fuel performance codes for someone else, the latest version of FRAPCON is used to try to do some audit calculations.

CHAIRMAN BANERJEE: The other thing that would be helpful, Paul, is maybe some of us know, but could you just say which ones are -- which vendor and which --

MALE PARTICIPANT: For PWR, do you have --

MR. CLIFFORD: I will be walking through each and every one of these codes in detail in my presentation.

CHAIRMAN BANERJEE: Okay, fine.

MEMBER REMPE: Before you leave the Slide 2, there's not very much data at 80 gigawatt days per metric ton uranium. Is there a plan for repeatability, additional tests? I've forgotten the numbers, but is it five to seven degrees or something?

There's a value quoted about how much for so much burnup, how much degradation occurs that is a rule of thumb, in one of your backup information documents we received?

There's not very much uncertainty for something where there's maybe one data point at eight gigawatt days per metric ton uranium that, instead of trying to get --

MR. CLIFFORD: Right. It's going to be 58 degrees Fahrenheit for ten gigawatt days. Well, the data that's available, I mean each one of these points represents multiple fuel rods, and this data is significantly high in the license burnup. License burnup right now is 62 gigawatt days. So this bounds that data.

MEMBER REMPE: So is there a plan for any repeatability test, is what I'm getting at? Do you guys feel comfortable -- what do you think the uncertainty is in the data that you've got from Halden and --

MR. CLIFFORD: He will make a presentation, where we've quantified the uncertainty based upon the data, the database we have.

MEMBER SHACK: But what range of burnups do you think you're covering? You know, FRAPCON is valid now up to what?

MR. GEELHOOD: We usually don't try to say it's out much beyond 62, because that's the licensing burnup that all the vendors are tied to. So we would be comfortable saying maybe up to like 70 or so. But beyond that, there isn't a lot of fission gas release data. There isn't a lot of temperature data.

These thermocouples, you know, Halden has gotten very good at making long-lasting thermocouples, but they do decalibrate in reactors. It's a very challenging environment, and so collecting some of this high burnup data takes a long time to get to the burnup, and sometimes the instrumentation can fail.

So you know, I don't know what the plans of the Halden reactor project are as far as getting higher burnup data. I think it would be up to the members on that Committee, if it's important to push for it and if other things are important right now, I think they're focused more on local work than on collecting high burnup temperature data.

MR. CLIFFORD: I'd also say that I guess we feel comfortable with the accuracy of FRAPCON, based upon the data we have available, and if the industry were to pursue --

MEMBER SHACK: Up to what burnup?

MR. CLIFFORD: Up to 62, and if the industry was to pursue higher burnups, then the burden of proof would be on them to gather more data, to bridge any gaps.

MEMBER REMPE: But as the regulator who does 50 gigawatt days per metric ton uranium, I don't see a lot of data, and as a regulator, you have the ability, if you want to, to say -- but I didn't hear the answer to what you think your uncertainty is, and is it ten percent or 30 percent?

MR. GEELHOOD: The temperatures we've calculated at standard deviations of about seven, five to seven percent.

MEMBER REMPE: Okay. So for instance the folks at Halden, there may be, and even in Wozniak's paper, he said maybe 30 percent on some of his data. What I'm getting at is I think maybe the regulator might want to see some repeatability tests, to have more confidence in what they have too.

MR. GEELHOOD: Right.

MEMBER CORRADINI: If I might just follow Joy's point, we're going to get to this later, right, in terms of how you guys roll in your estimates of uncertainty, to see the effect on stored energy.

MR. CLIFFORD: Correct. We'll get to that in detail. But to go back to your question, if our predictions of temperature were that far off, then we would see it in other places, such as void volume, such as fission gas release, rod internal pressure.

MEMBER REMPE: So you're within ten percent in everything you've got, for what the data -- that's what I'm getting to, because that's really pretty good for a test, considering some of the uncertainties in their measurements.

MR. GEELHOOD: Halden has told us, kind of informally, that they usually feel that their measurements are accurate within 50 degrees C. And so they don't typically say ten percent or five percent, and so we've found our models generally agree with Halden's measurements within 50 degrees C.

So we're kind of maybe as good as we can get, because if they think they're accurate within 50 degrees C, if we're that close, you know, getting closer doesn't necessarily mean anything.

MEMBER REMPE: Well speaking further, I guess I like seeing repeatability in tests, and I'm not sure there is.

MR. GEELHOOD: And so what Paul said too is when you see like one dot there, that's the instrumented fuel assembly, and many times there's many rods in there that are run at different conditions.

So I'll have some slides in my presentation, where I kind of show kind of the expanding LHGR versus temperature versus burnup, you know, so you can kind of see this is kind of the box where we feel validated, and you can see on maybe the edges of the box and maybe less data, and as you move in, more data.

MEMBER CORRADINI: But I think I know where Joyce is coming from. So let me ask her question differently. Are there any diamonds that are approximately the same burnup as a function of time? The way she's asking the question, she knows more than I. Is the answer no, no diamond is shot at or is aimed at about same burnout?

MR. CLIFFORD: The reported, you know, on the Y axis, that's the highest burnup that was achieved in the Halden reactor. So there are multiple rods that have progressed to the same exposure points in the Halden reactor, as measurements were being taken.

MR. GEELHOOD: So this might better be shown as a bar chart --

MR. CLIFFORD: Yes, right.

MR. GEELHOOD: That's why it's --

CONSULTANT WALLIS: So really, to extent this premise, it's a very low value up to the diamond area.

MR. GEELHOOD: Yes. You have one point.

CONSULTANT WALLIS: Right, because it's very confusing just to have one point.

MEMBER REMPE: But if I'm reading it correctly, above 50 gigawatt-day per metric ton uranium, I don't see a lot of diamonds. Most data were for 40 gigawatt-days per metric ton uranium or below, although there's multiple rods in the test.

MR. CLIFFORD: There's three public test programs that are there.

MEMBER ARMIJO: Well, let me make, make sure I understand. Let's say EFA 562, which is a 80, but it -- when the experiment was started, it was started at a low burnup, and I'm presuming that people were making temperature measurements as a function of burnup, and it wasn't just one data point taken at 80.

MR. CLIFFORD: Yes.

MEMBER ARMIJO: So you've got a whole column of diamonds for the same particular experiment.

MR. CLIFFORD: Right, right. So you have online temperature measurements periodically every so many minutes --

MEMBER ARMIJO: Right.

MR. CLIFFORD: Occurring over years at different power rates. So there's a lot of data to then tune your model to, to cover both the effects of power, temperature and burnup.

MEMBER ARMIJO: That's what I'm trying to get at Joy's question, is we actually have a lot of diamonds all the way up and down that column.

MEMBER SHACK: Well, it depends on how you plot the diamonds. I mean we've seen other Halden plots that look like clouds, because they're plotting everything for each burnup rate, each temperature measurement.

MR. CLIFFORD: And we have -- I mean you can't see this, but in -- this is NUREG/CR-7022, Volume 2. This is again a real assessment, and there is where you see predicted versus measured data, and if you walk through this, and I'll pass this around.

MEMBER REMPE: We have some electronic copies too.

MR. CLIFFORD: Okay. Well, if you look at Figure 3.8, there's a plot of one particular fuel rod over a period of time. We have measured versus predicted.

MEMBER REMPE: And things look good, yes.

MR. CLIFFORD: And there will be many, many of those. Some would fall into line better than others.

MEMBER REMPE: But let's also be honest, that they used expansion rods, and I assume it was a moly rod instead of something that transmutes. But they have to assume a profile with a peeking factor in the core, right? Am I correct?

MR. CLIFFORD: I'm pretty sure they measure --

MEMBER ARMIJO: But that's a very short core, Joy. That's not a full length of --

(Simultaneous speaking.)

MEMBER REMPE: They have expansion rods, and they have to know their power profile to get that.

MR. GEELHOOD: What do you mean by "expansion rods"?

MEMBER REMPE: They don't really put thermocouples in. They use thermal expansion rods, right?

MR. GEELHOOD: Oh no. There's two different ways that they can measure. So they can measure the total temperature of the rod using an expansion thermometer, and that's something that just expands. But then most often what they do is they drill out the top and bottom couple pellets, and actually insert a thermocouple in there.

MEMBER REMPE: So then they had to put a Type C in, or they had to put a Type N or K that can't go above 1,100 degrees steam, or they have put something in the transmute as a function of time as a correction factor.

MEMBER ARMIJO: They use a tungsten radium and they do have a transmutation problem. But they've calibrated for that.

MEMBER REMPE: They have correction factors, but they also have vendor to vendor variability in their Type K or their Type C thermocouples.

MEMBER ARMIJO: Well, I don't know about the Type Cs. I'm just talking about the higher temperature ones.

MEMBER REMPE: The Type C are tungsten uranium. Sorry. Go ahead.

MR. GEELHOOD: Halden definitely has like kind of evolved over time. In some of these earlier ones, there was more thermocouple decalibration, and they've definitely improved on their methods and you may know their methods more than I do. But they're data does seem more reliable with some of the newer tests than it did in the past.

MEMBER REMPE: And again, those prospective test reactors, they're the best too. I give them credit and all that, but it's just -- there's just uncertainties is all I'm trying to say.

MR. CLIFFORD: Yes, I agree. Fair enough.

CHAIRMAN BANERJEE: So I think we come back to uncertainties as we go through.

MR. CLIFFORD: Yes, we will. Absolutely.

CONSULTANT WALLIS: Well, could we ask, could you explain the Y axis now? What does "average burnup" mean? Is it the average over the length, over the diameter of the rod? Or is it the average of everything?

MR. GEELHOOD: The average of everything.

CONSULTANT WALLIS: So there are points in the rod that have much higher. How much does it vary in this stuff?

MR. CLIFFORD: Well certainly, you know, in high burnup fuel we have much higher exposure radially on the pellets.

CONSULTANT WALLIS: It varies a lot.

MR. CLIFFORD: It varies a lot.

CONSULTANT WALLIS: So there's an average, there's a radial average, and there's also a length average. Is this a length average?

MR. GEELHOOD: For the length, yes.

CONSULTANT WALLIS: So how much does it vary along the length?

MR. GEELHOOD: Maybe like ten percent. Similar to like a PWR or BWR, in that there's some like shape, but it's a pretty short core.

MR. CLIFFORD: It also depends on where they cut it from, the parent rod. Some of these rods were, started their irradiation life in a commercial reactor, and then they were segmented, and then instrumented, and then put in the reactor. So it would depend on whether they took it from the center of the core or the top part of the core.

MR. GEELHOOD: So a reinstrumented rod would have less --

CONSULTANT WALLIS: There's a sort of smudge around each point about, because of where you are in the rod.

MR. GEELHOOD: Well, so it's only measured at a few points.

CONSULTANT WALLIS: A few points.

MR. GEELHOOD: And so where it's measured is where we do the comparison, and so it would be like that, those ends burn up. Or in the case of an expansion thermal --

CONSULTANT WALLIS: It would help me in reading the documentation if this had been explained, because it does seem like this raises a lot of questions. What does it mean? What does one point mean, and what kind of average are you talking about? It would help if it were explained more in the documentation.

CHAIRMAN BANERJEE: Well, this may not be. But if you go back to the original paper of Wozniak and so on, that they have a lot of detail of the sort you're looking for.

MEMBER SCHULTZ: The power of ten. So we can draw what we can from the slide as it's portrayed. For FRAPCON, all of the data that's shown here in the more recent versions has taken into account all of the data.

MR. GEELHOOD: All of the data we're aware of.

MEMBER SCHULTZ: No, that's shown on this chart.

MR. GEELHOOD: Yes.

MEMBER SCHULTZ: Now you've put on here when other code were approved. That doesn't necessarily mean that the vendors used all of this data as a benchmark for their codes or --

MR. GEELHOOD: That's correct, and in addition, they may have commissioned private Halden tests to collect specific data for their needs. So they may have things that aren't here.

MEMBER SCHULTZ: That information was available, and the code version of FRAPCON, only really for those last few, was everything considered in the FRAPCON version, which was used to compare against the vendor codes as they were approved.

MR. CLIFFORD: The vendor would also, you know, as part of their documentation, they would compare against the data. I mean they would have to show that their code was valid, that they were a best estimate fit or a bounding fit, and then if they did use a best estimate approach, they'd have to quantify the uncertainty and then come up with an application model, which then uses the uncertainty. You'd get an upper or a lower tolerance on whatever they're trying to predict.

MEMBER SCHULTZ: So that's why I'm trying to understand. So for COPERNIC, for example, we can just suppose that the 515 would have been, it was available.

So it would have been incorporated into the review process for COPERNIC. Either it was used by the vendor explicitly in their code, or questions from the staff would have said well, how do you compare and please explain?

MR. GEELHOOD: Yes, and some of these that are at a later date, they release information as the irradiation goes. So there may have been lower burnup data from some of these later ones that the staff might have asked them to compare against.

MEMBER SCHULTZ: Right, and just so -- I don't want to drag this on, but for the last ten years, there hasn't been any high burnup data that's been produced at Halden, and you don't know, Ken, whether there's programs in play?

MR. CLIFFORD: Well, there's other programs I didn't report here. There's been a lot of programs on MOX that I didn't think was valid for this discussion, so I didn't include them.

MR. GEELHOOD: And the 681 is a uranium and a gadolinium rate. There's the 0_2 rods and the 0_2 gadolinium rods, and that is continuing. And so if we were to --

MEMBER SCHULTZ: Okay.

MR. GEELHOOD: --you know, Paul's going to go this next Halden meeting. He may come back and that point may move up, you know.

MEMBER SCHULTZ: Got you.

MR. GEELHOOD: You know, if we take a look at our comparison against them. So some of these lower burnup ones --

MEMBER SCHULTZ: Are still in progress.

MR. GEELHOOD: Are in the process moving up right now.

MR. CLIFFORD: One thing that may be worth noting is what's indicated here on the X axis, that's the approval date. If you go back, maybe it's a two-year NRC review. Maybe it's a two-year calibration period. So when they started calibrating their models, it may be four years before this approval date, just as information.

MR. GEELHOOD: Right.

MEMBER SCHULTZ: Understood. Thank you.

MR. CLIFFORD: Okay. Later on in the presentation, we'll be walking through the impacts of TCD on fuel rod thermal performance, for each of the codes and downstream effects.

But in general terms for this introduction, you could say that to grade thermal conductivity results in higher fuel pellet temperatures at a given power level, and that any codes that don't properly account for it will have an artificially low fuel temperature prediction.

This will impact the LOCA-stored energy, pellet thermal expansion, which will then feed back into fuel temperature. It will also affect fuel pellet gap size predictions and cladding stress and strain.

CONSULTANT WALLIS: Is there a discussion about gap? We're going to talk about gap. You've got to separate the effects of thermal conductivity and the gap resistance? It seems to me that if you stifle all the pellets and compress them in a long tube, they're going to lean against the wall. They're not going to be in the middle.

All the models assume the pellets are in the middle. So what is the error in that? I mean there must be parts of the cladding that are hotter, because they actually touch the fuel, and then there's a bigger gap on the other side, because the pellets lean against the wall.

There's no way they're going to stay in the middle, nothing to keep them there. I didn't see any consideration of this in FRAPCON.

MR. GEELHOOD: There's nothing right now

in the --

CONSULTANT WALLIS: What's the error? What's the implication of ignoring this eccentricity?

MR. GEELHOOD: Some of the vendors do have eccentricity models in their codes, and they don't really like add that much more.

CONSULTANT WALLIS: They don't add much on the average, but there are parts of the cladding which are hotter and oxidize more. Does that make a difference or not?

MR. CLIFFORD: Well, if the effect was really significant, then you would see potentially dryout, or you would see something in the field which would lead you to believe that maybe heavy oxidation, or something that would indicate that there is a need to model it. I guess I would say we haven't that need get to that level of detail.

MR. GEELHOOD: It's more of an issue to low burnup, because around 25 to 30 gigawatt-days per ton the cladding depth --

CONSULTANT WALLIS: That's right.

(Simultaneous speaking.)

CONSULTANT WALLIS: At the beginning it really matters.

Maybe you could take a homework problem

and add it as an appendix or something. So whether it matters or how much it matters and should we worry about it.

MEMBER SCHULTZ: There are some PNNL publications that look at these eccentricities and quantify the effect, on a separate effects table.

MR. GEELHOOD: Yes. I could dig it out and try to see what's been done, what's been decided in the past.

CONSULTANT WALLIS: It would be helpful, I think.

MEMBER ARMIJO: But Graham, it's not just a gap, you know. The pellets are all cracked up. So the gap is distributed within the inside and the outside. So it's sort of a fiction that we have a gap.

MR. GEELHOOD: Fresh fuel, there's a big gap.

MEMBER ARMIJO: Oh yes, fresh fuel. It cracks up when it's new. It cracks up the first time you go to power.

(Simultaneous speaking.)

MR. GEELHOOD: There's a pretty steep temperature gradient. So we have a relocation model, which kind of models this kind of effect of the pellet getting bigger due to cracks and it doesn't fit back together perfectly.

MEMBER SCHULTZ: But I know there's some publications that have looked at that particularly, and quantified the difference, given a cracked pellet or a centric.

CONSULTANT WALLIS: Well, if it's cracked, there's fission gas in the cracks which comes out, and you --

MEMBER SCHULTZ: Sure.

CONSULTANT WALLIS: So that's part of the gap gas.

MR. GEELHOOD: But see, the cracks are on a much higher order than the grain. Typically, what we do is we model the fusion out of the grains to the grain boundaries, and then release from the grain boundaries. So cracks is more of a --

CONSULTANT WALLIS: This talks about bubbles too, isn't it?

MR. GEELHOOD: Yes, and so the bubbles are what's on the grain boundaries typically, and then when those bubbles fill, we just release it to the void. So a crack is more of a macro thing when compared to the grain size.

CHAIRMAN BANERJEE: Paul, I don't mean to be a spoilsport or anything, but are you sort of -- how many more slides do you have?

(Simultaneous speaking.)

MR. CLIFFORD: Just one more slide, just one more slide.

CHAIRMAN BANERJEE: All right.

MR. CLIFFORD: It's just a high level overview of what the TCD is, and I think we can move on from this slide.

CHAIRMAN BANERJEE: Great. Thanks very much.

MR. CLIFFORD: The next presentation.

MEMBER REMPE: Mr. Chairman, the guy on the phone is complaining he can't hear certain members, and he said you and Sam were difficulty -- Mike, are they the only two that need to speak up, or are there other complaints you want to make?

MEMBER CORRADINI: Well, the only complaint is just Sanjoy and Sam are so shy that I can't hear you.

CHAIRMAN BANERJEE: It's because we're not saying very much.

MEMBER CORRADINI: But when you do say something, it's so important. I want to make sure I write it down in my notes.

CHAIRMAN BANERJEE: All right, okay.

MEMBER ARMIJO: We'll speak up.

CHAIRMAN BANERJEE: Okay. Let's move on to Ken's presentation.

Calibration and Validation of Fuel Models

MR. GEELHOOD: So my name is Ken Geelhood. I'm a contractor with the Pacific Northwest National Lab, and I maintain a contract with the Office of Research, to continuously update FRAPCON and FRAPTRAN, and then we also have contracts with NRR and NRO to assist them in doing their reviews of vendor fuel performance codes, new cladding alloys, methodologies for doing safety analyses. So I'm going to talk about --

CHAIRMAN BANERJEE: Did PNNL really do the development of FRAPCON originally?

MR. GEELHOOD: It's kind of like an evolving thing. There was a FRAPCON-2 was developed, or no. There was the FRAP codes. There's FRAP-S and FRAP-T. They were developed at Idaho National Lab, and then PNNL developed GAPCON, which took into account the gap analysis.

And then so there is kind of parallel development that was being funded, and then the NRC moved it all into one. So that's why FRAPCON came out of FRAP-S and GAPCON, so and then FRAPTRAN similarly. So PNNL since about '95, I think, has been the only contractor doing code development. But the Idaho National Lab definitely laid the groundwork for some of this coding.

CHAIRMAN BANERJEE: That was before your time, Joy or --

MEMBER REMPE: I wasn't involved in it at Idaho. That was --

MR. GEELHOOD: Gary.

MEMBER REMPE: And he's retired.

MR. GEELHOOD: Yes, he's retired, and Larry too.

MEMBER REMPE: He's also retired.

MEMBER ARMIJO: Hey Paul, I'm sorry. But you skipped all of your slides. One of the things I was really interested in is in a later slide.

MR. CLIFFORD: That was probably the close-up.

MEMBER ARMIJO: Okay, okay.

CHAIRMAN BANERJEE: Don't get anxious.

MEMBER ARMIJO: Well, I didn't see that that was closed, and I just thought Sanjoy had made you rush.

CHAIRMAN BANERJEE: No, no, no. I would

never do that. Let's go on.

MEMBER ARMIJO: Okay.

MR. GEELHOOD: I want to talk about what parameters that come out of fuel performance code are of interest to the regulators, and I'll talk a little bit about the extent of the database, the nature of the fuel performance codes, calibration parameters, model validation, the integral assessment we do and then the new capability we've had to do better uncertainty analyses with FRAPCON.

So these are kind of the parameters that the regulator is most interested in. First, the fuel and cladding temperatures. They can do these fuel melt overpower analyses and local initialization.

They want to know what the rod internal pressure is, so they can do cladding liftoff analyses; cladding hoop strain for the cladding strain overpower analysis; cladding fatigue and pellet cladding interaction. Pellet cladding interaction is something that, you know, the regulator is kind of starting to get into.

Corrosion and hydriding; there is a corrosion limits currently in place, and there will probably be hydrogen limits coming down the road; and then fission gas release is a concern, partially for pressure but also for dose calculations.

So there's kind of two types of data in the database. One is separate effects data. So there's material properties data where we just take the materials, irradiated or unirradiated, measure things like thermal conductivity, heat capacity, thermal expansion, various mechanical properties.

And then there's what we like to call behavior models. So like cladding creep is enhanced by radiation, the densification and swelling that occurs in the pellet with time. Fuel relocation we talked about that.

That's kind of the cracking of the pellet and how it doesn't fit perfectly back together, but it does take up some of the gap, fission gas release, and then also cladding corrosion.

And then the other side is integral effects data, which is centerline temperature. A lot of different models feed into accurately predicting centerline temperature, and so it's kind of that's something that would be more of an overview. Are all the models working well?

Fission gas release. Although it's on the behavior models, it's also in integral effect data, because it can be impacted by the temperature, the size of the gap, all these other things. Then void volume is something that's kind of in integral effect cladding corrosion.

Again, it's on both sides, but it's also something that the heat flux and the temperature of the cladding drives how much --

CONSULTANT WALLIS: By void volume, you mean these bubbles and things that are in the fuel?

MR. GEELHOOD: No. The macro void volume. So you take it in a hot cell and you puncture the rod and measure what the volume in --

CONSULTANT WALLIS: This includes the gap then?

MR. CLIFFORD: Gap and the plenum.

MR. GEELHOOD: The gap in the plenum, any kind of open porosity.

MR. CLIFFORD: Porosity.

MR. GEELHOOD: Yes.

CHAIRMAN BANERJEE: Have there been any integral tests on reactivity feedbacks, the effect of TCD on that?

MR. GEELHOOD: I guess I don't really understand.

CHAIRMAN BANERJEE: Well, reactor coefficients and things like that.

MR. GEELHOOD: There may have been, but that's kind of outside of the domain of FRAPCON.

CHAIRMAN BANERJEE: Right, right.

MR. GEELHOOD: So I think you'd have to -- maybe you know Paul. I mean --

MR. CLIFFORD: I'm just trying to think of --

CHAIRMAN BANERJEE: I'm going outside the domain.

MR. CLIFFORD: Yes, start-up physics testing or anything that's done at the reactor, where they are validating their physics codes.

CHAIRMAN BANERJEE: I think we can hold that for Ken --

MR. CLIFFORD: There's definitely --

CHAIRMAN BANERJEE: --if you want, because when it comes to implications for LOCA, certainly the reactor -- not LOCA, but the accidents.

MR. CLIFFORD: You can certainly calculate what the potential error would be introduced in your Doppler feedback during an AO overpower event, if your fuel temperature was wrong, of how you would validate that from a data perspective. That's the missing piece.

MR. GEELHOOD: There's definitely neutron detectors that sometimes get inserted into commercial reactors. But that probably would be more normal operational data than accident data.

CHAIRMAN BANERJEE: Well, it may also be that you have data during some rod withdrawal or something, which --

MR. GEELHOOD: That may be, yes.

CHAIRMAN BANERJEE: We'll revisit that as time goes on. This is more FRAPCON --

MR. GEELHOOD: Yes. So the physics is kind of more of an input. We input, impose the power shapes, rather than try to calculate it with this code. And then the last thing, it will affect data in cladding heat stream, is an effect of, you know, the gap is open or closed, on how much the pellets expand and things like that.

CONSULTANT WALLIS: You talked a lot about physical stuff, but I was impressed by this plutonium buildup. Because of the resonance, there's a tremendous amount of buildup.

MR. GEELHOOD: Yes.

CONSULTANT WALLIS: Doesn't that have a significant effect on what happens?

MR. GEELHOOD: Very much, and that is modeled in FRAPCON.

CONSULTANT WALLIS: It is, but you haven't said anything about it yet. It seemed to me a really significant effect, but it's got to be modeled right.

MR. GEELHOOD: Maybe, you know, and maybe I could have added that under behavior models. But you're correct. Like as burnup progresses, you preferentially build plutonium in on the outer shell.

So what that does is if you look at the radial power profile, it gets steeper and steeper, such that end of life, even the rod average burnup maybe 62, right in this little area, right on the edge of the pellet, it could be 100, 150 gigawatt-days per ton.

So that's something, the model that we do have in FRAPCON, that it is validated against. They can take EPMA data to look at immobile fission products, to kind of make sure that we're calculating that right. But our models are based on physics models, you know. So a physics model would inform our model.

MEMBER ARMIJO: Do you have any, in your integral effects data that you have in FRAPCON, do you have a fuel rod length change? Let's say --

MR. GEELHOOD: Model growth?

MEMBER ARMIJO: Not growth. Let's say

during a power ramp, you know, you can stretch, you literally actually can, as the pellets interact with the cladding.

MR. GEELHOOD: Cladding hoop strain.

MEMBER ARMIJO: Sometimes it's in the actual direction.

MR. GEELHOOD: Sometimes they do measure axial strain. It's not something that's particularly of interest to the regulator, because you know, how much that happens. It never fails in that direction during an AO event.

MEMBER ARMIJO: But it creates the biaxial stresses that are important in the PCI.

MR. CLIFFORD: And there are -- I mean the models are tuned based on length measurements, full-size length measurements. So it would be inherent in the data, and there would be not just free-standing irradiation growth, but there would be also be pellet cladding --

MEMBER ARMIJO: You feel there's any plastic deformation. This is really during those kinds of transients, where you can get a biaxial stress during the transient that disappears afterwards, and that actually happens, because we've measured it.

MR. GEELHOOD: With cladding hoop strain, there's been a lot of tests done in test reactors where they power ramp them, and they have -- then they measure what the plastic axial strain and hoop strain is, and you compare both of those. Axial strain is much more difficult, because there's slippage between the cladding and the pellets.

MEMBER ARMIJO: But I've done it. I've done it, and it's really a very impressive effect, that you can detect fuel failures using the axial strain. This is the test, much more readily than using the hoop strain, and it's probably been in some of these reports. So but you don't necessarily use it very much, I take it?

MR. GEELHOOD: We rely more on the hoop strain, because the NRC requires the vendors to predict that their hoop strain doesn't exceed some limit, and they don't currently have any kind of limit on the axial strain.

If they get into PCMI and you're right, that axial strain is a better prediction of PCMI failure, then maybe that would be something that the NRC would be interested in.

CONSULTANT WALLIS: It strains actually during a transient, because they go back.

MEMBER ARMIJO: It does.

MR. GEELHOOD: It does? It goes back?

MEMBER ARMIJO: Yes.

CONSULTANT WALLIS: But the slippage is very important, about how -- whether it goes back uniformly or --

MR. GEELHOOD: So it's going to be a function of burnup, because the bonding between the fuel and the clad changes with burnup. So a low burnup point --

CONSULTANT WALLIS: It's pretty complicated.

MEMBER ARMIJO: Yes, it is complicated. It's true.

MR. GEELHOOD: Okay. So this graphic kind of just shows what the nature of FRAPCON and FRAPTRAN are. So what's in blue is usually inputs. So the user has to input the rod dimensions, the coolant conditions and then the power history, and along with the power history is also that axial power profile across the length of the rod.

Then in green here, inside FRAPCON we do a iterative solution on temperature, pressure and displacement. So now you calculate one and then do the next and iterate that.

CONSULTANT WALLIS: You have to input the composition of the fuel, the gadolinium and stuff, don't you?

MR. GEELHOOD: So I guess I'd put that under like rod dimensions. But --

CONSULTANT WALLIS: Yes, all their properties, all the properties.

MR. GEELHOOD: Yes. So like yes, the enrichment and things like that, and then what's built in is down here in red, is the material properties and the behavior models. So we don't allow those to be tuned by the user. Some models, you know, allowing too much tuning, I think, in that area.

We kind of fixed that, so that we can be more confident in the outputs, and then the user just gives, you know, the specific information for their case. So the main solution, it's a one and a half dimension solution. So what that means is heat is transferred out radially, and we assume uniform, you know.

We've done, as Steve mentioned, sensitivity analyses on those things before. But we found, you know, it's a 1D solution is appropriate, and then the half dimension is that gas can transport up. So we don't do heat transfer in the axial direction, but we do allow, you know, mixing of the gas and the gap with that in the plenum.

So that's the second bullet, I guess, some of the axial effects. So the coolant obviously heats up over the length of the rod, based on how much heat is produced at the node below it, and then internal gas mixing. Then we use finite difference steady state heat transfer. This is now in FRAPCON. FRAPTRAN is really similar, except it can do results of transient heat solution.

Then we do a rigid pellet model with radial relocation. So what that means is the pellet is kind of like a rock. So if it expands out, the cladding is forced to expand out too. There's no feedback in that. The cladding is imposing strain jammed on --

MEMBER ARMIJO: So you don't use a cracked pellet?

MR. GEELHOOD: We do. So that's what this radial relocation is.

MEMBER ARMIJO: Okay.

MR. GEELHOOD: We say it'll expand out, but it won't fit together perfectly. So only about half of what originally came out would be recovered back when the pellet and cladding come in contact with it. So we define a hard contact and a soft contact.

CHAIRMAN BANERJEE: So let me just ask you. Going back to Graham's question, this is from a computational point of view, very straightforward procedure. There's nothing complicated. Why can't you simply do a 2D calculation?

MR. GEELHOOD: We could.

CHAIRMAN BANERJEE: That would take into account the sort of problems you are alluding to? It's not a big overhead.

MR. GEELHOOD: Yes. I mean it could be done. It just hasn't been done.

CHAIRMAN BANERJEE: Is there a reason that you -- I mean --

MR. GEELHOOD: I think the biggest reason is typically, the NRC doesn't do much more than what the vendors do, and the vendors feel performance curves are very similar in structure to this.

CHAIRMAN BANERJEE: Let me ask you the question differently. Have you assessed the sort of effect that he asked about some of your 2D codes, and shown that it's negligible? I'm sure you add 2D codes.

MR. GEELHOOD: Yes.

CHAIRMAN BANERJEE: If nothing else,

somebody in your lab will. All right, okay.

MR. GEELHOOD: But I mean I haven't recently done any assessments, but assessments have been done that kind of show, you know, for a difference, isn't a big difference.

CONSULTANT WALLIS: Then you look at your next slide. Maybe that's why I asked the question, because the double T in the gap is around 60 percent of the double T in the fuel, and if there's no gap on one side and there's a double gap on the other, it looks to me as if that's a significant effect on --

MR. GEELHOOD: I guess this is a cartoon.

CONSULTANT WALLIS: No, I know, but you shouldn't show cartoons if they're not --

CHAIRMAN BANERJEE: If it's a cartoon, what is the answer to his question? Is it 60 percent?

MR. GEELHOOD: It is not 60 percent. It's probably more like five percent.

CONSULTANT WALLIS: Then you shouldn't show these things which are misleading like that.

CHAIRMAN BANERJEE: Well, that's artistic license.

CONSULTANT WALLIS: No, it's not. This is a technical document.

CHAIRMAN BANERJEE: Well, this is

partially artistic. Anyway, so what you're saying is that there have been assessments done.

MR. GEELHOOD: There have been assessments done.

CONSULTANT WALLIS: It's a five percent?

MEMBER CORRADINI: Can I just make sure that Graham's question is, at least I understand what he's asking, because I don't think you guys are answering his question. If there's a circumferential variation on the gap, has there ever been a measurement to know how much of a circumferential gap?

I'm always at the point that you can't drive the model past what you measure, and I'm not exactly sure you can measure any of this.

MR. GEELHOOD: I think that's a really good point, is the NRC has been interested in what can be measured, and you're right. It's not something you can measure. So we can do a calculation --

CONSULTANT WALLIS: Well, I say you can be pretty darn sure that it's touching on one side.

MR. GEELHOOD: Yes.

CONSULTANT WALLIS: So you don't need to measure it to know.

CHAIRMAN BANERJEE: But you can certainly assess the effect.

CONSULTANT WALLIS: Yes.

MR. GEELHOOD: Yes, and these are --

CHAIRMAN BANERJEE: And if it's not significant --

MR. CLIFFORD: When we run our production calculations to see, evaluate our EPU, we're not doing that. But we are assessing the impact of tolerances on gap size, initial gap size. So we do have a feel for, you know, if you have combined the narrowest pellet with the thinnest cladding and achieved the maximum gap through tolerance, what that impact would be. So we do have a feel for it.

CHAIRMAN BANERJEE: I guess he was concerned about whether you could form -- I don't want to speak for Graham; he's perfectly able to speak for himself, but this formation of hot spots in mediums where you might get more hydriding or --

MR. GEELHOOD: Oxidation, and currently, that would be kind of included in the uncertainty in our corrosion and hydrogen pickup models, in that you know, we see variation, radially and axially, in both of those parameters, and so that leaves uncertainty.

So you know, we've quantified what those uncertainties are, and so it would be kind of implicitly included maybe in that.

MR. CLIFFORD: But if you just look at fuel that's in reactors, you don't see dramatic differences looking at one fuel rod to the next, over the course of time in a reactor. One side is not more corroded than another side, markedly so.

You can't see it. So we may not model this perfectly for our evaluations, but there is a relatively small differences, especially over the course of time.

As you mentioned, it's somewhere between let's say 15 to 30 gigawatts per ton or kilogram. It's going to close. Both sides are going to close. So as we're talking about high burnup effects of thermal conductivity degradation, that's not a factor.

CONSULTANT WALLIS: I don't think it affects the outside of the cladding much, because so there's so much -- such good heat transfer to the coolant. But it does affect the temperature of the fuel, in addition to the gap.

MEMBER ARMIJO: It would be coolant there, and if it's in contact. But it doesn't --

MR. GEELHOOD: If you're interested in centerline melting, then if one side is touching that's cooler, but the other side is hotter. So it's not going to impact the centerline temperature much, and that's what drives fuel melting, would be the centerline.

So I don't know that if the edge of one side is hotter and the edge of another side is cooler, if that impacts anything that the regulator is interested in, you know. Scientifically, it may be of interest, but I don't know that.

CONSULTANT WALLIS: Well, I think the regulator is also interested in what's the effect of things you're ignoring. Just because the regulation ignores something, it doesn't mean it isn't something that might matter. So as Jim has already said, it's fairly easy to do a 2D calculation. Oh, you've done it?

MR. CLIFFORD: It's probably been done --

CHAIRMAN BANERJEE: But do you have the answer?

MR. GEELHOOD: I could probably dig out the answer, you know, if we look in some other documents.

MEMBER SCHULTZ: And I know it's been done. There were papers that were published in I think the early 90's.

MEMBER CORRADINI: So let just ask a different question. I'm assuming the NRC is following the big expensive money that DOE is doing for CASL. One of the things CASL is doing is three-dimensional calculations, similar to what's being done at CEA in France, and the effects on fuel behavior.

So at least I assume you're observing some of the more detailed calculations that are being done. That may be a way to get to Graham's questions, because then at least people are doing sensitivities even now, and I think Oconee is their model plant.

MR. CLIFFORD: Right. Yes, we've had presentations made on CASL at the various fuel vendor meetings that we attend every year. So we're aware of what's going on.

MEMBER CORRADINI: Then I guess I understand where Graham's coming from. So you guys, the staff might have some fun at these meetings by asking them to do some of these calculations, to prove their models are worth anything.

MR. CLIFFORD: But I mean in the big picture, you're looking at a transient analysis, where there's generally a lot of conservatism built into the first principle, key contributors to the consequence analysis. And now we're down at a very finite level, you know, where there are very small differences.

MEMBER CORRADINI: I understand. I just

wanted to try to get to Graham's point about if there are people thinking about this, in terms of where the uncertainties are because of spatial effects. That supposedly is where they're investing some resources to try to understand some of this stuff.

CHAIRMAN BANERJEE: Do you know some of the results, Mike? Even though I'm part of this, I never attend any meetings.

(Laughter.)

MEMBER CORRADINI: Well, I do know that, that I thought FRAPCON was the basis, and I should know the name of the tool they're using for the advanced fuels model. But I can find out. I think --

MALE PARTICIPANT: Is it --

MEMBER CORRADINI: --is that Graham's point is a fair one, that somebody should be thinking about this and seeing the effects, even though they are in some sense sensitivity calculations.

MR. CLIFFORD: But I mean if you were to do a PIRT on LOCA, and you got all the way down to the spatial effects on pellet location within the fuel rod, it would be so low on your rankings that you wouldn't even put any effort into it. That's why you do a PIRT.

MEMBER CORRADINI: I'm not disagreeing

with you. I'm just trying to close that loop for Graham's question, that's all.

CONSULTANT WALLIS: Well, PIRT doesn't answer it. PIRT is the opinion of some experts, who may not have done any calculations. One calculation is worth 1,000 opinions of experts. You haven't done it.

CHAIRMAN BANERJEE: Well CASL, by the way, focuses more on normal operation.

MR. GEELHOOD: Yes.

CHAIRMAN BANERJEE: I think what Mike was saying, it would be more just routine or maybe even anticipated occurrences, but that's about it. Why don't we move on? I mean we know what's on this slide.

MR. GEELHOOD: Okay. I guess just to kind of walk through the radial temperature solution, we start with the coolant temperature and we work inward toward the pellet.

So we calculate the bulk coolant temperature, assuming a single closed coolant channel, just a single rod code. If you're interested, there's the equation there, and all these equations are in the documentation.

CHAIRMAN BANERJEE: In a bundle of cores

or core, there's radial mixing. That's not taken into account.

MR. GEELHOOD: That's not taken into account here. The cladding surface temperature then, the minimum of the heat transfer through forced convection or nucleate boiling, and what that does is make FRAPCON applicable to a BWR or PWR. You don't have to tell FRAPCON necessarily it's a BWR or PWR. It's going to figure it out, based on the coolant temperatures and pressures that boils.

CONSULTANT WALLIS: I don't understand this minimum thing. I mean if it boils, it boils. If it doesn't boil, it doesn't boil. There's nothing to minimize really.

MR. GEELHOOD: Go

It's going to boil, and then the cladding temperature gradient is according to the steady state heat transfer through a cylinder. Then there's heat transfer through the gas gap by radiation conduction through the gas, and then once the gap closes, through contact. So conduction dominates in the open gap situation.

MR. GEELHOOD: And I go back to cites. Conduction is it's not boiling, and then when it boils, the minimum will become the nucleate boiling.

So that's just the mathematical equation.

CONSULTANT WALLIS: You don't need any kind of a correlation of when boiling commences and things like that, subcooled boiling?

MR. GEELHOOD: Oh that's like higher boiling? Like so that's done in FRAPTRAN, where we analyze various accidents. So we can do like a loss of flow accident, and calculate that kind of boiling in a PWR. But this is just like --

CONSULTANT WALLIS: I think that a normal code would say is it boiling, isn't it boiling, will calculate the appropriate coefficient.

MR. GEELHOOD: That's how it does it.

CONSULTANT WALLIS: You don't have to minimize anything.

MR. GEELHOOD: Well, that's how mathematically -- like in a BWR, it's not boiling on the bottom, and then this second one will be --

CONSULTANT WALLIS: You have to do a good job about the first initiation of boiling.

MR. GEELHOOD: Yes, and so that, by calculating the minimum of these two, is how we decide at what elevation it's boiling. Then this is maybe a little bit more esoteric, but then the fuel temperature is calculated using this finite difference approach.

We use variable mesh spacing to kind of give more detail in the area where things are changing faster and less where it's flatter, and then we kind of numerically solve the steady state integral, and we used some matrix algebra to do that. So all that is built into the code and user is exposed to that, but if you're interested, that's what it is.

CHAIRMAN BANERJEE: So you used sort of a formulation which conserves energy?

MR. GEELHOOD: Yes.

CHAIRMAN BANERJEE: Yes.

MR. CLIFFORD: So it would kind of be like you use approximation?

CHAIRMAN BANERJEE: They call it the difference intervals.

MR. GEELHOOD: So basically we break it up into all these radial nodes, and assume each radial node is constant and we kind of start on the outside and just work our way in.

CONSULTANT WALLIS: So what is the mesh size here?

MR. GEELHOOD: It's up to the user to specify the number of radial nodes. But typically, we use about 17 or so radial nodes in a pellet.

CHAIRMAN BANERJEE: So you can take into account the flux depression in the pellet?

MR. GEELHOOD: Yes, and so that's calculated and gives more power produced on the outside than on the inside.

CONSULTANT WALLIS: So when you get to this plutonium build-up, do you make finer grids?

MR. GEELHOOD: So we've already kind of like this variable mesh more spacing, that gives finer grids on the edge, because we know already that --

CONSULTANT WALLIS: So the grid changes. It evolves as the plutonium builds up?

MR. GEELHOOD: So there's different ways. Some people you could do an equal volume nodes, which would still give closer spacing by the edge. But we found that wasn't enough to capture the steepness of that build-in. So we've artificially packed then in tighter on the edge.

MEMBER SHACK: But you specified that. It's not something like a rung cutter thing, where it's adjusting step size during the calculation.

CONSULTANT WALLIS: It doesn't adjust the grid.

MR. GEELHOOD: The grids are constant throughout the entire run.

CONSULTANT WALLIS: Throughout the life cycle?

MR. GEELHOOD: Yes.

CONSULTANT WALLIS: That's a bit odd, because you need really to get finer towards the end.

MEMBER SHACK: As long as they're fine enough at the end, you're just --

(Simultaneous speaking.)

MR. CLIFFORD: But at the beginning, it doesn't hurt you that you're maybe too fine.

CHAIRMAN BANERJEE: For the 1D calculation, there is -- you can just become really fine. So it doesn't matter, I guess. Brute force the problem.

MALE PARTICIPANT: So I mean like 30 years ago --

CONSULTANT WALLIS: Do you do sensitivities of the mesh size, because that's the obvious thing --

CHAIRMAN BANERJEE: And do convergence testing?

MR. GEELHOOD: We have done that in the past, you know. At what point do we have enough radial nodes, so the temperature isn't changing anymore?

CONSULTANT WALLIS: Seventeen is the magic number?

MR. GEELHOOD: Well, I mean it's kind of a guideline. I mean some people use like even as few as ten. But 17 definitely gets enough so it's not changing your views more or less.

CHAIRMAN BANERJEE: So tell me, this whole thing is just a succession of steady states in the calculation, right?

MR. GEELHOOD: Yes, yes.

CHAIRMAN BANERJEE: So you're solving a problem which you could do time-stepping through it, but just do it --

MR. GEELHOOD: Oh, we do do time steps.

CHAIRMAN BANERJEE: So you do time steps? I mean when you calculate at different burnups, you essentially input whatever --

MR. GEELHOOD: You input the power age burnup --

CHAIRMAN BANERJEE: Well, that's the history you put in.

MR. GEELHOOD: Yes, yes.

CHAIRMAN BANERJEE: You sample that history, right?

MR. GEELHOOD: Yes.

CHAIRMAN BANERJEE: But you keep the former history as to what is happening to that or not?

MALE PARTICIPANT: History-dependent.

CHAIRMAN BANERJEE: That's really what --

MR. GEELHOOD: But we don't have like finer internal steps. So if you've specified this power at one day and this power at 50 days, we just kind of say this is the first time step, here's the answer and everything's constant throughout that time step, and I move to the next time step.

CHAIRMAN BANERJEE: Yes, that's what I was --

MR. GEELHOOD: And so, you know, when you see the power history, you almost have to imagine it as step functions, you know, as just each time step, and we say try not to go bigger than 50 days for the time steps.

But you can go down as low as hours, because the steady state and transient solution converge after about three seconds in the fuel rod, just due to the material properties. And so --

MR. CLIFFORD: And it really depends also on if you're coupling this to your core depletion calculation, it depends on how fine the time steps are when you depleted the rods. Just extract.

CONSULTANT WALLIS: But it's limited. It's not sort for rapid time change --

MR. GEELHOOD: No, this is not -- so this is for steady state and what we call slow transient. So like AOO or a power ramp would be acceptable. In a RA of LOCA, those things are done in FRAPTRAN.

So moving on to the material properties models, the models themselves are what we like to call semi-empirical, and the semi part is because we choose a mathematical form that's kind of known. Like a 1 over T form is good for thermal conductivity, and then we fit the fitting parameters to fit the data.

CHAIRMAN BANERJEE: So the material properties primarily become a function of the integrated slots. Is that it, or how they change during --

MR. GEELHOOD: Probably temperature is what --

(Simultaneous speaking.)

CHAIRMAN BANERJEE: Well, the temperature as well, as a source.

MR. GEELHOOD: And some of them are impacting by flux or burnup and some of them aren't.

CHAIRMAN BANERJEE: The temperature, of course, is a local variable --

MR. GEELHOOD: Yes.

CHAIRMAN BANERJEE: In the sense that at that time step, whatever is the temperature affects that. But the properties are affected by the flux it's exposed to over the history.

MR. GEELHOOD: Some of them are, yes.

CHAIRMAN BANERJEE: Yes, some of them are.

MR. GEELHOOD: Yes, and so then that's kind of what FRAPCON is that's nice. It's a little platform that calculates the temperature, the burnup and the flux at every little point, and then puts that into each property model, and then that gets the property.

Then you iterate back, recalculate the temperature and burnup all those things. So you converge on the solution.

CHAIRMAN BANERJEE: But I thought your little exposition about having sort of step changes meant that you were sort of making an approximation to the integral slots or something, so that you could easily use that without doing a transient calculation.

MR. GEELHOOD: So maybe, yes. The integral flux over the time step, which is maybe like 10 to 50 days, you know.

CHAIRMAN BANERJEE: Yes.

MR. GEELHOOD: Or in the case of a slow transient, you know, hours.

CHAIRMAN BANERJEE: But some of the properties are clearly going to be a function of integral flux.

MR. GEELHOOD: So most of the properties in here aren't going to change in 10 to 50 days, you know. The amount of flux that you gain in that amount of time is insignificant for these properties.

So I guess this last bullet maybe answers some of your last concerns. As we look at comparisons between irradiated and unirradiated data, to determine if there's an radiation effect, and if those such data are applicable, or if we should focus more on irradiated data or if, you know, including the unirradiated is also would be a good idea, because there's some things that don't seem to change much with irradiation.

CHAIRMAN BANERJEE: Dale would have pointed out, of course, that that should be an I, not an E.

MEMBER SHACK: Impirical.

CHAIRMAN BANERJEE: We're not there now, but --

MEMBER SHACK: That's okay. The

spellchecker was turned off.

CHAIRMAN BANERJEE: Okay.

MR. GEELHOOD: How about that? Anyway, so the behavior models, some are also semi-empirical. Like for example, for the fission gas release model, we assumed that it diffuses out a grain to the grain boundary in the form of these bubbles, that they're then released.

But then the empirical part is fitting the constant, such as what the diffusivity of the gas out of the grain, and what's the saturation concentration that causes stuff to come out of bubbles.

CONSULTANT WALLIS: That part is very difficult to review for a reviewer, because he has to go back to whole other documents, and it can take forever.

MR. GEELHOOD: Yes.

MEMBER ARMIJO: Yes. I was going to ask, in your model, do you actually take into account the microstructure of the pellet as it changes at high burnup? For example, in the outer rim, there's a much -- seems to be a much finer grain size than in the bulk of the pellet.

So you'd have, there would be grain boundaries accessible to fission gas for release. Now does it get that level of detail, or you basically say all the properties, the pellet at this burnup are constant. There's no radial --

MR. GEELHOOD: No. So I mean we don't like use the difference in radial burnup into radial temperature, and do have one of our gas release models. So one's kind of still under development, actually does calculate what the restructure is in this rim. So yes, there's a very small grain size on the edge, and it gives a much higher porosity on the edge too, because of the huge bubbles out on the rim.

MEMBER ARMIJO: Right.

MR. GEELHOOD: And so those are kind of things that are coming into the newest models.

MEMBER ARMIJO: But that's not in the current version?

MR. GEELHOOD: It's in the current version. It's an option that the results come together.

MEMBER ARMIJO: Okay.

CHAIRMAN BANERJEE: So if I understand it, we are about a quarter through your presentation now? So let's --

MEMBER ARMIJO: Moving right along.

CHAIRMAN BANERJEE: I mean I don't want

the Committee to feel, the Subcommittee to feel constrained, but let's move along.

MEMBER ARMIJO: Okay.

MR. GEELHOOD: So the calibration parameters, Paul asked about calibration parameters, and all the parameters are in the material properties models or the behavior models. We don't have any external calibration parameters that, you know, we just put fudge factors on things.

So we haven't had to add any tuning parameters beyond the empirical parameters in the behavior and material properties models.

MEMBER SHACK: So they're all tuned just to the separate effects data?

MR. GEELHOOD: Yes, and then FRAPCON combines them, and we found it to get pretty good results with that.

CHAIRMAN BANERJEE: It restores your faith in science.

MEMBER REMPE: What happened or explain again how you did cracking? I mean isn't that -- that effects thing by thermal conductivity, and there's limited data that said oh, it was cracked after a quick look, is kind of how you find that, right? So how do you eliminate the cracking?

MR. GEELHOOD: So I think that the cracking happens on such a macro level, that it maybe doesn't impact the overall thermal conductivity. I think the burnup and the lattice damage that's being done in the fission, the introduction of fission products into the matrix impacts the connectivity much more than the fact that we have now a cracked pellet.

And so, and that's supported by the fact, you know, we've taken thermal conductivity data from irradiated disks which aren't cracked, and applied them into here, and we can product the temperatures fairly well in Halden.

And so there's no evidence before us right now that would say that these, the cracks somehow, you know, degrade the transfer of heat more, or you know, in a significant way.

MEMBER SHACK: But that comes back sort of to Sam's question. When you do these rings, is the only thing that's changing in the ring the temperature, or do you actually have different models for rings in the center, rings on the rim? You said you had some different model for rings on the rim in the new version. But originally, was it all just temperature-dependent? So same models, but you just -- the rings only were temperature regions? Is that

--

MR. GEELHOOD: And also burnup.

MEMBER SHACK: Burnup, okay yes. Burnup or fluence.

MR. GEELHOOD: So burnup for the fuel and fluence for the cladding and then, yes, just temperature in different ones. But yes, like the grain size was held constant.

MEMBER SHACK: But now in the new model, at least on some of them, you can put in a different structural --

MR. GEELHOOD: Well, it just happens automatically.

MEMBER SHACK: It happens automatically.

MR. GEELHOOD: So the code has been tuned to data that's been collected, that shows that we're trying to get this restructuring and smaller grains on the rim. So at the appropriate burnup and in an appropriate temperature range, it just kind of makes that choice for you.

MEMBER REMPE: Meaning that it's all fuel vendor independent when you do that.

MR. GEELHOOD: Yes. So far we haven't seen, you know, a lot of differences between vendors in that regard.

MR. CLIFFORD: That doesn't mean something like MOX wouldn't affect it. That's for $_{U02}$.

MEMBER REMPE: But if someone comes along with something new and better and you prove it experimentally, you'll have to have it --

MR. GEELHOOD: There's going to be like an evolution, and I think all the vendors that are involved say the same thing. They're all making very stable, highly reliable pellets.

Like 40 years ago, you might have seen a lot of variation between vendors because, you know, they couldn't get them as dense as they can now, and so the pellets weren't necessarily as stable, you know, lot to lot, vendor to vendor. But now everyone's kind of converged on these very dense, very stable pellets.

So the impact of the calibration of parameters. Recently, we did a study where eight of the material property and behavior models were identified as those having significant impact on the outputs of regulatory interest. We kind of varied parameters in all the models and came up with these eight, thermal conductivity, thermal expansion, gas release, swelling and then the cladding, creep, thermal expansion, corrosion and hydrogen pickup.

Those are the models that have a significant output on those outputs of regulatory interest that I mentioned earlier. So a standard error based on data is calculated for each of those models and put into the code, which allows the user to say "I want to bias thermal conductivity up by 1-sigma." Then you just put one in, and the whole model would be biased up by one.

CONSULTANT WALLIS: That's rather fascinating. I mean some of these models, it seems to me there's an error of 50 percent or something. Get to the bottom line, and it's 70 percent.

MR. GEELHOOD: Yes, definitely interesting that like you could have a wide variation, but its impact on the output we're interested in may not be that high. So Paul asked me to kind of talk about the evolution of fuel thermal conductivity modeling.

Prior to 1996, to my knowledge, no models contained the effect of burnup on fuel thermal connectivity. In 1992, Lucuta published data from what he called Simfuel, which was fresh fuel doped with simulated fission products, and that was kind of -- he kind of thought for all these like gases and cesium iodide being jammed in there, it's going to definitely change the thermal conductivity. So those data showed that there was a decrease in thermal conductivity with burnup, and so in 1996, he published his revised thermal conductivity model based on his earlier data, and then in 1997, PNNL released FRAPCON 3.0, and that had the Lucuta model.

And I guess the Lucuta maybe did about half of what it needed to do, because in between 1994 and 2004, Ronchi and Carrol had this laser flash data from actual $U0_2$ disks that were irradiated. They kind of sandwiched them between metal plates and irradiate them.

So they're constant temperature and constant flux across the whole thing, and they were able to show that the radiation damage, you know, putting all these defects and dislocations, also had an impact on the connectivity. So those data showed more degradation than was seen in the Simfuel.

CHAIRMAN BANERJEE: But let me just ask you. Simfuel tried to simulate the effect of fission products and gases and stuff, by putting other stuff in there. Is that it?

MR. GEELHOOD: Well, if you know, with both cesium and iodine, you can find non-radiative isotopes of cesium iodine.

CHAIRMAN BANERJEE: The surrogates

essentially.

MR. GEELHOOD: Yes, and then, you know, can find something, a substitute for neptunium or something that's not radioactive.

CHAIRMAN BANERJEE: Right.

MR. GEELHOOD: So Simfuel, the idea was it's expensive to do things in a hot cell. So try to do things, you know, that could be done in a glovebox by simulating these things.

CHAIRMAN BANERJEE: So the fact you put in the appropriate amounts and make a pellet --

MEMBER SHACK: Right. So it's chemical changes, but the other forms of radiation damage aren't accounted for.

MR. GEELHOOD: And so I think the end result, even if you could a dope a pellet with the radioisotopes that are actually produced, you still wouldn't get enough to get the actual, all the fast flux going through, causing damage as well.

CHAIRMAN BANERJEE: So the Ronchi and Carrol data now used actually irradiated disks?

MR. GEELHOOD: Yes.

CHAIRMAN BANERJEE: And what does the laser flash mean there?

MR. GEELHOOD: Oh, that's the way --

that's the easiest way or the most modern way to measure thermal conductivity. It actually measures thermal diffusivity. But a laser comes up underneath it and it's in a little sample holder. So you know how much energy is deposited in, and you can measure how much it heats up, and then from that, you can get the diffusivity --

CHAIRMAN BANERJEE: It's just a way to add a pulse of energy.

MR. GEELHOOD: Yes. So the laser puts a known quantity of energy in, and you measure how much it goes up. And then if you also measure the density --

CHAIRMAN BANERJEE: And you would measure that what, a thermocouple how much it goes up or what?

MR. GEELHOOD: I don't know exactly how the instrument works, but I think --

MEMBER REMPE: Most of them it's thermocouples.

MR. GEELHOOD: Okay.

MEMBER REMPE: We have one in my lab.

MR. GEELHOOD: If that measures diffusivity, then if you also measure the density and the heat capacity, then you can calculate the thermal conductivity, and the heat capacity's done in a differential scanning calorimetry, where you just keep it up and watch your thermocouples.

MEMBER ARMIJO: Were those data on higher burnup, or were they kind of without, and they didn't -- they took them up to what, what kind of burnups?

MR. GEELHOOD: So the last Ronchi data was up above 100 gigawatt-days per ton, which is actually important because we need the connectivity at each radial node. And so even though the licensing burnup is 62, out at the edge the burnup is 100 or higher.

MEMBER ARMIJO: Yes.

MR. GEELHOOD: So one --

CHAIRMAN BANERJEE: Did it verify the sort of behavior that you showed early on on Halden, that you go through a minima and then the thermal conductivity starts to rise at higher burnups?

MEMBER ARMIJO: Temperature.

CHAIRMAN BANERJEE: Sorry, that was a function of temperature.

MR. GEELHOOD: Well, what that is, and the reason it goes down and then up is at low temperatures, it's done, the thermal conductivity is controlled by phonon heat transfer, so lattice vibrations. But then as you get to higher temperature, you get some electronic heat transfer.

So it's a ceramic, but then at higher temperatures, the electrons become more free to move around. So that may start to like dominate it, and the electronic part of it isn't necessarily impacted by burnups.

CHAIRMAN BANERJEE: But all those curves came together, right, so that at high temperature they convert?

MR. GEELHOOD: Because the electronic term isn't really impacted much by burnup. It's the phonon term, because you've added the fission fragments in the lattice, and also just locations in the lattice, that just make the vibrations --

CONSULTANT WALLIS: Presumably because photons that won't go across the bubbles too.

MEMBER REMPE: On the Ronchi and Carrol data, did they use a push rod dilatometer to measure expansion, so it had a density measurement?

MR. GEELHOOD: I think they used to pictometer to measure density.

MEMBER REMPE: Okay. So they did something, and also how high a temperature did they go to?

MR. GEELHOOD: So that's something that's tough about this, is you can measure high temperature, but really the only thing that's valid is measuring the thermal conductivity at the radiation temperature, because in the reactor, you get kind of like this defect annealing and creation.

So if you irradiate here and measure here, it's going to be different than if you irradiated here and measured here, because as you heat the sample up, you're going to get some annealing out of defects that you wouldn't have gotten if you irradiated here, and so they've actually assumed that experimentally, that they'll measure it three times in a row and it keeps changing, because as they're measuring, they're annealing defects.

So it's very important to the disk and laser flash. You have to irradiate them at the temperature and then measure them at that temperature. So if you kind of wanted to see the big picture, you'd need an array where you're irradiating at different temperatures, maybe of some cover rig that helps you control the temperature, and then measure each one at that irradiation temperature. So each disk really only gives you one or two good thermal conductivity measurements.

MEMBER REMPE: Just out of curiosity, what temperatures did they measure at?

MR. GEELHOOD: Usually like 800 to 1,000 degrees C, because you know, that's more of interest than normal operating temperatures, and --

CHAIRMAN BANERJEE: Well, I guess is Graham's answer correct though, that he gave to me, that it's photon transfer?

MR. GEELHOOD: Phonon.

CONSULTANT WALLIS: No, no, no, protons across the bubbles.

CHAIRMAN BANERJEE: At high temperatures.

CONSULTANT WALLIS: Protons across the bubbles. Radiation across the bubbles.

MR. GEELHOOD: I'm sorry.

CHAIRMAN BANERJEE: Yes. At these temperatures, it must be protons.

MR. GEELHOOD: There could be. I mean --

CHAIRMAN BANERJEE: At that temp, I was talking about the high temperature data. So that must be virtually red hot or white hot.

MR. GEELHOOD: So I think, yes. I mean there definitely could be radiation, and you know, you could do some tests of which one's faster.

(Simultaneous speaking.)

CHAIRMAN BANERJEE: Maybe the dominant effect, because otherwise it doesn't make that much sense. Okay. Keep going.

MR. CLIFFORD: Ken, just before you, we'll get into more of this when we go into the models, present the models.

But we say no models contain effective burnup on fuel thermal conductivity, which is correct as far as I know it. But the first information that came from Halden is that fission gas release models were under-predicting high burnup fission gas release, and temperatures at high burnup were higher than models were being predicted.

So that there were corrections that were made to some models at least, to address that.

MR. GEELHOOD: And some of the vendor models just accepted penalties on their predictions.

MR. CLIFFORD: Right, that's right.

MR. GEELHOOD: And if fact it is right, this thermal conductivity degradation, the penalty they accepted should have been a relative penalty rather than an absolute penalty because, you know, if it's 100 degrees C per gigawatt-day at one temperature, at double the temperature it's going to be double that amount, because you know, the thermal conductivity degradation.

MR. CLIFFORD: Given that this has been

demonstrated, the root cause.

MR. GEELHOOD: So you know, a relative like penalty would have been better, because we measure down here.

But now if we're doing LOCA initialization of fuel melting, we may be way up here. So I think this is continuing on the evolution a bit. So in 2003, PNNL released FRAPCON 3.2, and that included the current thermal conductivity model that matched the irradiated data.

CHAIRMAN BANERJEE: That's the data from this --

MR. GEELHOOD: Carrol and Ronchi. And so this is the current model. So we have a phonon term that is a function of gadolinium temperature and burnup, and then an electronic term, which is just a function of temperature, and I kind of talked about where each term is dominant.

CONSULTANT WALLIS: Are these terms dimension-less or something, and then made dimensional to get them right, or are they --

(Simultaneous speaking.)

MR. GEELHOOD: So K-95 is the thermal conductivity of 95 percent theoretical density --

CONSULTANT WALLIS: So A is the dimensions of one over connectivity.

MR. GEELHOOD: Yes. So I mean A is -- everything is in the right unit to get watts per meter K. If you look in the manual, you know A has whatever units --

CONSULTANT WALLIS: Got to get the units right.

MR. GEELHOOD: Yes. So the count is all given and you just have to input temperature in Kelvin and burnup and figure out days for time and gadolinium weight percent, and then you'll be good.

MEMBER ARMIJO: As you build in plutonium, how does that -- do you adjust that model?

MR. GEELHOOD: We don't, but you know, that may be explicitly accounted for, that are implicitly built into the burnup term, like if the plutonium is significantly impacting it, you know.

MEMBER ARMIJO: Would it be like the gadolinium term in a way, just --

MR. GEELHOOD: It might be. We haven't done that, but we've correlated with burnup and plutonium building relates with burnup. So in a sense, you know, that's --

MEMBER ARMIJO: It's in there, but you don't know exactly how?

MR. GEELHOOD: We have a different model for MOX, and we haven't found that the thermal conductivity -- the thermal conductivity of MOX is different, but it's not different with 12 percent MOX or 80 percent MOX. So it's different than UO_2, but it doesn't seem to be a strong function of how much plutonium is in it.

CONSULTANT WALLIS: Well, the plutonium is caused by a different effect. On the average burnup is a radiation -- but the plutonium is just that resonance absorption which is only part of the story. So the burnup and the plutonium are really separate physical things, but they're caused by different physical phenomenon.

MEMBER ARMIJO: But I was talking about the chemistry of the pellet. It changes.

MR. GEELHOOD: But it's a slightly different question. So in the LWR, the flux is the same from one reactor to another, such that plutonium build-in and the burnup rate, even though they're caused by separate things, such as the steam rate, yes.

(Simultaneous speaking.)

MR. GEELHOOD: Yes.

CONSULTANT WALLIS: The spectrum you're

seeing is similar.

MR. GEELHOOD: Yes. I mean all PWRs have the same spectrum, and the BWR spectrum really isn't that much different from, for that particular application.

CHAIRMAN BANERJEE: So you don't have a photon term, as Graham said. It's just --

MR. GEELHOOD: Phonon.

CHAIRMAN BANERJEE: Yes. No, no. Phonon is low temperature stuff. The high temperature, you just have --

MR. GEELHOOD: Base electronic term.

CHAIRMAN BANERJEE: Yes. So that term would obviously dominate as T becomes large, because it's exponential.

MR. GEELHOOD: And that's why that turn up of --

CHAIRMAN BANERJEE: Right. But is that the correct form? What do you think, Graham? I mean radiation goes as T to the 4, right? No, I mean it goes as T to the 4.

CONSULTANT WALLIS: The transfer across the bubbles is probably very effective for irradiation, because maybe the bubbles are fairly small.

MR. GEELHOOD: They are fairly small. So then --

CHAIRMAN BANERJEE: But still --

MR. GEELHOOD: I mean that would probably be more of a science project.

CHAIRMAN BANERJEE: But this fits your data.

MR. GEELHOOD: Yes. There may be --

CHAIRMAN BANERJEE: But does it actually fit the very high temperature data, or --

MR. GEELHOOD: No. So there's high unirradiated data that fits that well. So this electronic term in particular is when you're talking about high, high, above 2,000 is fit to that data.

CHAIRMAN BANERJEE: See one of the questions that we faced in one of the EPUs, I think it was St. Lucie I --

MEMBER REMPE: It was.

CHAIRMAN BANERJEE: It was. If my memory serves me right, was you know, there was limited high temperature data --

MEMBER SHACK: But there's high temperature and there's high temperature.

CHAIRMAN BANERJEE: Yes.

MEMBER SHACK: Right.

MR. GEELHOOD: There's like high for normal operation, and then there's high for these theoretical power to -- LOCA.

CHAIRMAN BANERJEE: Well, I think it was more related to the fact that you didn't have a combination of high temperature and high burnup.

MR. CLIFFORD: We have a plot that's coming up here, that shows linear heat rate versus burnup for all the data points that we have, that we use to calibrate the model. So I think that'll probably come up.

CHAIRMAN BANERJEE: Okay. We can revisit that, and then there was the question related to the veracity of these fits, but anyway --

CONSULTANT WALLIS: Was this based on some physical model, or is it just somebody's favorite form of correlation?

MR. GEELHOOD: Probably more someone's favorite --

(Simultaneous speaking.)

CHAIRMAN BANERJEE: If it was physically based, we should be able to drive it, which I doubt we can do.

MR. GEELHOOD: Yes. A lot of these things, you know, a lot of people like to talk around first principles.

But you know, at some point, there's something you have to measure, and you know, where it may be operating at a higher temperature, but we're fitting to the data, and that's what's important to the staff, is that it has data to back it up.

CONSULTANT WALLIS: My experience is what would really be famous is to have a correlation that no one can explain. If someone can find a rationale for it, then of course it's trivial. Anybody could have done that.

(Laughter.)

MEMBER REMPE: So we've heard that the MOX thermal conductivity equation is different.

MR. GEELHOOD: Yes.

MEMBER REMPE: What is driving the difference? Can you --

MR. GEELHOOD: Probably just chemistry. You know, an unirradiated model has a different thermal conductivity than a radiated MOX, or an unirradiated $U0_2$. So --

MEMBER REMPE: Is it generally lower? Is it generally -- it's a point while you have --

MR. GEELHOOD: So it's lower thermal conductivity, because you would expect slightly higher temperatures in MOX at the same power levels of CO_2.

MR. CLIFFORD: And we haven't licensed MOX yet, so we haven't gone through the exercise of really getting together all the data and validating it.

MEMBER REMPE: I was just curious.

MR. GEELHOOD: But there is a lot of MOX data available. So the Office of Research has funded development to make that FRAPCON applicable to MOX.

CHAIRMAN BANERJEE: So just to dig here a little, is there a correlation between the sound speed in this and thermal conductivity? If it's a phonon term, it must be related to the speed of sound, right?

MR. GEELHOOD: I guess if someone clever to probably back out what the apparent speed of sound was and check it and see if we're right or not.

MEMBER SHACK: A kind of panoply of regulatory interest.

(Laughter; simultaneous speaking.)

MEMBER CORRADINI: I sense a Ph.D. thesis for Sanjoy's students.

CHAIRMAN BANERJEE: Not mine, Mike. I'm not into solids.

MR. GEELHOOD: So this is just predicted -- you want me to go quickly through like the eight models that have been identified, and just kind of show some representative data for this. It's kind of like the data that we have.

So this thermal conductivity, which is kind of the first one, predictive versus measured. So the light points are all beyond an irradiated point, and then the dark points are the irradiated from Ronchi and Carrol.

The reason we have such high connectivity ones for the unirradiated is because those are all the room temperature points. And so we don't have irradiated data from that, because you don't irradiate at room temperature, and as I said, you want to measure and irradiate at the same temperature.

So these dark points down here, that's kind of the area we're working in, moreso than this other stuff. This other stuff is just to get the general broad form of the model.

MEMBER ARMIJO: And all these data were measured with the same --

(Simultaneous speaking.)

MR. GEELHOOD: They came from a lot of different programs.

MEMBER ARMIJO: But the irradiated data were, all the --

MR. GEELHOOD: The Ronchi and Carrol are

not, they're too different. It's not one paper that just by both of them. Ronchi did some work and Carrol did other work. So their equipment --

MEMBER SHACK: But this is all laser flash data here?

MR. GEELHOOD: Some of this unirradiated data may be due to some older method, but all the irradiated data is the laser flash, and it doesn't include that.

CHAIRMAN BANERJEE: The unirradiated data is the Simfuel data or --

MR. GEELHOOD: No, I didn't include the Simfuel data, because currently our models are not appropriate to calculate the Simfuel, because our models calculate unirradiated or irradiated, and the Simfuel is somewhere in between, and when we determined that the Simfuel data didn't accurate predict all the impacts of radiation, we discarded it.

So you know, a model has no way to say "only do the chemistry part, not the irradiation part."

MEMBER SHACK: Okay.

(Pause.)

MR. GEELHOOD: This is all UO_2, I'm sorry.

MEMBER REMPE: But it's all laser flash.

Even the irradiated is laser flash.

MR. GEELHOOD: The irradiated definitely is. The unirradiated spans near 40 or 50 -- so there could be stuff before laser flash, some other way of measuring it.

MEMBER REMPE: Thanks. Sorry I got you sidetracked.

MR. GEELHOOD: So this is, oh I guess we calculated plus or minus 8.8 percent relative, and that's why you see these lines diverging. For fuel thermal expansion, there's our data and the lines are the upper and lower 2-sigma, and we calculate about a ten percent relative uncertainty.

CHAIRMAN BANERJEE: What are the red things?

MR. GEELHOOD: That's a good question. So when we -- so they're what we call outlying data. So when we did this exercise for the NRC, there were some data points that were so far out. So we employed a statistical test that said recalculate the standard deviation from all of the data, and then if there's some data that are beyond like, I think it's like 6-sigma, then you can say, you know, that data must be an outlier, and you can eliminate it as an outlier and recalculate a more representative standard deviation.

Because especially when you don't have a ton of data, if you have one or two outliers that can really drive your standard deviation to high values, you can use these statistical tests to identify some of these data as outliers.

CHAIRMAN BANERJEE: Are these from a particular sort of test, the red ones?

MR. GEELHOOD: They may be. We have like our database spans like 40 or 50 years, and so it's very probable that some of them may have come from -- this is all unirradiated thermal expansion.

CHAIRMAN BANERJEE: But you did, you see the data, right?

MR. GEELHOOD: Yes. We have access to all the data. So I can look back and, you know, try to decide if they all came from one, or maybe one experimenter had other, you know, not very tight control over his experimental methods.

MEMBER REMPE: So all of this was done on unirradiated fuel?

MR. GEELHOOD: This is thermal expansion now, yes.

MEMBER REMPE: And so did they do this with actually fuel in cladding, or did they just take it like a push rod dilatometer sample, and that's all they did.

MR. GEELHOOD: I think yes.

MEMBER REMPE: And how does unirradiated compare with irradiated for thermal expansion?

MR. GEELHOOD: We haven't, no one's measured thermal expansion on irradiated fuel. Some of these things aren't the easiest to do. So --

CHAIRMAN BANERJEE: But when you did those, somebody did those? Someone conducted it -- they were probably done -- where were they done, ACL or something?

MR. GEELHOOD: I think they were done in Europe somewhere. So both Ronchi and Carrol are from Germany or ITU.

CHAIRMAN BANERJEE: They probably could have some thermal expansion.

MR. GEELHOOD: I'm sure, you know, there's many laboratories that could do these sorts of tests, but --

CHAIRMAN BANERJEE: It is important?

MR. GEELHOOD: I don't think that it's important, and this isn't like swelling and densification. This is just strictly thermal expansion. There's not a lot of theoretical reasons that we would think thermal expansion would change a lot with burnup.

MEMBER REMPE: Defects maybe?

MR. GEELHOOD: I mean I guess there's not a lot of like, you know, in other irradiated material. There's not a lot of --

MR. CLIFFORD: Gas expansion.

MR. GEELHOOD: That's different, though, and that's accommodated for. But as far as just thermal expansion, there's not a lot of history of irradiated materials that would tell us that it would change the thermal expansion.

MEMBER REMPE: I just wondered about defects, annealing out --

MR. GEELHOOD: I mean definitely a question.

MEMBER REMPE: Silicon carbonite does see a change. I mean that's something, but I don't know how it makes --

MR. GEELHOOD: Thermal expansion or in swelling, because I know they get --

MEMBER REMPE: Thermal expansion.

MR. GEELHOOD: Okay. Resistivity and thermal expansion both, people have done that. But I don't know how fuel does. We don't test it.

CHAIRMAN BANERJEE: So in transience, the thermal expansion doesn't come into affect the gap?

MR. GEELHOOD: Well, it drives the stream.

CHAIRMAN BANERJEE: Sorry? It drives what?

MR. GEELHOOD: It drives -- so the pellet expands during the transience, and it would drive the cladding stream. So if the swelling --

CHAIRMAN BANERJEE: Why isn't it important?

MR. GEELHOOD: Well, so then I guess we have like some circumstantial evidence that it's not changing, because we can predict the hoop strains fairly well. So that would tell us probably we're predicting the thermal expansion fairly well.

MALE PARTICIPANT: In an integral test?

MR. GEELHOOD: But that's more of an integral --

MEMBER ARMIJO: You know the temperature.

MEMBER SHACK: The hoop strains, you are looking oat that as above the burnup pushing --

MR. GEELHOOD: So we look at various ramp tests.

MEMBER SCHULTZ: --and that includes the thermal expansion and the swelling and the relocation.

MR. GEELHOOD: Well, the swelling and

relocation has been -- those don't happen very fast. So if you look at the ramp test, it really is just kind of looking at that thermal expansion.

MEMBER SCHULTZ: But the initial condition incorporates --

MR. GEELHOOD: Although for most high burnup of gas, it's closed and so just expands into it. But yes.

CHAIRMAN BANERJEE: Okay. Let's move on.

MR. GEELHOOD: Okay. So this is the fission gas release data we have for $U0_2$. So there's power ramped and steady state data in here, and this is just our best estimate model, and then what we did is we biased the gas diffusivity up and down, in such a way that we could over-predict and under-predict all the data.

So then rather than putting an uncertainty on our outputted gas release, we put the uncertainty on the diffusivity, that's just actually plus or minus 100 percent on diffusivity, and then that gives us a way to bias the gas release that comes down.

Fuel swelling. Right now, we predict lower swelling up to about 80 gigawatt-days for time, and then higher swelling above. So what each of these points is, it is an estimate from Halden of what the swelling rate was, because they've got some rates where they can actually measure the length change in the stack, and correlate that to swelling.

So they kind of get this and then they fit a line to it, and say okay, for this one, it was about, you know, this many, delta V over V for ten gigawatt-days for time. They seemed to think or see that that rate goes up at higher burnups. So we have that included in our model.

MEMBER REMPE: On your gas release?

MR. GEELHOOD: Yes.

MEMBER REMPE: What is the gas? Is it all one? I mean do you ever do compositions issues?

MR. GEELHOOD: It's a combination of xenon and krypton.

MEMBER REMPE: Is it ever of interest to know when one -- comes out versus another? I know the French are looking at that, using ultrasonic techniques. So is that of interest from a regulatory perspective, or nobody cares really?

MR. CLIFFORD: Well, there's other Halden sweep gas measurements that were taken..

MEMBER REMPE: Of the composition.

MR. CLIFFORD: Right. Well, they measure, specifically measure the isotopes' power and burnup.

That's important for dose calculations, as opposed to pressure, if you cared about how many moles of gas there is.

MR. GEELHOOD: So ANS maintains a standard 5.4. It tells you how to calculate radioactive gas release. This is kind of the stable gas release that drives the pressure inside the rod, whereas the radioactive gas release would impact your dose calculation.

MEMBER REMPE: Okay.

MR. GEELHOOD: That's about all for swelling. This is just some density that shows, you know, again our model, and we calculated an uncertainty on that swelling. Cladding irradiation creep, this is stress relief annealed cladding, which is mostly used in PWRs and some BWRs.

So we calculated uncertainty on that, and then we also have a model for recrystallized, which is M5 recrystallized in most Zircaloy-2 and BWRs, and we calculated an uncertainty on that. So all these uncertainties are kind of built in, so you can just choose to bias them however you want.

This is axial growth. Again, you'll see some, I guess we eliminated the B&W data as they didn't fully characterize everything that they needed to, you know. This is axial growth, but we didn't have the actual as-built original lengths, only the final lengths.

So we had to correlate the final length with the nominal length, and so there's definitely uncertainty in doing that, and then the Siloe data. That's on a fast reactor. So we think maybe the axial growth in a fast reactor might be different, based on the rate of flux accumulation.

CHAIRMAN BANERJEE: Sorry. I don't mean to interrupt, but when I looked at your gas release, you have two panels, and one you over-predict and one you under-predict. Can you go over what that meant?

MEMBER SHACK: It's deliberate.

MR. GEELHOOD: Yes. So this is our nominal prediction, and then in order to figure out what the upper and lower bounds are, we couldn't really just put an upper and lower bound, because is an integral thing, gas from all these different nodes.

So what we needed to do is we biased the diffusivity up by some now, until we over-predicted them all, and then biased it down by that same amount, until that we under-predicted them all. So then that value is a 2-sigma. Typically, within 2-sigma. So that's what I'm trying to show here, you know, that

I've got 2-sigma upper and lower.

CHAIRMAN BANERJEE: Okay. You can just go on.

MEMBER CORRADINI: Can I ask a question about that? So we're talking about Slide 19, right?

MR. GEELHOOD: Yes.

MEMBER CORRADINI: Can you hear me?

MR. GEELHOOD: Yes.

MEMBER CORRADINI: Okay. So I just want to make sure. I think I understand what you did. Is that a common practice when you have an integral quantity?

MR. GEELHOOD: Yes.

MEMBER CORRADINI: In terms of materials, trying to characterize the materials uncertainty, what you just described?

MR. GEELHOOD: Yes, yes. Some different vendors like choose different parameters within their models, to say this is what I'm going to use as my uncertainty parameters. But diffusivity is as good at any, because you know, there's plenty of knowledge on gas diffusivity and they vary quite a bit. So --

MEMBER CORRADINI: Okay, thank you.

MR. GEELHOOD: So I think I had been talking -- axial growth throughout for recrystallized cladding. This is just an example of cladding corrosion. We have a lot of data for different types of alloys, and we have different uncertainties for different alloys that we collected with the presently available data.

Vendors may have more data on this, because they take a lot of this corrosion data poolside and typically, you know, we require them to show that data with their specific corrosion model. But we kind of have general models that are based more on the publicly available data, and hydrogen pickup, similar. This example's for Zircaloy-2, 4.

I mean but they have different, different uncertainties on different pickup models for different alloys. So we had talked earlier about the range of the assessment data, and so this is --

CHAIRMAN BANERJEE: Maybe I was going to stop you at this point, and take a break, because we're going from -- you're going to go on to integral assessments now, right?

MR. GEELHOOD: Yes.

CHAIRMAN BANERJEE: So perhaps we should just take a 15 minute break. Let's make it 12 minutes. I'll be a hard chairman, so 25 to 11:00, if that's okay.

MR. GEELHOOD: Yes.

CHAIRMAN BANERJEE: Then we'll come back and continue.

MR. GEELHOOD: Sounds good.

(Whereupon, a short recess was taken.)

CHAIRMAN BANERJEE: All right. We are going back into session. Still an open session. Go ahead.

MR. GEELHOOD: So we're on Slide 28 now. So if you have the printout, this is kind of a little animation. You'll see that you won't see as much on the printout.

So this is the data that was available LHGR on the Y, and rod average burnup on the X, between basically all throughout the 80's, and then in the 90's, you can see what data we added to that, and then since the year 2000, we've added all that.

So it kind of defines what our range of what we know is for temperatures versus LHGR or LHGR versus burnup, and typically the higher the LHGR, the higher the temperature.

CHAIRMAN BANERJEE: Could you give us just a rough idea of how temperature and LHGR are correlated, in rough terms? Other than saying the higher the LHGR, the higher the temperature.

MR. GEELHOOD: So I mean the power in the rod produces heat, and so the more heat that's in the rod, the higher the temperature. So they're related to the thermal conductivity and the heat capacity.

CHAIRMAN BANERJEE: So if I wanted to sort of translate this into normal rod average LHGR, but this rod average temperature or the maximum temperature, you could produce --

MR. GEELHOOD: We could make a very similar plot, because we have a lot of comparisons that we showed, that I showed you when I passed this around, that was LHGR versus temperature. And so instead of taking the LHGR, I take --

CHAIRMAN BANERJEE: Take the temperature.

MR. GEELHOOD: Take the temperature, yes.

CHAIRMAN BANERJEE: Well that's the direct measurement of this?

MR. GEELHOOD: Yes.

CHAIRMAN BANERJEE: Yes. LHGR is also a direct measurement.

MR. GEELHOOD: So LHGR is kind of what the NRC staff think about more, because the vendors will propose some sort of envelope that they can operate in, and the staff will decide if that envelope is acceptable. So this plot is more to show this is the envelope that we feel comfortable for FRAPCON.

MEMBER REMPE: So if I correlate this with that P graph earlier, where there were like three tests above 50 gigawatt-day per metric ton uranium, how did you decide to plot so many points here? Is it because of different fuel in the tests, or is it every --

MR. GEELHOOD: These are different rods, and then at each kind of like day, when the measured the temperature, there's a point.

MEMBER REMPE: Three tests with a lot of days of data and --

(Simultaneous speaking.)

MR. GEELHOOD: You know, each IFA can hold 6 to 12 test rods in it.

CHAIRMAN BANERJEE: So let me ask just this question which sorts of comes up. So you're limited to 60-odd fuel disks per MTU, right?

MR. GEELHOOD: Yes.

CHAIRMAN BANERJEE: In terms of what the staff --

MR. GEELHOOD: That's the licensing for most.

CHAIRMAN BANERJEE: Is there a limit put on the LHGR, based on this data? Like is there sort of an envelope that the staff --

MR. GEELHOOD: Well typically, each vendor will propose their own envelope. But you know, it will go constant out for a while, and then it usually comes down something like that, and it's based on their data, which maybe this data plus other data, they may not have used all this data, and usually the staff asks them to include more data that we know about.

MR. CLIFFORD: Right. What you would do is you would develop a bounding curve based on those data, that now would be the range of applicability of the code. Then based on the fuel rod design, you would have a different value in your tech specs that says "the fuel cannot operate beyond this power at this burnup."

MR. GEELHOOD: Because they'll do all their safety analyses and show they're safe within some envelope.

CHAIRMAN BANERJEE: So the effort is made to always stay within the range of this data, is that it?

MR. GEELHOOD: Yes.

CONSULTANT WALLIS: But these are a lot more data than just the Halden data?

MR. GEELHOOD: This is only Halden data.

CONSULTANT WALLIS: All Halden data.

MR. GEELHOOD: Because this is our temperature assessment database, and the only place we've assessed temperature is from Halden data.

CONSULTANT WALLIS: But it's all Halden.

MR. GEELHOOD: So it's this one, and we'll get to one later, the gas release data, that's other places as well.

CONSULTANT WALLIS: So the flux isn't varying much along the rod?

MR. GEELHOOD: Not so much, no.

CHAIRMAN BANERJEE: Is this how we resolved the controversy bill eventually, by looking at the --

MEMBER SHACK: That was one of the things we did. There was a, you know, there was a bound put on the thing, and it was consistent with this data, and we decided that that was acceptable.

CHAIRMAN BANERJEE: Okay.

MR. GEELHOOD: Okay. So this is just another way of looking at it, and this is predicted versus measured temperature now. And so this is the data we had available in the 80's, and how well our current model predicts it. And then if we add on the

90's data, you can hardly see it because it seems to be predicted fairly well.

And then after the year 2000, then we have more data and then this is our sigma of about five percent on the predicted temperature, and those lines are actual 2-sigma bounds, which should bound about 95 percent of the data.

CHAIRMAN BANERJEE: Is that little --

MR. GEELHOOD: This is predicted minus measured over measured. So kind of like the relative under/over prediction, and so that's just another way of looking at it.

MEMBER ARMIJO: This was for gad?

MR. GEELHOOD: Oh, good one. This is for gad. So all the gad data has come since the year 2000, so there's not really an animation like the last one, and we calculated again about five percent uncertainty on that, for a 1-sigma. Then there's a the predicted minus measured over measured. So again, the relative under/over prediction as a function of burnup.

What this demonstrates to us is we're not kind of developing any sorts of bias as burnup progresses. So now this is the range of our fission gas release data, and so this comes from more than just Halden. This comes from some commercial plants, other test reactors.

CHAIRMAN BANERJEE: But if you go back to the previous slide, you're not developing biases, but there are specific tests which seem to lie over, and specific tests which seem to lie under, right?

MR. GEELHOOD: Yes, yes.

CHAIRMAN BANERJEE: And which you use and --

MR. GEELHOOD: So sometimes we get that, and some of these like these points that are really high right here, those are very low temperature. So that's just due to the nature of mathematics, that when you over-predict a low temperature by 50 degrees, it comes out as a 30 percent rate.

If you over-predicted 1,000 degrees by 50 degrees, it comes out at like five percent. So sometimes when you see these like kind of flyers, you know, I looked back in some of these. So you can see that one down there, like this yellow one right here.

You know, so that's a pretty low temperature. It's around 600 K. So that's not really that high. So you over-predicted a little. Relatively, it may be up more.

CONSULTANT WALLIS: It's a funny plot,

because this addition is more realistic. There's no reason why to do relative temperatures. There's no reason why you should predict exactly an absolute zero, for instance. There's no reason those lines have to go through the origin.

MEMBER SCHULTZ: Yes, they can't.

CONSULTANT WALLIS: So this is a better plot really.

MR. GEELHOOD: Yes. I mean there's different ways people like to look at it, and so that's why I put down all the different plots, so you can kind of see do we have biases with burnup. Are we getting more biases with higher or lower temperature, and so --

CHAIRMAN BANERJEE: This is all at all sorts of different LHGRs and everything, right?

MR. GEELHOOD: Yes.

CHAIRMAN BANERJEE: So those brown points up there --

MR. GEELHOOD: Yes.

CHAIRMAN BANERJEE: Are they all at relatively low LHGRs, which means low temperature --

MR. GEELHOOD: Pretty low. We can go to this one.

MALE PARTICIPANT: Back one slide.

MR. GEELHOOD: So yes, there's some right there, you know. It's kind of the nature of doing this sort of thing is, you know, we don't put in a lot of tuning parameters to say oh, it's this rod. So you know, put in 11 percent uncertainty on, you know, we've developed what we think is the best estimate model, and so sometimes --

CHAIRMAN BANERJEE: So the browns are plus or above, and the blues, light blues under.

MR. GEELHOOD: Yes. You know, we try to make an average deviation as close to zero as possible, or we strive for that.

But then sometimes, you know, one experiment might be biased higher and one may be biased lower, and it's unknown is that due to their measurement uncertainty or how well they know, have reported the powers which feed into ours, or is it something fundamentally different about that particular rod that did that, you know. So there's a lot of different uncertainties that --

CHAIRMAN BANERJEE: How well does the Halden correlation fit that? Your correlation seems a little different from Halden, right?

MR. GEELHOOD: It's a little bit different, but we compared it and it's very similar, and they --

CHAIRMAN BANERJEE: Did they predict this as well?

MR. GEELHOOD: They had their own code called FTEMP, and it's not nearly as sophisticated as FRAPCON. We've actually --

CHAIRMAN BANERJEE: In terms of what, material properties?

MR. GEELHOOD: But we have put the Halden correlation into FRAPCON before that, something we even do. Sometimes when we're helping the staff do regulatory reviews is we might put a vendor model into FRAPCON, to see how our model and their model, how they do. So the Halden model predicts very similar to ours.

CHAIRMAN BANERJEE: Thanks.

MR. GEELHOOD: So that's the range of the gas release data. Higher LHGR in some cases then the temperature, because you're not limited by the limitations of various temperature measurement techniques.

So the fission gas release, even though you know it is tuned to data, but it is somewhat of an indication of how well you're predicting the temperature as well, but as a secondary indication in the direct temperature measurement.

CHAIRMAN BANERJEE: Come again? Let's go back to that. Secondary, because --

MR. GEELHOOD: Well we talked about it earlier before. We knew about this. People just tuned their models higher.

CHAIRMAN BANERJEE: Tuned it, right.

MR. GEELHOOD: And so, you know, we think we know about it. So we've tuned our model, but that doesn't necessarily mean that there's something else we --

CHAIRMAN BANERJEE: But the reason for that, it's much easier to measure fission gas, than to measure temperatures.

MR. GEELHOOD: Yes. Because typically, you only measure it after irradiation. You do a puncture and then kind of take it out, which is why, you know, this is like the full histories of all the rods, but when we actually look at the steady state, you know, we have puncture measurements from, you know, 20 or 30 or 40 rods. It's not as many points as we have there.

CONSULTANT WALLIS: Now what's the relationship? I mean you've got zillions of points.

MR. GEELHOOD: So this one there was a

bunch. This is like, you know, the full power histories of the rods we had, and so maybe there's like 20 or 30 points for each one point here, because at end of life, then we puncture or we don't do it, but someone punctures the rod and measures it.

So then you have one datapoint. But that datapoint is kind of an integral of the entire power history. So now we've calculated about two and a half percent absolute uncertainty on the gas release.

CHAIRMAN BANERJEE: That's pretty impressive.

MR. GEELHOOD: Yes. I mean we're pretty happy with how that's been done, and I guess I should make the point. Typically in reactor, they really see releases down in the 0 to 5 percent range, sometimes up higher. But these higher release ones occur in a few rods in the reactor, and they're of the biggest concern to the regulator, because those are the ones that would drive a cladding liftoff analysis.

So we've specifically tried to make sure our code is good at predicting those high release ones, rather than worrying -- you know, some people would say well, you know, a measurement is one percent gas release, and you predicted one and a half, so you're over-predicting by 50 percent.

We don't necessarily care about that as much, because that's not going to impact a pressure analysis as much as getting these higher ones, you know, predicted well.

MEMBER SCHULTZ: And if you were drawing something from the previous scatter plot showing the power versus burnup, you draw some level of confidence or comfort that it looks like the same plot that you had for temperature.

MR. GEELHOOD: For temperature, except they got a little higher.

MEMBER SCHULTZ: So this concept of having something that representatively is high enough in terms of power, and long enough in terms of burnup, you're covering the bases associated with the parameters.

MR. GEELHOOD: This is the same data, but predicted minus measured versus burnup. So it shows kind of the absolute over/under prediction as a function of burnup, and you know, we actually don't have a lot of data beyond 60, which is one reason that the staff has chosen not to extend burnup, is there just isn't a lot of data, and the staff typically like to have data to evaluate, you know, expanding that envelope.

And in fact FRAPCON tried to under-predict some of those higher burnup ones. So but it's hard to know when you don't have two. Is this under-prediction a trend, or is it just like these ones back here were also under-predicted?

MEMBER SCHULTZ: But if you compared this plot to a version of FRAPCON which was mid-90's time frame, it would look much different than this, in terms of the scatter of data. This is a tremendous improvement over what was the predicting capability 15 years ago.

MR. GEELHOOD: Yes. So we've recently added --

CHAIRMAN BANERJEE: So you're sure that's the thermal conductivity correlation?

MR. GEELHOOD: Yes.

CHAIRMAN BANERJEE: You must have some form of correlation for the fission gas release. What does it look like?

MR. GEELHOOD: So it's more complicated than just a single equation.

CHAIRMAN BANERJEE: Don't be afraid. We can --

MR. GEELHOOD: No, I understand. I mean we -- so I mean it's easier to describe, than to like put it in terms of equations.

CHAIRMAN BANERJEE: All right.

MR. GEELHOOD: But we start with gas being produced inside a grain, and we kind of idealize that grain as a sphere with radius or diameter, I guess, being the grain size, and then we allow that gas to diffuse out to the grain boundaries, and then there's some of what we call resolution.

The radiation takes some of the gas that's on the grain boundaries and shoves it back in, you know. So there's that constant diffusion out and resolution.

Ultimately, at a high enough temperature, the diffusion out will beat the resolution. But then once that gas gets to the grain boundaries, then we calculate at various temperatures what the saturation is.

So gas can kind of continue to build up and build up, until it reaches a saturation point, and then that gas is released off the grain boundaries, and the grain boundaries can begin to saturate again.

CHAIRMAN BANERJEE: So how do you calculate saturation?

MR. GEELHOOD: So that's another. It's an empirical fitting parameter, but it's a function of the gas pressure or the cladding pressure pushing back on the pellet. So it's kind of how much that holds in, and then also the temperature and also the grain size. So a smaller grain would have more room for --

CHAIRMAN BANERJEE: If I understand the model has parameters, which somehow have to be input with regard to grain size and diffusabilities, saturation conditions --

MR. GEELHOOD: So there's --

CHAIRMAN BANERJEE: And I suppose some sort of redissolution model.

MR. GEELHOOD: Yes. So there's maybe four different parameters that we can --

CHAIRMAN BANERJEE: Adjust.

MR. GEELHOOD: Adjust, you know, and we have adjusted them. We don't allow the user to adjust them, but you know, one is the diffusivity out, and we found that actually changes with burnup. And then what the resolution rate is and then what the --

CHAIRMAN BANERJEE: So how much did you have to adjust this to fit the data? So let's say you had data up to some relatively low burnup. I take it the structure of the model has stayed roughly constant over time?

MR. GEELHOOD: In the past 10 or 15 years, yes.

CHAIRMAN BANERJEE: Yes. So you must have used it for lower burnup fuel initially, and then in the last ten years have to adjust it for higher burnup.

MR. GEELHOOD: So we took the model from a paper that was written, and then we modified --

CHAIRMAN BANERJEE: Who wrote that paper?

MR. GEELHOOD: Messi.

CHAIRMAN BANERJEE: Werner.

MR. GEELHOOD: He's in Sweden, I think.

CHAIRMAN BANERJEE: Okay.

MR. GEELHOOD: Anyway, so he wrote this, and so we took the structure of that model and we found that he constants he proposed weren't, didn't do a good job. So we used these four kind of fitting parameters.

We adjusted until we could fit our database, and we kind of thought that when we fixed some of the, you know, as we make changes and get more data, that we might have to do a readjustment. But the last time we added more data, it actually fit fairly well.

CHAIRMAN BANERJEE: That was the question I was asking you, yes.

MR. GEELHOOD: Yes, and so I don't have it showing in any of these pictures, but we could say that some of the data was model calibration and some is --

CHAIRMAN BANERJEE: Test.

MR. GEELHOOD: Test data that is kind of independent assessment.

CHAIRMAN BANERJEE: So it's not training data; it's test?

MR. GEELHOOD: Yes, and but we have -- we don't have, you know, a ton of data here, and so it kind of behooved us to use all of it for training data, rather than trying to hold some back. But now as more data is kind of trickling in, that could be considered the test data and it hasn't necessitated any kind of refit so far.

CHAIRMAN BANERJEE: So my impression, though, is that you haven't had a lot of high burnup data very recently though. You said there are these rods which are going to be taken to high burnup.

MR. GEELHOOD: Yes.

CHAIRMAN BANERJEE: When in the next Halden meeting you learn about that?

MR. GEELHOOD: Maybe yes.

CHAIRMAN BANERJEE: Maybe.

MR. GEELHOOD: But then --

CHAIRMAN BANERJEE: But we'd be very interested to know how the model does.

MR. GEELHOOD: Yes.

CHAIRMAN BANERJEE: Are they going to do any puncture tests on those, or is it just --

(Simultaneous speaking.)

MR. GEELHOOD: Probably. But then that doesn't happen until the test is over, over.

CHAIRMAN BANERJEE: Right.

MR. GEELHOOD: You know, so they'll kind of give us snippets of --

CHAIRMAN BANERJEE: That will be exciting. I want to know how it works.

MR. GEELHOOD: Yes, you know, to get some more and, you know, we would be interested if the vendors would publish, you know, some of this data that we could use to do assessment. But you know, to my knowledge, that isn't typically done.

CHAIRMAN BANERJEE: You know, someone said three constants are enough to fit the shape of an elephant.

(Laughter.)

CHAIRMAN BANERJEE: It's whether the shape of the elephant remains constant that's important.

MR. GEELHOOD: As long as you use the exponential, huh? Or maybe hyperbolic signed.

MEMBER SCHULTZ: Ken, for the topic of today, as you changed the high burnup thermal conductivity model, did you change the constants in the fission gas release model?

MR. GEELHOOD: That time we did have to do some refitting, because the temperatures changed so much that, you know, they were tuned for the old temperature predictions, which were probably too low. So but since we've kind of settled on the thermal conductivity model we have since 2003, we also fit the gas release, and then as more data comes out, it's more been confirmation data for us than --

MEMBER SCHULTZ: There was no changes at that point?

MR. GEELHOOD: So nothing's kind of like indicated a need for further changes.

CONSULTANT WALLIS: What surprised me was the model is based on a sphere.

MR. GEELHOOD: Yes.

CONSULTANT WALLIS: And this presumably is because it's easier to analyze a sphere.

CHAIRMAN BANERJEE: Diffusion through a sphere --

CONSULTANT WALLIS: There's no sphere there.

CHAIRMAN BANERJEE: --is a 1D problem.

MR. GEELHOOD: It is what it is, and maybe like --

CONSULTANT WALLIS: But isn't the -- the fuel is cylindrical?

VOICES: No, the grain.

CONSULTANT WALLIS: The grain. The microstructure is spherical? Is that it?

MEMBER ARMIJO: No.

CHAIRMAN BANERJEE: Is there any evidence that the microstructure is spherical?

(Simultaneous speaking.)

MR. GEELHOOD: So like, you know, typically if you look at a micrograph, you'll see these grains, and they're roughly equiaxed. So you know, you could draw a circle and it would be reasonable. So then you assume, because you can take micrographs at different angles and they're equiaxed in both angles.

So a sphere is not an unreasonable way to model the grains. You know, there's more advanced modeling that's done, where they push them together and they have like some weird polygon. But --

CONSULTANT WALLIS: So it's a sort of gravel or something like that?

MR. GEELHOOD: When we have so much uncertainty on the diffusivity, then getting the geometry of like a grain exactly right is --

CONSULTANT WALLIS: Once it gets out of the grain, it's free to go?

MR. GEELHOOD: Once it gets out of the grain, it goes to the grain boundaries, and kind of gets -- you will see a lot of bubbles decorating grain boundaries. Then once it gets out of those, then it's free to go.

CHAIRMAN BANERJEE: Well, you say there's some redissolution backwards.

MR. GEELHOOD: Yes, I'm sorry.

CHAIRMAN BANERJEE: Due to the fluence, right?

MR. GEELHOOD: So that reduces what's in these bubbles. Some of it's constantly going in, as others is coming out.

CHAIRMAN BANERJEE: Yes. Standard store stuff.

MEMBER ARMIJO: Yes.

MR. GEELHOOD: And this, they call it a two-stage diffusion problem, and it's fairly typical among handling of fission gas release.

MR. CLIFFORD: About the athermal term?

MR. GEELHOOD: In the diffusivity?

MR. CLIFFORD: Yes.

MR. GEELHOOD: I mean there -- Paul was saying, you know, in diffusivity there's a athermal term. So we found no matter how low the temperature you radiate, you'll get like some gas released. And so that's why, you know, we don't just let the diffusivity go to zero. We kind of have some athermal bit of it that's kind of being released, especially at high burnup, no matter what.

CHAIRMAN BANERJEE: Okay. It's just sort of a diffusion model, with some diffusion along the concentration gradient.

MR. GEELHOOD: Yes, yes. For that first thing, and then the other one is kind of like a fill it, like a tire that eventually bursts. So we got the capability to do stochastic uncertainty analyses with FRAPCON, and Paul has actually been using those a lot of in some of his analyses of power uprates.

So what it allows us to do is to run many realizations or instances of FRAPCON-3, by varying the manufacturing uncertainties, the model uncertainties and the power uncertainties. So this package then reads data from each realization, compiles distribution throughout each output of interest.

So on our, one of the earlier slides we said, you know, these are the outputs of interest. So what it does is it allows staff to vendor, validate vendor predictions and nominal and upper tolerance limits for various code outputs.

Because ultimately, what the vendor upper tolerance limit is, that's the bottom line more than the nominal, and FRAPCON always predicted nominal. So this allows us to say this is what we think the uncertainties in the model are.

You tell us what your manufacturing power uncertainties are. We'll plug that in and we can calculate FRAPCON's version of an upper tolerance limit, and compare it to the vendor one.

It doesn't rely on assumptions of normality or on input or output distribution as the RMS methods typically do. So typically, the industry has employed more of a Rubian square, where you vary one thing at a time and then add up the sum of the squares of all the deviations.

CHAIRMAN BANERJEE: So what statistics do you rely on here? Is this --

MR. GEELHOOD: So when you get your

output, you know, the code tells the user, you know, if you want a 95-95, you need to run 200 realizations.

CHAIRMAN BANERJEE: Oh, okay. Some form of nonparametric?

MR. GEELHOOD: Yes. Then you'll get your 200 realizations, and it looks at those outputs and says "Okay, your upper 95/95 is X." So it's a more straightforward thing, rather than relying on various assumptions that are kind of buried in more simplistic ways. It's just kind of --

MEMBER SHACK: But you do a sim normality for most of your input distributions?

MR. GEELHOOD: So I'll get to that in a second. So --

MR. CLIFFORD: It depends on the --

MEMBER ARMIJO: There's a whole bunch of options.

MR. GEELHOOD: This is a screen shot from the thing. So these are all manufacturing things, and for instance on the dish diameter, it read the nominal value, but you can give it any of these distributions. So if you wanted the normal one, you could, and then one of these boxes here would ask for the standard deviation.

But you can do these log normals or

uniform or different distribution if, you know, the vendor has indicated that on their manufacturing, maybe they have a log normal because they get to a stop some point or, you know, the tool non-uniformly.

So those are available to you if someone reports that that's the case. And then similarly, these are the --

CONSULTANT WALLIS: How does the pellet resintered density get to be one kilogram per molecule? That's a pretty light pellet, isn't it?

MR. GEELHOOD: No. So the one above that, that's the pellet density. It's 95 percent theoretical.

CONSULTANT WALLIS: What's the resintered density then?

MR. GEELHOOD: There's a standard resintering test that most of the vendors use to calculate what their maximum end reactor densification is. And so --

CONSULTANT WALLIS: So it's a change in density?

MR. GEELHOOD: Yes, yes.

CONSULTANT WALLIS: Oh, it's a change?

MR. GEELHOOD: So what they do is they put an as-manufactured pellet in a furnace of 1,700 K I think. I can't remember the unit.

MEMBER ARMIJO: Very high.

MR. GEELHOOD: And they leave it there for like some period of time, I think it's an hour, and then they measure how much the density increased. This standard says that's how much end reactor densification you can expect.

CONSULTANT WALLIS: It's a very small change.

MR. GEELHOOD: Pretty small, on the order of about one, half percent to one percent of the theoretical density.

CONSULTANT WALLIS: Right.

MR. GEELHOOD: So this is just some sample case. You know, if you measured more, you would put in more. But those are what the vendors supply.

Going on the next one, these are the model parameters. So these are all the ones I just discussed. So you know, the standard deviation is still thin, and you just say, you know, "Do I want a bias it in a normal distribution? Do I want to use half of Ken's predicted standard deviation? Do I want to use twice of what he thinks it is? Do I want to use exactly what he thinks it is?" So it allows the user to do --

CHAIRMAN BANERJEE: A lot of user input, right?

MR. GEELHOOD: Well for this one in particular there is, because --

MR. CLIFFORD: It depends on what your targeted parameters. If you're looking at cladding strain during an AOO, then you may want to change fuel swelling. I'm sorry, fuel thermal expansion.

MR. GEELHOOD: Yes.

MR. CLIFFORD: But if you were looking at end of life rod internal pressure, then you may want to alter fission gas release.

MR. GEELHOOD: So and maybe you don't know what the impact of one of these things is on. So you could just vary that one and then see did it have any impact, and if it didn't, then you can say well next time I run, I'm not even going to worry about that.

So it allows the user to kind of like run these various sensitivity analyses as well.

MEMBER REMPE: Have you come to such insights yet, what's driving some of the model results?

MR. GEELHOOD: So we did a study earlier for the Office of Research, and it kind of drove our selection of these eight parameters, that we varied like all kinds of things, you know, inputs and model parameters, and kind of see which ones had more or less of an impact. I think that's NUREG/CR-7001.

MEMBER REMPE: With the eight or the most you'll -- you want to say oh, what's really driving you to swelling or something like that?

MR. GEELHOOD: Well, I mean like different ones are different things. So like if you're looking at power to melt, then thermal conductivity drives it the most, although swelling has some impact, because it says when the gap is going to close.

MR. CLIFFORD: So like if you turn on the fission gas release uncertainty, you know, your model of fission gas, your nominal end of life rod internal pressure may be 1,600 psi. But, you know, with this turned on, your 95/95 will jump up to a 22, 23, an insignificant increase.

I think when we presented all the results of the different EPUs last year, we generally reported the nominal and then the 95/95, so you could see what the change was as a result of turning on these various uncertainties.

MR. GEELHOOD: So then this is just some examples of the output. So we get these distributions, you know, and you can decide oh maybe this internal pressure is not, the output distribution is not normal. You know, at some point you can't get to any lower pressure. But maybe it's this kind of T distribution.

Then you also get inputs and outputs for each realization. So if you want to do more on your own than what the package provides here, you can import this into Excel or whatever --

CONSULTANT WALLIS: Alpha and gamma, these are the statisticals. So .05, .95 is 95/95?

MR. GEELHOOD: Yes, and so this last one is, you know, it will tell you the number of runs --

CONSULTANT WALLIS: .99 percent with .001, 99.9, 99.9 percent, 9.9 percent.

MR. GEELHOOD: Yes. So you can go --

CONSULTANT WALLIS: But the thing that's so strange is that there's a lot of tail, because that's a much higher value for internal pressure than 95/95. It means there's a huge tail going on.

MR. GEELHOOD: Yes, yes. This isn't like the answer. This is just kind of a sample case we ran. But you're right. In general, like some of these things have like a significant tail, because you know, if you do a worse case analysis, these are your worse case thermal conductivity and worse case gas release, you can get really high pressure in these things.

And if you used, you know, make it the smallest tube and the biggest pellet --

(Simultaneous speaking.)

MR. GEELHOOD: You know, and your plenum length is real low, because you put an extra pellet in, you know. So you know, you can incur at the perfect storm that's going to get you out to pretty high pressures, you know. So but that doesn't necessarily mean the 95/95 is there.

CONSULTANT WALLIS: So the regulator has to make some decision, whether he's going to make a perfect storm or big storm or a 95 percent storm or what.

MR. GEELHOOD: And there's guidance that's been published in various reg guides and stuff, that kind of say, you know, 95/95 would be a good limit. So but it is ultimately the regulator who would make that decision.

This is just a little bit more of the input and the output. So you can kind of see if one thing. This is the uncertainty on the gas release, and you can see it is correlated to the internal pressure, you know.

If you got kind of a shotgun pattern, it might say it's not correlated. But when you get these increases with increasing uncertainty, or an increase in the value, then that says it's correlated. So that could tell someone like Paul gas release is important for this. There's various tests for normality that you can do. So this one is not that normal, because you would expect if there was normal, the dots would be on the line.

So I think this is my last slide. So I kind of talked about the fuel performance codes and what they're used for, the kinds of validation data. All property and behavior models have been validated to be best estimate versus data, and then these eight property and behavior models have been identified to have a significant output, impact on the outputs of interest, and then the standard deviations have been calculated and built in for each of those.

We have a fairly large database of integral assessment data that's been used to validate the code, to show that it provides the best estimate prediction of fuel temperature, in particular, you know, that we're talking about now, and we've calculated uncertainties for that temperature of around five percent.

We've added this capability to do stochastic analysis to calculate various upper tolerance limits. So that's what I have, and I think I'm going to move on to Paul.

CHAIRMAN BANERJEE: Well thanks very much, Ken. We're running about --

CONSULTANT WALLIS: Can I ask one quick question. All this is based on Halden data?

MR. GEELHOOD: All what?

CONSULTANT WALLIS: The temperature.

MR. GEELHOOD: All the temperature is definitely based on Halden. The FRAPCON is based on many, many different --

CONSULTANT WALLIS: To be compared with stuff from real reactors and all that?

MR. GEELHOOD: Oh yes, yes.

CONSULTANT WALLIS: That's what you also showed us, didn't you?

MR. GEELHOOD: Yes. So some of the gas release came from real reactors. I didn't show you like corrosion. Oh, I guess I showed some corrosion. That's from real reactors, because the flux in Halden is lower than the flux in a PWR or BWR. Our code can account for those differences, and then you know, apply the new flux to --

CONSULTANT WALLIS: Just when I was going to get into it, and some of this, some of the material we read did show some Studsig data and so on, and there was -- it was different from other data. You're not going to get into that, though?

MR. GEELHOOD: A lot of this data was ramp test data, and so, you know, when I showed gas release predictions, I showed steady state and ramp test. A lot of that ramp test data came from Studsig. I didn't show the predictions of strain, predicting and measured. But a lot of that also comes from various ramp tests, Studsig included.

MEMBER ARMIJO: I was going to ask a question. When you found that the thermal conductivity in the old codes that's non-conservative at high burnups, and then you made, you adjusted your codes and you wound up with much higher temperatures.

MR. GEELHOOD: Yes.

MEMBER ARMIJO: You know, what other parts of the code were overly-conservative? You know, the other -- because of the fission gas release is the finger you're nailing all your analyses to. So if you raise the fuel temperature to account for thermal conductivity degradation, there must have been something else that was predicting the fission gas releases that was overly-conservative?

MR. GEELHOOD: Yes, like the four or five tuning parameters in the gas release model had to be changed.

MEMBER ARMIJO: Okay. What were they?

MR. GEELHOOD: Well like the multiplier on the diffusion, the diffusivity.

CHAIRMAN BANERJEE: The pellets, I mean the grain size?

MR. GEELHOOD: What the grain -- well, the grain size we pretty much just -- it's pretty standard.

MEMBER SHACK: That's a real parameter.

MEMBER ARMIJO: Yes. That you can measure.

MR. GEELHOOD: That's something you can measure. But then what the resolution rate is, how much saturation on the grain boundary there could be. And so, so we have these like parameters that have been kind of empirically derived, and so you know, if in the future we decided at really high burnup there's even more, then we would have to go and somehow adjust --

MEMBER ARMIJO: But it wasn't any one particular parameter that was way out of line --

MR. GEELHOOD: I mean it's kind of a balance between like all three or four of them, to get them to like predict our, you know, fairly. Even though it doesn't look like a lot of data, it comes from a lot of different conditions. So to get one model that predicts all that, you know, is kind of a little bit of a balancing act.

MEMBER SHACK: It takes Von Carmen's three point numbers.

MEMBER SCHULTZ: So you adjust everything that you can, in order to get the best answer for all the set.

MR. GEELHOOD: Luckily, we have more data --

(Simultaneous speaking.)

MEMBER ARMIJO: Well sometimes you can't, you can't -- you have data, and so those are fixed, and then little by little, you get to the things that are just guesses, and then those are the ones you mess with.

MR. GEELHOOD: Yes. I mean a lot of these like kind of more fundamental parameters, it's either difficult or impossible to make a measurement, I mean to do a diffusion experiment in reactors. It would be an engineering, you know, feat to design that experiment.

CONSULTANT WALLIS: You didn't say anything about MOX.

MR. GEELHOOD: And I wasn't asked to say much about MOX, but I could say more about MOX if you had --

CHAIRMAN BANERJEE: I'm going to have to interrupt this, because we're already --

MEMBER ARMIJO: Way too interesting.

CHAIRMAN BANERJEE: 45 minutes, actually 50 minutes behind schedule. So that means that of course we'll have to reduce our lunch break. But before we do that, we really do need to close the session now.

So I think if we could just make sure that everybody is, who should be here is here, and who shouldn't be here is not here, and we will go into closed transcripts now.

(Whereupon, at 11:19 a.m., the meeting adjourned to closed session.)

P R O C E E D I N G S

3:07 p.m.

Resolution/Future NRC Actions

CHAIRMAN BANERJEE: We're back, and we have both Paul and Ben. Paul, you are going to lead, right?

MR. CLIFFORD: Yes. Okay. The last presentation is just a brief description of what the root cause, and what corrective actions the staff has taken to try to ensure that we don't find ourselves in the same situation 10 or 20 years from now.

Root cause, going back to the slides I presented this morning, which show the available data, you know, back in the early 80's when a lot of these codes were developed, really illustrated that the root cause is just the continued use of these legacy codes, well beyond their range of applicability, and that allowing plants to use fuel more aggressively with these legacy codes was not the most advisable strategy.

I think part of the cause would be just due to the very nature of the regulatory environment, and the fact that it's difficult to revoke the approval of these legacy fuel performance models, since they're being cited in plant tech specs and they're being used very reload, and the hurdles that are introduced because of 51.09.

MEMBER REMPE: So you're approving new codes, and what if there's another issue that's not defined yet, that crops up because of new data --

MR. CLIFFORD: We'll get there, we'll get there.

MEMBER REMPE: Do you have a conditional approval now or what?

MR. CLIFFORD: We'll get there.

MEMBER REMPE: Cool.

(Laughter.)

MEMBER REMPE: I didn't look ahead, okay.

MR. CLIFFORD: I'm glad we did. Corrective actions. We should be scrutinizing any future changes in fuel design or operating limits, along with the supporting empirical data, to ensure a high level of confidence in model predictions, and this would be applicable to any future license burnup limit extensions beyond 62, the introduction of pellet additives or changes in the physile content of the pellets.

I mean you could argue that a lesson learned would be that we shouldn't have allowed 62 gigawatt-days when we did, if in fact we only had data up to 40 at the time. Maybe that's a lesson learned. But going forward, I think the best corrective action would be to require periodic requalification of analytical models, or to institute a sunset clause and the staff's approval of future models.

MALE PARTICIPANT: What does OGC think of that?

MEMBER ARMIJO: Paul, do you really mean requalification or rejustification in a sense, without -- I don't know what requalification means, but I suspect it means a huge effort versus a defense of the adequacy of the existing model, you know, like no new phenomenon discovered in the last five years, that sort of stuff, more qualitative arguments.

MR. CLIFFORD: It's all explained here. This was our first attempt.

(Simultaneous speaking.)

MR. CLIFFORD: When we approved PRIME a couple of years back, you know, we were in the midst of identifying TCD, and we were recognizing that we had these legacy codes, and something needed to be done. So we introduced condition of approval in the safety evaluation.

I mean you can read the whole thing, but essentially every five years, GE will have to submit a letter identifying any new data, and showing that that data does not change the best estimate predicted capabilities of their tools, nor does it change the uncertainties they're assuming in their safety analysis.

CONSULTANT WALLIS: Do you think this is a template for future codes?

MR. CLIFFORD: I think this a template. Right now, our strategy is that a very similar condition would be put on all future approvals. We're looking at a new version of RODEX for AREVA. It's RODEX4, but applicable to recrystallized cladding. The previous approval of RODEX -- this is the type of condition we would put in that SE.

So this approach requires action on the part of the industry to keep track of information, and to continuously demonstrate to themselves that their codes remain applicable. It also gives the staff a vehicle to then open up that review.

When they submit this letter and it shows up to say their biases and uncertainties have changed because there's more data now, then that gives us a vehicle for then opening up that review and demanding action.

MEMBER CORRADINI: Paul, can I ask a

question? You're using the PRIME example, right, on Slide 24?

MR. CLIFFORD: Yes, correct.

MEMBER CORRADINI: Okay. So has the staff gone further to lay out a time line about their review, so that you don't get in this bollix again, that let's say there's new data that shows, because of cladding or fuel, that some sort of condition requires a reanalysis.

They now have a new model. They give it to you and it's years before they get it, and then they have, they're in a situation where there would be -- the licensee is going to use something in that process.

So this sounds good, but what's the time line for the complete eventual issuance of the licensee being blessed with a new technique? This is only part of the puzzle.

MR. CLIFFORD: No, I agree. But this solves half the problem.

MEMBER CORRADINI: Well, let me -- maybe, because unless I see the full picture, I'm not sure what problem it solves at all. I want to be a little bit pretending to be, if I happen to be, let me pick one. Dominion and Kewaunee, since that's now officially irrelevant.

Why would I agree or not fight about all this, unless I saw the end game making sense? That is, you can't just think about the applicability or the first part of the problem. You have to lay out the time line of the whole problem.

Otherwise, you could just make a mess later on from all of this. I guess this sounds like a good step, but unless you lay out now that they, every five years they look for some new evidence that requires them to change the model, then staff has got to, in some sense, also put a way out in their time line for review, so that then the licensees can now use the model, or I should say develop a process to use the new model. You guys then have to approve that.

MEMBER SCHULTZ: Mike, doesn't that follow the last bullet? The vendor is going to be identifying and dispositioning any bias on model predictions, or any increase on uncertainty, and the next step would be for the staff to review that letter and get back to the vendor, as to what needs to happen next.

MR. CLIFFORD: Yes. It's kind of difficult to do that.

MEMBER CORRADINI: Well, but if I only see a part of the solution here, I worry that the other piece of the solution could be more complicated than we first suspect, or we just speeded up one part of this, but the rest of the process still takes 10 to 15 years.

So I guess what I'm curious about is how this all lays out, given that there's so many moving parts.

MR. CLIFFORD: You make a good point. That's something we can think about. But it is difficult, without having an idea of what the error or what the impact is for future change or a future problem, and how we would go about --

MEMBER CORRADINI: But now I'll just make even a more provocative statement. It seems to me if you want to do this to the license or to the vendors, and the technology, something comes up in the technology, then staff has got to come up with some sort of review process that's a bit more expeditious, not only for the --

Let's just take an example. There's some sort of change or some sort of knowledge about a new material or something that creates a difference, that you've got to contend with. Now the next step would be staff would then, depending upon the severity or the degree of change, staff's going to have to come up with a different review process, not views.

Otherwise, you're going to get in this process the licensee is never going to adopt any of this, because they just see this endless set of steps. So we could just come back to where we are now. I mean I can't remember which of the presenters it was, Ben was trying to explain all this thing.

It muddles the mind on all the possibilities, simply because it takes so long.

MEMBER SCHULTZ: Well, also what you're pointing out Mike is that, and I look forward in the slides, I don't see a solution to the problem that we did describe, which was licensees aren't adopting, or in a position to need to adopt, the new models as they are approved by the staff.

MEMBER CORRADINI: Yes, and I betcha that's a business decision. It's a time and business decision.

MEMBER SCHULTZ: It is.

MR. CLIFFORD: And we've had dialogues with the vendors, and we've talked openly about okay, when you submit PAD5, we want you to submit a retirement plan for PAD4, and put it right in the --

put it right in the topical report so we can approve it.

MEMBER SCHULTZ: And the other codes that they have.

MR. CLIFFORD: And the other codes.

MR. JACKSON: In terms of regulatory response or regulatory action, if the five-year look under this condition, under the PRIME SE should uncover something large, I mean I think we would take immediate action or more dramatic action, versus something that's very minor, and we could deal with that.

MEMBER ARMIJO: You know, that's what worries me about this thing. If you found a large effect like TCD, then I could see this as very valuable. But you know, the amount of data we have today as opposed to the data that was available when these old codes were approved, it's a lot more and a lot better.

So unless you find something really significant, this process should be very simple and straightforward.

(Simultaneous speaking.)

MEMBER CORRADINI: --to what I'm saying. The staff, I think it's commendable the staff has come up with a way to try to, you know, come up with the time windows that the vendors have to report on stuff. But on the other hand, there ought to be, instead of using the term severity, I'll just use it as a change in the prediction.

If the change in prediction is five percent or pick some number, then the review process and the recalibration for all parties, including the licensee, ought to be fast. If it's ten percent of 15 or something that's really major, then you're going to have to go through a serious review.

So it's not just the time, but it's also the level of change that to have to deal with.

MEMBER SHACK: Yes, but I don't see that this does anything. I mean this just tells them they have to inform the staff. The staff then has to make a decision as to whether some real severe regulatory action is warranted, or that's very nice. We file this letter and it's --

MEMBER CORRADINI: Okay. Well, that's fine, but then it really --

MEMBER SHACK: At least you have the information and it's been considered. I mean the prime responsibility is always on these people for safety, not the staff. It puts the responsibility where it belongs, and gets them involved. I think it's a great idea.

MEMBER ARMIJO: I guess I'd have a lawyer look at this, because the word "may augment the existing PRIME qualification," you know, I'd be more concerned if its "may degrade or undermine." You can always augment a qualification by new data, a little more data.

But it seems like you really want to avoid the problem we have right now, that TCD wasn't implemented in a timely way, and we've known about this for how many years, 10, 15 years?

MEMBER SHACK: Yes. The "which may" should be "which may affect" existing PRIME qualification.

MEMBER ARMIJO: Well, I wouldn't care. I wouldn't care if we found things that showed that PRIME was very conservative, and it was -- that's up to them if they want to come back to you and say we'd like to get some benefit. But I would care if they found out that hey, this new data on fission gas release is really something's changed, and it's degrading our --

CHAIRMAN BANERJEE: But this is early information though, right?

MEMBER ARMIJO: Well no.

(Simultaneous speaking.)

MEMBER ARMIJO: This is a big deal. It depends how it's done.

CHAIRMAN BANERJEE: Imagine that you were doing some work in any field. You'd be expected to stay up on the development and what's going on.

MEMBER ARMIJO: Of course, of course.

CHAIRMAN BANERJEE: And then just an informational letter. They're asking you to write a letter to inform them of new sources of data, whatever uncertainties arise with your model against this new data, if there's any, and how you're going to deal with it or what you plan to do. I mean this is not taking any action whatsoever.

MEMBER ARMIJO: This could be like perpetual requalification, even if there's no safety impact.

CHAIRMAN BANERJEE: They say there is no safety significance and the staff throws up, what does it matter.

MEMBER ARMIJO: Okay.

CHAIRMAN BANERJEE: They don't have to do anything with it.

MEMBER SHACK: The staff, then, sort of

has to decide when this done whether some action is required. But I mean most of these, I suspect, will end up --

CHAIRMAN BANERJEE: Like if we change one correlation in a code or something, I mean we're not going to ask for that code to be requalified.

MEMBER ARMIJO: That's what it says.

CHAIRMAN BANERJEE: No, it doesn't say that.

MR. CLIFFORD: Well, they can't change any correlations.

MEMBER SCHULTZ: They can't change the correlations without approval of the staff.

MR. CLIFFORD: Right.

CHAIRMAN BANERJEE: Well, in general imagine that you have a code called NOTRUMP or something, which I know more about all this stuff. You change DNB correlation or something in that, you know, you have to qualify that. You give the database to the staff. We do it all the time. Every time we have a new fuel, we change the DNB correlation. What's the big deal?

CONSULTANT WALLIS: It reminds of certain GSI, where the new data comes in faster than any kind of reaction --

CHAIRMAN BANERJEE: That's a completely different --

MEMBER SHACK: But this is clearly different. I mean this is not, you know, if they want to propose a change in a correlation, that's one thing. But in this one, we'd say when those new Halden data come out, you have to go back and look and see if in fact it changed your model --

MR. CLIFFORD: It won't affect your model.

MEMBER SHACK: It changed your model.

CHAIRMAN BANERJEE: Doesn't change it.

MEMBER SHACK: If it doesn't change it, it's fine. If it somehow changes it, you have to change and disposition that. I mean but I would think, you know, it's very different from introducing a new correlation.

CHAIRMAN BANERJEE: No. I misspoke about the DNB, because you'd still show that the W-3 or whatever it is works on your new data, that's all.

MEMBER ARMIJO: Well, augmented database means a bigger database, and the database is always going to get bigger. If it doesn't change the answer, why are you going through this exercise?

(Simultaneous speaking.)

MEMBER SHACK: --to find out if it does

change the answer.

MEMBER ARMIJO: Well, you'll know pretty well, pretty quickly when you take the data, you know. The fission gas release numbers are consistent with the original database. Why mess around? You'll have the staff and everybody else churning perpetually, depending upon how this is managed.

MEMBER SHACK: They'll just write the letter saying that this is consistent with the existing database.

CONSULTANT WALLIS: Well, there's a problem --

MEMBER ARMIJO: That's what I would -- if it was done that way, Bill, I wouldn't be so worried. But I just, the way it reads, it sounds like it's going to --

CONSULTANT WALLIS: Well, it discourages investigation, because every time you discover something new, you have to go through this.

MEMBER ARMIJO: That's part of the negative, yes.

(Simultaneous speaking.)

MR. CLIFFORD: Every five years they have to submit a letter.

CHAIRMAN BANERJEE: You assess your

database.

MEMBER SCHULTZ: So this is in place --

(Simultaneous speaking.)

MEMBER ARMIJO: They've cut a deal on PRIME already.

MEMBER SCHULTZ: This is in place?

MR. CLIFFORD: For PRIME.

MEMBER SCHULTZ: And so did you have to ask if this was going to be applied retroactively to everyone, or to the other codes?

MR. CLIFFORD: No.

MEMBER SCHULTZ: They didn't ask that?

MR. CLIFFORD: We haven't made that decision. We're going to --

(Simultaneous speaking.)

MR. JACKSON: This is just the type of thing we're thinking about, you know, having been through this experience with --

(Simultaneous speaking.)

MEMBER ARMIJO: You'd pretty much need to do this with any new code, right?

MR. CLIFFORD: Oh, absolutely.

MEMBER ARMIJO: I mean it wouldn't be fair to --

MR. CLIFFORD: It's our first attempt to

ensure that the industry is staying on top of the data, and at least recognizing in a public letter that their codes are becoming outdated.

MEMBER SHACK: Or not.

MR. CLIFFORD: Or not.

CHAIRMAN BANERJEE: We have made this comment on the reactor physics codes.

MEMBER SCHULTZ: Well, I think this is a good idea. I'm just concerned that the other part of the problem needs to be addressed, and that is that movement to new methodologies needs to happen.

MR. CLIFFORD: Right, and that gets us to our next slide.

MEMBER REMPE: Before you leave this, though, I guess I'm so curious about a point I think Steve raised earlier, about how the licensees are impacted by this. Just because the vendor says okay, my code has to change, will there be -- I mean earlier, you said that the licensee has it in their tech specs.

Will they have PRIME approved in 2010, and then can they continue using PRIME approved 2010 or will PRIME need to be updated automatically, because I caught the vendor.

MR. PARKS: Those tech spec COLA

references for GE plants only reference NEDE-24011, which is GESTAR. So GESTAR is a motherhood document that's updated on a regular basis. Amendments are submitted to the staff for review.

One could conceive this SE condition in such a way as if they write a negative report that says their model's impacted, we would expect to see a revision to adjust that in an upcoming GESTAR revision, which we would then review.

But no licensee needs a licensing action to adopt, because once the latest revision of GESTAR is approved, licensees can use this.

MEMBER REMPE: Automatically, licensees will update it.

MR. PARKS: So for this framework, it works, right.

MEMBER REMPE: And what if they say "we think it's still fine, it works fine," but you guys say "no, we don't think it's fine."

MR. CLIFFORD: At least we had that dialogue.

MEMBER REMPE: Okay.

MR. CLIFFORD: At least we had that dialogue. Right now, we don't have that dialogue.

MR. JACKSON: So the regulatory process is in place, you know. For Westinghouse, Part 21 applies. So if they find an error that's important to safety, they're required to report it, and you know, there's a couple of words in there important to safety and error, and these are interpreted different ways.

The 5046 requirements apply to licensees, and if it's an error that affects temperature, you have annual reporting, you have reported if it exceeds 50 degrees. So that's, you know, that's the situation we have now, and you know, we've addressed the TCD issues through that way.

But what Paul's saying is we could do better perhaps, and this would lower the threshold a little bit on topical reports, for when we would get the information. Obviously, whenever we get the information, if we find a plant that's in non-compliance or that there's a safety factor, we'd have to take action.

This would just give us the information to make that decision. The decisions would still be just as difficult. So the situation we have now --

(Laughter.)

MR. JACKSON: This situation we have now is there's plants that are, you know, that are taking the RAC up, and this affects my PCT by 20 degrees.

Well, that doesn't merit regulatory action on my part, to tell them to do something before 2016 or 2017.

But if it's 200 degrees or more, I might take a more dramatic regulatory action. This is just a way to get the information, so that we can get it into our regulatory processes and start working them through.

MEMBER SCHULTZ: I think this approach is very valuable, and it will be even more valuable, if like in this case, GE and it goes into the GE licensing methodology and GESTAR, and all licensees are going to be affected by or be using that methodology, if GE does the analysis, all GE fuel users.

MR. CLIFFORD: Right.

MEMBER SCHULTZ: So that's a good thing, and if that can be done also for Westinghouse and AREVA plants, that would be great. Because the licensees will read this. Those that are using GE fuel are going to be paying attention to this five year report in 2015, and they'll be looking to see whether it's going to change or not, and they'll be involved in the decision to some degree, at least they'll be aware of the decision.

MEMBER CORRADINI: So Steve, can I follow that up? I mean so you've been on the other side of this. So if they see this, are they going to then be more apt to want to learn the new technology or be part of it, so that they use it, or are they going to be apt, from a business decision standpoint, to stand back and watch everybody say "Okay, who's first, but not me"?

MEMBER SCHULTZ: No. Everybody is going to pretty much go through it together, and here, what I see is that in 2015, all GE fuel users are going to be very interested in this report, and be asking GE, through the Owners Group most likely, so what happens next, now that you've evaluated the new data and discarded some, and they'll be following the NRC reaction to that, and what happens next as to whether there's going to be any model changes or not.

There's nothing in here that says model change is what'll happen. It's more likely to be, as Ken was mentioning with FRAPCON, where they got new data, they put it into their model and put it on the chart, looked really good, fit real fine, no changes were required.

MEMBER CORRADINI: Okay, okay.

CHAIRMAN BANERJEE: What does "demonstrate" mean here? "GNF must demonstrate." I mean that's in the fourth line there. I mean that can be a pretty broad term.

MR. CLIFFORD: Well, "demonstrate" would mean if there's a new Halden rod, then they would have to use PRIME to simulate the burnup profile in the Halden reactor, compared against the measured data, as an example.

MEMBER ARMIJO: Well, but you can apply it to every new, every experiment that comes out, and it may not change the story at all, you know. All the fission gas release data that comes out, the database is big already. You add more stuff, but you go through another complete analysis.

I don't know what you're going to -- I don't know where you're going with this Paul, but I think it could turn into a nightmare, or maybe I'm just reading it the wrong way. But I know what you're trying to do, and I wish something like this had been there when there was no data.

But now we've got a lot of data, fuel swelling, cladding creep, fission -- we have tons of data on that. TCD, we weren't so rich, but we are now, and you know --

MR. JACKSON: When we imposed this license condition, GNF was notified. I mean there was some dialogue with GNF.

MEMBER ARMIJO: Well, that's their problem. They signed up for it, you know. It's going to work, you know, it will come back to the staff.

MEMBER SHACK: If Sam was still in charge, it would have been a different story.

(Laughter.)

MEMBER ARMIJO: I wish Harold was here, because like he says, he's an amateur lawyer. But I would say the staff should be very careful too, because if this comes back, you'll have every five years mountains of stuff coming back for your review, and it could be trivial stuff, and you will have to set up some process that says "Hey, this is true, but this is not nothing, worth doing this much work. There's nothing new here." And then every five years, there's not going to be a hell of a lot of new stuff coming out.

MEMBER SHACK: Oh yes, there's no doubt. You put a test rod in Halden and it takes you seven or eight years to irradiate it.

MEMBER ARMIJO: You know, it's just --

MR. JACKSON: Well, we receive data on the annual 50.46 reports, the large change 50.46 reports, the Part 21 reports. We have a system that when the reports come in, we can deal with them.

MEMBER ARMIJO: I can see a situation where some Russian guy publishes some stuff from a PWR, and he's got some unusually high fission gas release data and everything else. New data, everybody knows about it.

The Westinghouse guys and the AREVA guys are going to be sweating blood, of how first either say it's valid or it's not valid or justifying that, and you know --

MALE PARTICIPANT: They have an opportunity --

MEMBER SHACK: Well, they'd be doing that anyway, Sam. If they see data that doesn't look right, they're going to ask whether it's right or you know --

MEMBER ARMIJO: Well obviously. But you know, you have your own database.

MEMBER SHACK: I don't see anything wrong with just having people look at the data.

MEMBER ARMIJO: It depends how you handle it, how you manage it.

MR. CLIFFORD: The other option would be essentially a sunset clause, and surprisingly independent from us developing this PRIME SE condition, the IAE had conducted a periodic review of the NRC, and one of their recommendations was that we should consider limiting the approval of codes to specific periods of time.

MEMBER ARMIJO: I don't have a problem with a sunset clause, but it's got to -- it can't be every five years, you know. There is a time when all codes may need to be.

MR. JACKSON: You know, what is it, every ten years they perform a --

MR. CLIFFORD: Safety review. Periodic safety review.

MR. JACKSON: What's the name they use?

MR. CLIFFORD: That's right.

MEMBER CORRADINI: That's for the plant.

MR. CLIFFORD: That's for the plant, correct.

MEMBER SHACK: Right. The periodic safety review is used around the world. They don't go to the level of detail that would actually go in and look at the data for the codes. They do look at that broadly, though. Periodic safety review.

MR. CLIFFORD: So we've gotten at least one recommendation from the IAE, that says we should limit the duration of which codes are approved.

MEMBER SHACK: You know what that letter's saying. This is a hell of a lot bigger club.

MR. CLIFFORD: Well yes, but --

(Laughter.)

MEMBER ARMIJO: This is a, you know, you wouldn't do this every five years. You would put a much longer sunset period, I would think.

CONSULTANT WALLIS: Twenty years?

MEMBER ARMIJO: Yes.

MR. JACKSON: Well, it's a good point.

MEMBER ARMIJO: In this case, you know, it takes time to get enough data, unless there's something really bad that happens, and something comes out that's a new finding that you've got to deal with right away. You know, with enough time, yes, you should modernize all your codes.

CONSULTANT WALLIS: I think I see one good thing out of this, is that, you know, if we have a new generation of regulators. If we say every 20 years, then the new people will wonder what's in the code and why it's there. They're going to have to, they have to look at it.

MEMBER ARMIJO: Okay, well --

MR. CLIFFORD: Okay. So that would be another approach we would consider.

MEMBER SHACK: Or an additional approach.

MR. CLIFFORD: Or an additional approach. This is the last slide, Conclusions. All the fuel vendors recognize the need to address TCD in fuel performance models and downstream safety analysis. I guess in summary, the BWR fuel performance methods are the effects of TCD.

GE and Westinghouse have fully implemented corrections via new codes. AREVA has RODEX4 and hopefully will be transitioning their fleet from RODEX2A to RODEX4. The story is not as straightforward in the PWR world, as we spent most of the afternoon talking about.

With respect to fuel mechanical design explicitly, and not downstream analysis, AREVA has migrated or will be migrating to COPERNIC, or is applying penalty factors, and Westinghouse is awaiting new methods.

The last bullet is what we just talked about. We are considering implementing safety evaluation conditions, which would mandate periodic requalification or notification with respect to the future use of fuel performance models.

CHAIRMAN BANERJEE: Why are BWRs so much more advanced than PWRs with regard to this? Is there any reason?

MEMBER CORRADINI: Well, they're better, right?

(Simultaneous speaking; laughter.)

MALE PARTICIPANT: They boil.

MEMBER CORRADINI: I was trying to help Sam out.

CHAIRMAN BANERJEE: It seems a lot more complex, but --

MEMBER ARMIJO: They boil, boiling water.

MEMBER SCHULTZ: Not in terms of fuel.

MR. CLIFFORD: I can't answer that. I can't answer why certain vendors are ahead of other vendors in addressing this issue.

MEMBER SCHULTZ: Just for clarity, Paul, is AREVA migrating to COPERNIC, or are they going --

MR. CLIFFORD: For their B&W plants, they're migrating off of TACO3 to COPERNIC. But their longer-term strategy is to migrate to GALILEO, once it's approved.

MEMBER CORRADINI: And now it's been almost a whole two hours, so I don't remember. But is GALILEO supposed to be both a B and a P friendly approach?

MR. CLIFFORD: That's our understanding.

CHAIRMAN BANERJEE: And probably in HTGR as well.

(Laughter.)

MEMBER ARMIJO: I suspect that we won't see that for a long, long time.

MEMBER SHACK: Right after 50.46(c) is finished.

MEMBER CORRADINI: Yes, but it's still B so it's checked.

CHAIRMAN BANERJEE: But the more acute problem is PAD5, which is there right now. PAD5 has been submitted or --

MR. CLIFFORD: No.

CHAIRMAN BANERJEE: --or shortly will be submitted?

MR. CLIFFORD: Shortly will be submitted, which means it's already been developed in the final documentation.

CHAIRMAN BANERJEE: Do you -- I saw somewhere that you'd review hopefully and get it all, if it's all fine, out by 2015?

MR. CLIFFORD: Correct.

CHAIRMAN BANERJEE: Right, and then what happens is really the question? 2015, imagine PAD5 is now approved. Will they have to go back and look at any of these plants with PAD5?

MR. CLIFFORD: I think what you'll see is with 50.46(c) looming, which is going to cause a lot of plants to reanalyze LOCA, I think you'll see a consolidation in the LOCA methods. I think when plants are told they have to spend the money and redo their LOCA, they're going to say okay, well I'm going to get off this Appendix K. What's the latest and greatest realistic model you have? Use PAD5, use the latest and greatest.

If the vendors were smart, they wouldn't offer all of these methods, because they've got to maintain these codes. Would you prefer to have one code or ten codes that do the same thing?

MEMBER CORRADINI: Paul, can I ask a question about that? But we're still in the middle of rulemaking for C, right?

MR. CLIFFORD: Yes, we are.

MEMBER CORRADINI: So will that even be done in five years?

MR. CLIFFORD: The original schedule was it would be done next year.

MEMBER CORRADINI: Okay. Well, that's not what I was asking.

(Laughter.)

MR. CLIFFORD: Well, but there's been a slight change in direction. So I really can't tell you what the schedule is. Right now --

MEMBER ARMIJO: We're going to review that pretty soon, right?

MR. CLIFFORD: Right. We're going to be talking about it next week.

MEMBER CORRADINI: Okay. Well then never mind. We'll wait until Sam brings it up in his Subcommittee.

MR. JACKSON: In addition to the 50.46(c) though, we've had several utilities commit to redoing their analysis, reanalysis for their commitments under 50.46 letters in the 2015, '16 and '17 time frame.

MR. PARKS: Right. But it's important to remember that regulatory commitments can change, per the 50.59 regulations that apply.

MR. JACKSON: Oh yes.

MR. PARKS: So if they decide that their conditions aren't satisfied or the climate isn't amenable to them redoing an analysis, because the rule hasn't been revised or because the methods haven't been approved, they may push back that date.

MR. JACKSON: Right. My expectation is if PAD5 is approved in 2015, they would use that reanalysis they committed to in reporting this error. But once again, that's just speculative, because they can change commitments. 50.46(c) may exist, and who knows what it will be?

MEMBER SHACK: Do you know whether PAD5 is a major redo of PAD 4.0, or is it PAD 4.0 TCD with some quality control?

MR. PARKS: That may be proprietary.

MEMBER SHACK: That may be proprietary.

MR. JACKSON: I mean we've had several meetings with them, and I don't know, we're not --

(Simultaneous speaking.)

MR. JACKSON: We don't expect surprises, I guess, is the way I would characterize it.

MEMBER SHACK: So there's the provisions here that focus on TCD. Ben, in your presentation, the issue of thermal conductivity degradation has caused, of course, the additional reviews of the LOCA methodology and results.

We talked in some detail, but not great detail, about the ASTRUM methodology and its application, and some surprises, I'd call them surprises, that have come about with regard to the plant analyses that you -- some of which -- that you look at in detail, and it's causing you to look at those that have been submitted in more detail.

Is there something else that ought to be a follow-on with regard to the best estimate LOCA methodologies that is being learned here, that we haven't focused on completely?

MR. PARKS: I would say that when I presented my conclusions, I included recommendations. I wouldn't say that they're recommendations, so much as areas I plan to investigate further and sort of my thinking on the priorities, given the way my data is aggregating or data are aggregated.

I guess having said that, to go too much more into what we need to do with respect to the best estimate methods, it depends on the method and whether it's being revised or whether we expect to be in use for a long time, and you know, we're not looking at a static picture, because we are changing our review practices for implementations of those methods, and the vendors know that.

We've discussed how our reviews have changed over the years with the different vendors. So it's just a very fluid situation in some respects that continues to change. It's hard to say, you know, there's a specific recommendation here or a specific finding at this point.

But the way we review the information that we gather certainly always factors into how we conduct ourselves going forward. I'm sorry it wasn't a simple answer to the question, but it's very complicated.

MEMBER SHACK: It's not a simple question. I didn't expect a simple answer.

MR. CLIFFORD: But we are in the midst of reviewing the Westinghouse full spectrum LOCA topical report, and we're dealing with some of these issues, with sampling fuel rods and the effect of thermal conductivity degradation, and also remember that 50.46(c) is going to put a kind of a spin on all these calculations too, because instead of having a burnup-independent acceptance criteria like 17 percent, you're going to have an acceptance criteria that goes from 17 or 18 percent down to six percent.

So they're going to have the sample rods, because the acceptance criteria for which they're demonstrating compliance to is changing. So all these issues are going to be addressed as part of full spectrum LOCA, and you guys will have the opportunity to review that, right?

MEMBER ARMIJO: We're looking forward to it.

MEMBER CORRADINI: But the question, I

guess Paul, I think what you're saying, I can see how it consolidates. But in some sense, that a lot of these things are happening together, and there's inter-X, I'll use the term "system interactions."

So it seems that as the staff develops some sort of thinking process as to what comes first, what comes second, so that -- you don't do something, then it's just redone because of another issue?

MEMBER SCHULTZ: Is the timing -- let me ask it maybe little differently. Is the timing right with regard to thermal conductivity degradation, so you feel comfortable that that will be in its proper place as you're going forward with these improvements to the BE LOCA?

MEMBER CORRADINI: Yes, because if they're linked, in some sense they've got to be phasing away, that they all make sense. Because I agree with you. 50.46(b) or (c) whatever which one it is, it will essentially force people to pull together and try to improve their whole methodology for analysis.

MR. PARKS: I would say that given that there is going to be some number of years before all of these things come together, and so we've got a rulemaking activity and a methodology revision, and a bunch of commitments in 50.46 letters to reanalyze, all of those things coming together in a couple of years.

We know that it's going to be a while before this thing is resolved fully. So in terms of estimating the effects of errors in ECCS evaluation, it's appropriate that they apply a lot of rigor and they think very hard about how they estimate these effects.

So I think that are we in the right place, and is this coming together at the right time? With respect to TCD and LOCA analyses, I think we're going to be in the right place in a few years, and I think that the various people who have reported the effects of TCD are good to sit for a while.

And we're also being a little bit indefinitely in our closure evaluations for these things, that when we open TACs and review them, we say "Should another report or error be, you know, brought to our attention, we intend to revisit this conclusion."

So we're kind of keeping track of what happens in the future too.

MR. JACKSON: If I can add on, I mean there's a lot of things going on. So we're reviewing full spectrum LOCA, and because I think we understand enough about TCD now to be able to --

MEMBER ARMIJO: Make sure it's done correctly.

MR. JACKSON: Convince ourselves that that's fully addressed. So you know, we have the knowledge base to review that acceptably. Now we have a new rulemaking that may or may not go into effect, and what's in there is, you know, subject to change. So you know, I think that we have enough knowledge about TCD to implement the new rule, should it go into effect or should it go into effect in a similar way.

So the rule is kid of a question mark. It's not clear when it's going to come. You know, I expect it to come and I think we know enough about TCD to implement that. Now in this interim period, we're evaluating the reports. We're moving forward. We've addressed the high priority plants and we're moving on to the next one. Since we've learned more, we go back and revisit.

So in terms of looking forward, I think we're in a good spot. We're closing out the issues that we have in front of us as well, and --

MR. PARKS: Now Dr. Corradini, I think to get back to your original question, I guess by virtue of the fact that the various fuel vendors are making the best decisions they can to phasing various methods over certain points of time, and develop a unified analytic framework that applies to many plants that are only maintaining one code, that's one way to make sure that it's all coming together at the right time and right place.

And then the other thing is, you know, with respect to these methods, it's a group of 20 NRC staff and/or contractors, and we all work on the same floor. So you know, we closely interact with one another, and we track and talk about what we're doing, so that we're not stovepiping ourselves.

We also reach out to our other colleagues in Research and New Reactors, to make sure that we're, you know, keeping track of what's going on there with respect to the latest data that might be coming in, or what's happening on the new reactor licensing front.

MEMBER CORRADINI: Okay, that helps. Thank you.

CHAIRMAN BANERJEE: So you did your audit at Westinghouse, the group of four or five people on roughly what? Five calculations or five submittals that went through?

MR. PARKS: I can say that there were five submittals, but to go into too much more detail than that, it's proprietary.

CHAIRMAN BANERJEE: We're in open session, okay. I keep forgetting, we're not in closed session. All right. But do you plan any more audits? I mean there are some curious results.

MR. PARKS: Sure. I wouldn't exactly call it an invitation, but for lack of a better word, the invitation's been extended. In other words, we wouldn't oppose if you need more information, that you call us up and ask us questions, have an audit, do as you need.

We've actually taken, in terms of 50.46 report reviews, when we get a whole bunch of reports that come in and document the same change or the same error, we're trying to make sure that we're getting to the vendor as efficiently as possible, so that we don't have to ask five licensees five questions, and get five of the same answer.

So we don't have anything on the calendar or planned or approved at this point, but the possibility is always there. It's always considered, and it's nothing we rule out.

MR. JACKSON: Right. So we're planning on pursuing those issues that have been brought up, and when we present those issues to the licensees and then the vendors, we'll have to decide what the most efficient way is. Many times, we choose an audit because --

CHAIRMAN BANERJEE: More compact.

MR. JACKSON: It's more compact. Other times you choose not to, because you'd like to see the RAI responses formally responded to on the docket. So typically, we take the combination of the two. But we'll make that decision and whatever we base our safety planning on will be on the docket at the end. But it's certainly on the table.

CHAIRMAN BANERJEE: Okay. Well, are there any other questions? Would you like to make some closing remarks?

MR. JACKSON: I would.

CHAIRMAN BANERJEE: Then we just caucus as a Subcommittee after that.

MR. JACKSON: Okay, thank you. First of all, I'd like to thank the ACRS members, the consultants and the staff. This has been a good meeting. I appreciate all the support, particularly before. In terms of proprietary information, that was a challenge.

So I think it's a good meeting. I think your insights and views are important to us as we proceed forward. I want to congratulate Paul and Ben and Ken for the good presentations. It's been a long day, but they did a very good job.

I'd also like to thank the staff who worked with Ben and Paul, and many of which are sitting behind us right now, who have all contributed to this. So I'm proud of their efforts as well. So that's really all I wanted to say. Thank you.

CHAIRMAN BANERJEE: First of all, let me thank all of you and particularly Paul and Ben. Very interesting presentations, and your colleague from --

MR. CLIFFORD: Behind the pillar.

CHAIRMAN BANERJEE: Ken, thank you as well. It was a great presentation. I enjoyed it very much. We still have to decide as a Subcommittee what we want to do, in terms of should we have a brief presentation to the full Committee or how we feel.

What I'll do is I'll go around the Subcommittee, and ask for any remarks, and you can have some feedback at that time. Okay. So I think with that, thanks very much. We look forward to hearing more. This is a story which is ongoing, and both on the fuel and on the safety analysis side.

MEMBER ARMIJO: Did I miss my opportunity to make a comment?

CHAIRMAN BANERJEE: No, no, of course not. We haven't actually --

MEMBER ARMIJO: Oh, we haven't started that?

CHAIRMAN BANERJEE: --started that process yet.

MEMBER ARMIJO: My mind was wandering.

Joint Subcommittee Discussion

CHAIRMAN BANERJEE: Let's start with Graham and we'll get his comments, and then we'll move --

CONSULTANT WALLIS: I'm not sure your consultant should go first. FRAPCON, I liked the presentation. It's a huge task, and you've got 15 phenomenon, 200 subroutines, all this stuff put together. So there's no way we can review all the details.

The overall picture is that you put together an evolving and improving code and it works with reasonable and probably adequate accuracies. So that's about all I need to say. I think it's very good that the NRC does this, because in some other areas, we tend sometimes to see the NRC having no way to fall back on a confirmatory analysis by its own people, or its own people who really understand the phenomena so they can really understand what is being submitted.

This is an area where I think you really are ahead of the game. That's great. TCD, there's clearly a transition period between the old codes and new codes. The most satisfactory thing would be to bring in the new codes that fully account for the farm.

So I sympathize with your struggles. I'm not sure I can advise you what to do, except keep on working through the woods until you come out the other side. I know it's not always easy. On the issue of how new information gets incorporated into codes, this is something that many of us have thought about for years.

I think it's a big issue, and I don't want to wade into it myself. But I think it's an area where your discussions with the ACRS in the future could be very useful. It's one of the functions of the ACRS, to sort of help in these sort of major decisions about how do you handle this issue, which is going across the board. So I think that ACRS should be able to help you in that area.

CHAIRMAN BANERJEE: Thanks, Graham. Steve.

MEMBER SCHULTZ: A couple of general comments. One, on the technical side, just to reemphasize. I think we have identified, as a result of the thermal conductivity degradation investigation, that in terms of the application to analysis and all the 50.46 related reports that have come in, that it does raise some additional questions associated with the methodology.

It could raise them, and so that investigation that you had indicated, Ben, that you're going to continue, and I'm using you. Hopefully in the context of you plus other staff, that in fact that is carried through to a full conclusion, that you keep investigating it until you understand what's driving the changes, and you know the staff understands it as well as the vendors, that they understand how these differences are coming to affect the result.

In that regard, in terms of the staff contributing to this, on occasions like this, thermal conductivity degradation, you mentioned the numbers of staff. I'm not going to get into resources, but these issues come to be every once in a while, and this is an important one, and the investigation, as we've seen over the last few years, is very intricate and detailed, and involves lots of different issues.

It's a real opportunity for knowledge development, and for training and learning for a new generation into the business, as it were, and Graham mentioned this previously, and I hope the staff is gaining fully from this opportunity to investigate a problem. A problem of this type doesn't come up very often, and to be involved in its investigation and solution is very important.

So I'd encourage management of the staff to be sure that the work gets spread around, so that knowledge management and learning goes hand in hand, as well as resolving the problem. And I, with Graham, I certainly hope that this is an opportunity.

I was glad to see that, in moving forward, you're looking at ways in which to incorporate learning within the industry, and applications where new data will be examined thoroughly by vendors and licensees and the NRC on a periodic basis, not just National Labs and others. So that'll be the development integrated into the regulatory process.

CHAIRMAN BANERJEE: Thank you, Steve. Mike?

MEMBER SCHULTZ: I'm sorry. In terms of full Committee --

CHAIRMAN BANERJEE: Yes.

MEMBER SCHULTZ: I think it would be good to have a short summary for the full Committee at this point in time. I think it's been three-quarters of year.

CHAIRMAN BANERJEE: The last, yes, the last EPU, St. Lucie 2.

MEMBER SCHULTZ: It came up in the context of that. A lot of good work has been done. It's not, we can present it not as a closure discussion, but certainly an hour presentation as an update would be appropriate.

CHAIRMAN BANERJEE: Okay. Mike, I wanted to give you a chance before everybody else.

MEMBER CORRADINI: You do? Thank you. I guess I wanted to thank the staff. I think this is a nice summary. Sanjoy had told us that the whole point of today's Subcommittee meeting was really to try to get at least the Thermohydraulics Subcommittee and interested other members up to speed as to where all things sit, and how they fit together. So I think the staff did a very nice job in putting that together for us.

In terms of what to present to the full Committee, I would agree with Steve's last comment. I think it's important that we have some sort of informational briefing. I think the initial set of slides that Paul put together would be the source of that.

I think details about FRAPCON and details about how this is all sorting out relative to your analysis and the staff's analysis are interesting, but they might take us away from kind of the big picture, and I think that's important that the full Committee gets an idea of the big picture.

I guess my only other comment was that I'm still struggling with how this forest of things comes together and how the licensees adopt, as appropriate, these new techniques. That's why I was asking Paul at the end about the five-year notification as a good start.

But I'm still struggling with how eventually the licensees are going to be able to, with some obviously expeditious time table, adopt appropriate new methodologies, because they're going to be looking for higher, they're going to be looking for new fuel types or new cladding types, and all this kind of rolls together.

So I think that's a good start. I just would ask the staff to kind of think about that, and how it fits together in terms of levels of importance and timing. Other than that, Sanjoy, did you want anything else from us?

CHAIRMAN BANERJEE: No. I think from you, that's fine. Thanks, Mike. I'm going to give Sam a chance to speak.

MEMBER ARMIJO: Thank you. Thank you, Mr. Chairman. First of all, I'd like to thank the staff. This was, the presentations were very well prepared, and they addressed the things I really wanted to learn. They put everything in perspective, because we've been looking at TCD effects under EPUs one at a time, and we didn't know where everything was coming together, whether the problems had been resolved, where problems remained, and how big these problems are.

I think you did a very good job of that. I really like your charts, Paul, on the code by code, of where it stands and what needs to be done to make those work. I think these are the sorts of things you'd want to present in a full Committee briefing for information.

I think some stuff on FRAPCON, showing that it's really in pretty good shape. Because without it, I'd really be nervous that we could rely on these numerous codes to tell us what is really going on. So I think a little bit of that would be worthwhile in a full Committee briefing.

I'm still trying to understand myself why TCD is turning out to be such a big deal in the ECTS BWRs. I don't know whether it's physics, I don't know whether it's statistics methodology or what. I'll have to talk to my colleagues on that, and see if they can help me out.

If I looked at your Chart 4, that chart of thermal conductivity as a function of temperature, I just conclude that we're running too much of our cores at low temperatures, and if we just heated them up, we would get rid of this problem.

But I'm not kidding too either, because it seems -- well, you know, all the stored energy that's going to be giving us more problems as a result of this stuff is coming from low temperature fuel, and you know, a lot of things I've seen, as people are getting more and more conservative, putting more fuel in, particularly the EPU guys operating at lower and lower temperatures, and they may just be building up a bigger problem for themselves from a certain standpoint.

But that's just something for you to think about. Overall, I was really happy. I learned a lot and I appreciate the effort the staff put into preparing this material.

MEMBER SHACK: I haven't got much to add. You know, it was a very good presentation. I think it really -- it's been a long time since we talked about this, and I think the overall view is much improved while we're looking at this EPU by EPU.

I really do like the idea of the license condition or the conditions that you put on the SE, that they come back and they review this. I think that's a good idea, and it should be pursued, you know, with other kinds of modeling efforts. I think it's a plus.

I agree. I think the Committee, the full Committee would like to hear about this. Sort of basically a pared-down version of Paul's presentation, I think, is probably all we could possibly get in.

CHAIRMAN BANERJEE: Joy?

MEMBER REMPE: I guess again, to be repetitive, I really appreciated the education you provided today and the summary. With respect to the EPUs, I think that if you hadn't had FRAPCON to come in and try and explain all the different factors that the various vendors and licensees were trying to explain to us, we wouldn't have had much confidence.

So I guess that's where I'd like to make a plea to the NRC, that they continue allocating bucks to review additional data that comes from Halden, and incorporate it and keep FRAPCON up to date, and monitor it, not just rely on the licensee to notify you of new data that's coming out.

Again, I kept emphasizing those uncertainties, and I would like to make sure we have lots of confidence in what we're doing here. So that's one thing. An off the wall comment is what about severe accidents in MELCOR? Are you going to put thermal conductivity degradation into MELCOR? Is there a need to?

MEMBER CORRADINI: Do you want five degrees or 500 degrees?

MEMBER REMPE: Well, at some point, it seems like it might be important to think about it.

MEMBER SHACK: They get to such high temperatures that the problem is solved.

(Simultaneous speaking.)

MEMBER REMPE: I don't know, but it's just something I was wondering about, and then again, I agree with my colleagues about, that we really should have this brought to the full Committee, not only because of the work that's being done, about the proposal to have the recertification, because it's something that ought to be in evaluation every five years. But maybe that's a lesson that should be expanded to other areas.

CHAIRMAN BANERJEE: Great. Thanks, Joy. So I think you've got fairly clear feedback from the Subcommittee, that we do want to have maybe an hour's presentation to the full Committee.

MEMBER SHACK: Give them more than that. I mean an hour is --

CHAIRMAN BANERJEE: Okay. I think we'll work with P&P and give you a little bit more. I agree with Bill, because I was just going to say that like Sam, I personally, and I think it would be great to have, would like to see at least a brief presentation on FRAPCON, because I feel that that's been very helpful in finding our way through the EPUs that we have to do.

So it would be worthwhile, not going through all the details and so on, but at least establishing that FRAPCON is a well-validated code, which takes into account these TCD effects, and reassuring the Committee that in the future, whatever the vendors put up, if you have something which is in the nature of confirmatory calculations, that we can rely on FRAPCON giving an assessment of these TCD effects. So I think that would be valuable itself to present.

And also, of course, we would like to see Sam and others have pointed out, an overview like Paul did of the codes and what their status is and what's under development, keep it, you know, relatively short. But at least it gives you a bird's eye view of the situation.

MR. CLIFFORD: Is one of our ground rules that it's open?

CHAIRMAN BANERJEE: We can close it. That's not a problem.

MR. CLIFFORD: I mean FRAPCONs are open. My presentation was, most of it was open. But the table by table stuff was closed.

MEMBER ARMIJO: Yes.

CHAIRMAN BANERJEE: Sam, I mean what's your sense of that? We can always close the full Committee meeting, but you're the boss of the full Committee meeting.

MEMBER SHACK: We dislike closing full Committee meetings if we can avoid it.

CHAIRMAN BANERJEE: We have often.

MEMBER SHACK: We have, and you know,

certainly, you know, we need --

MEMBER ARMIJO: And it's these tables that are the ones that --

CHAIRMAN BANERJEE: Well, you know, I think also some of Ben's conclusions need to be presented, because there's some curious effects there. So that we would need to close it for anyway.

MEMBER ARMIJO: We should because, you know, there are some problem areas, and you ought to be able to speak frankly to the Committee on the problem areas, and if we don't close it, you may have to be so diplomatic that they mistake medicine for candy.

(Simultaneous speaking.)

CHAIRMAN BANERJEE: I mean we have closed it.

MEMBER SHACK: Parts of it could be.

MEMBER ARMIJO: And then you might a part of it that's open.

CHAIRMAN BANERJEE: May I suggest, then, that we perhaps have about half of the briefing open, and half of it closed. We'll try to arrange it in our unusual fashion, so that it's not too disruptive, and we've done it often before.

I think in the closed part, it would be

useful to have some of this proprietary information, and also I think present at least an overview of the issues that you see occurring with regard to the safety, downstream safety analysis, primarily if it's LOCA-focused. I think that's what we'd like to see.

That's probably the area that has caused us some concern with the EPUs. So it would be worth just revisiting that, and giving us an overview of the status. So this is essentially a status. We're not looking for any sort of decisional process at all, just information.

MR. JACKSON: Okay. We can support that.

CHAIRMAN BANERJEE: Yes. So the staff will get in touch with you, because we have to schedule it and see what needs to be done, okay. So I'd just like to close by thanking all of you all over again, and look forward to seeing you again at the full Committee.

MR. JACKSON: Thank you.

CHAIRMAN BANERJEE: Okay. Oh. I keep forgetting my duties. I've been chairman for too long.

(Whereupon, at 4:11 p.m., the meeting was adjourned.)

Calibration and Validation of NRC Fuel Performance Models

FRAPCON-3.4

Ken Geelhood
Pacific Northwest National Laboratory
February 20, 2013

Overview

- Fuel performance parameters of regulatory interest
- Extent of database
- Nature of FRAPCON-3.4 and FRAPTRAN 1.4
- Calibration parameters
- Model validation
- Integral assessment
- Uncertainty analysis with FRAPCON-3.4

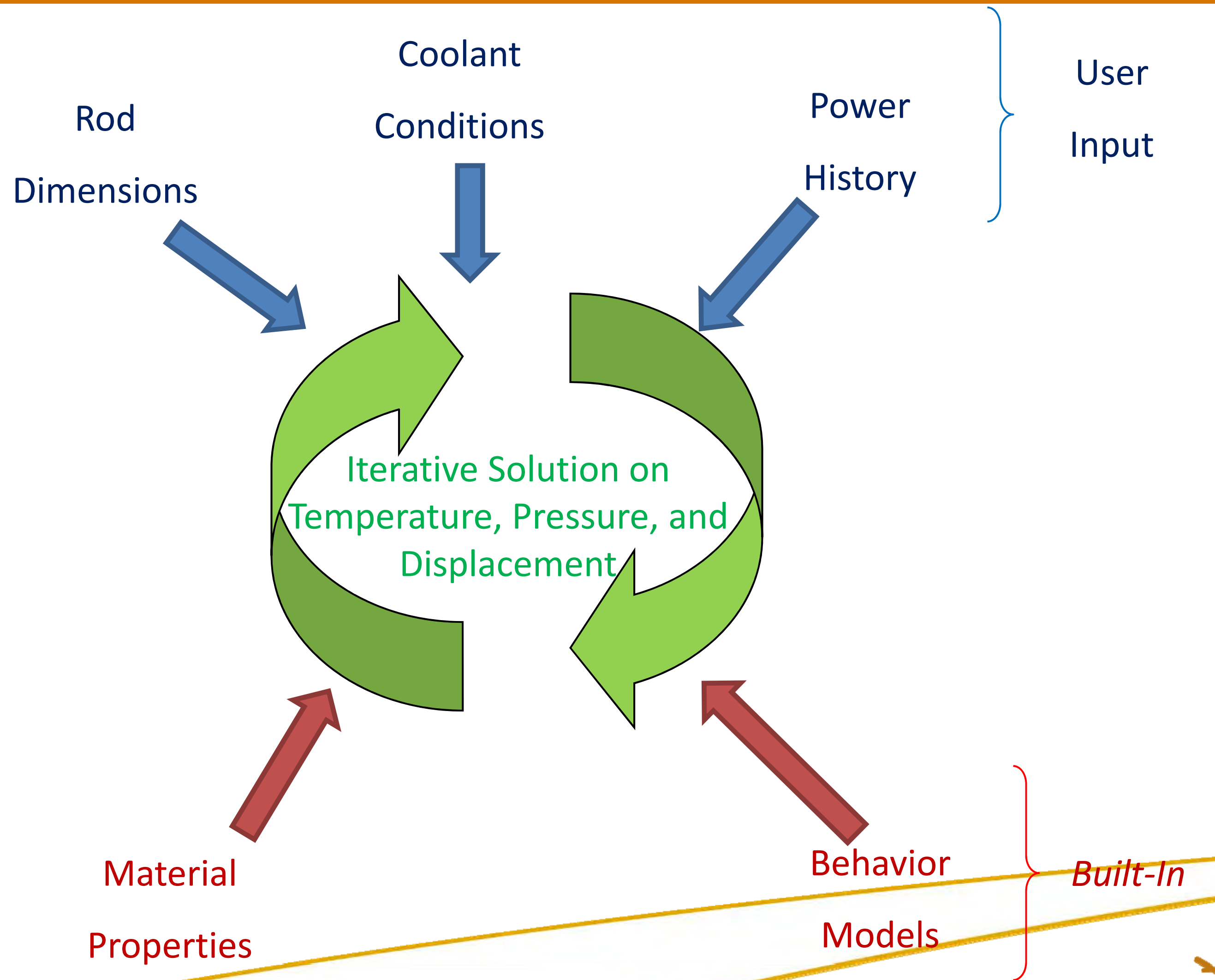
Fuel Performance Parameters of Regulatory Interest

- Fuel and cladding temperature
  - Fuel melt overpower analysis
  - LOCA initialization
- Rod internal pressure
  - Cladding lift-off analysis
- Cladding hoop strain
  - Cladding strain overpower analysis
  - Cladding fatigue
  - Pellet cladding interaction
- Cladding corrosion and hydriding
  - Corrosion and hydrogen limits
- Fission gas release
  - Dose calculations

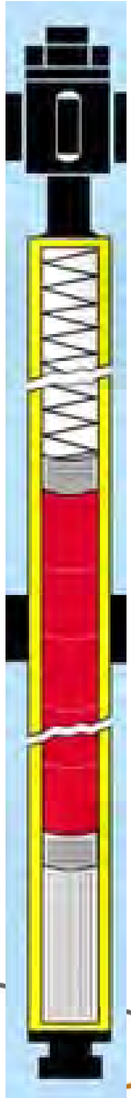
Extent of Database
Two types of data

- Separate effect data
  - Material properties data
    - Thermal conductivity
    - Heat capacity
    - Thermal expansion
    - Mechanical properties
  - Behavior models
    - Cladding creep
    - Fuel pellet densification and swelling
    - Fuel relocation
    - Fission gas release
    - Cladding corrosion
- Integral effects data
  - Centerline temperature
  - Fission gas release
  - Void volume
  - Cladding corrosion
  - Cladding hoop strain

Nature of FRAPCON-3.4 and FRAPTRAN 1.4

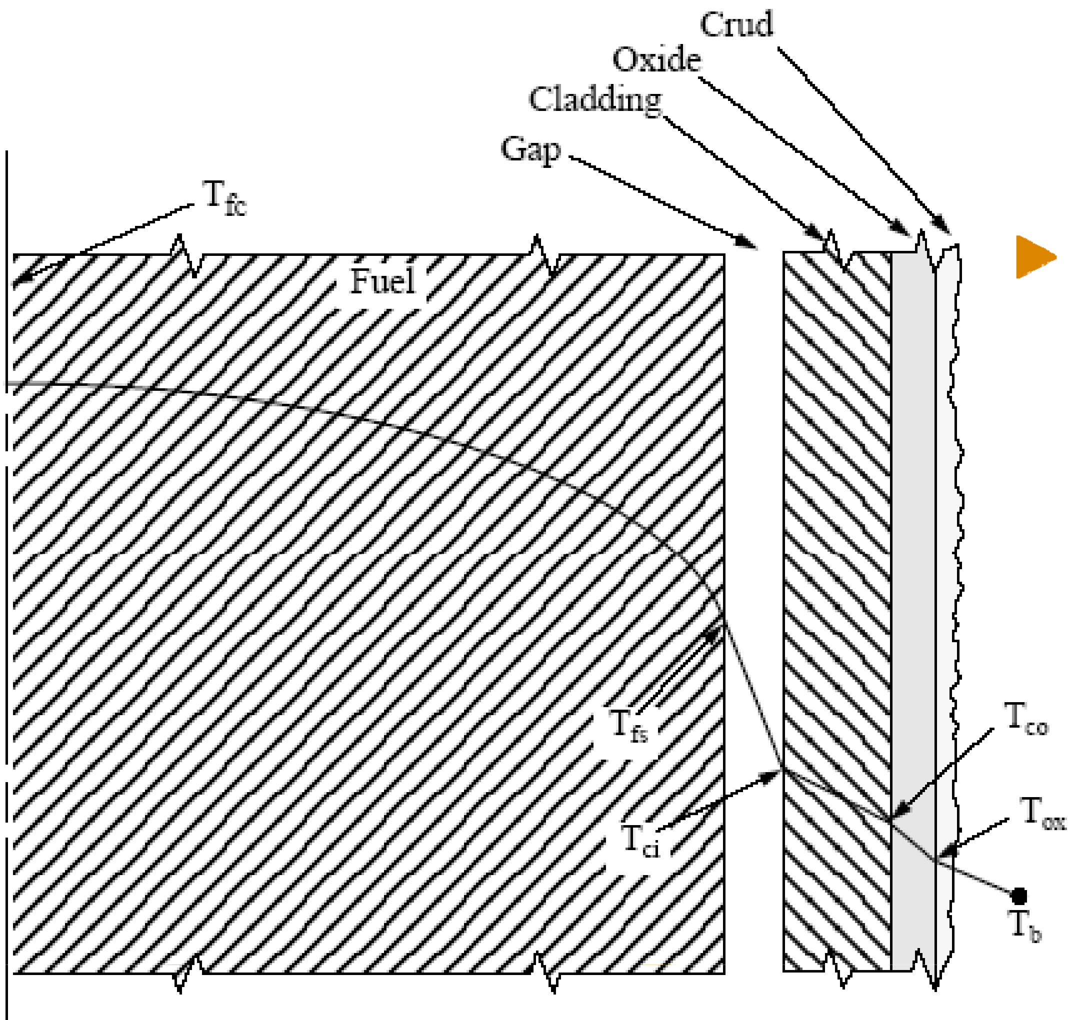


Main Solution



- 1 ½ dimensional solution
  - Heat transfer in radial direction
  - Some axial effects included
    - Internal gas mixing
    - Coolant heatup along the rod
  - Finite difference steady state heat transfer
  - Rigid pellet model with radial relocation possible
  - Thick-wall formula for cladding stress and strain

Radial Temperature Solution



- Solution starts with coolant temperature (T_b) and works inward toward the center of the pellet
- FRAPCON-3 calculates bulk coolant temperature assuming a single, closed coolant channel

$$T_b(z) = T_{in} + \int_0^z \left[\frac{(\pi D_0)\, q''(z)}{C_p G A_f} \right] dz$$

Radial Temperature Solution (cont.)

- Cladding surface temperature is the minimum of

$T_w(z) = T_b(z) + \Delta T_f(z) + \Delta T_{cr}(z) + \Delta T_{ox}(z)$ *forced convection*

-or-

$T_w(z) = T_{sat} + \Delta T_{JL} + \Delta T_{ox}(z)$ *nucleate boiling*

- Cladding temperature gradient according to steady-state heat transfer through a cylinder

$$\Delta T_c = q''(z) r_o \ln(r_o / r_i) / k_c$$

- Heat transfer through gas gap by:
  - Radiation
  - Conduction through gas
  - Contact

Radial Temperature Solution (cont.)

- Fuel temperature calculated using finite differences
  - Variable mesh spacing is used, and the spatial dependence of the internal heat source is allowed to vary over each mesh interval.
  - Steady-state integral form of the heat conduction equation

$$\iint_S k(T,\bar{x})\vec{\nabla}T(\bar{x})\bullet\vec{n}ds = \iiint_V S(\bar{x})dV$$

  - The terms of this equation are approximated for each radial node

$$\iint_s k(T,\bar{x})\vec{\nabla}T(\bar{x})\bullet\vec{n}ds \approx (T_m - T_{m-1})k_{lm}\delta^s_{lm} + (T_m - T_{m+1})k_{rm}\delta^s_{rm}$$

$$\iiint_V S(\bar{x},t)dV \approx P_f P(Q_{lm}\delta^v_{lm} + Q_{rm}\delta^v_{rm})$$

  - Solution solved using matrix algebra to solve the equations for each node simultaneously

Material Properties Models

- Semi-emperical
- Mathematical form of each model based on form known to predict property of interest
- Fitting parameters based on fit to data
- Comparison between irradiated and unirradiated data used to determine if there is a radiation effect and if both sets of data are applicable

Behavior Models

- Semi-emperical
- Mathematical form of each model based accepted mechanisms that control behavior of interest
- Fitting parameters based on fit to data

Calibration Parameters

- All parameters are in material property models or behavior models based on fits to separate effect data
- No further tuning parameters have been added

Impact of Calibration Parameters

- Recently 8 material property and behavior models were identified as those have a significant impact on outputs of regulatory interest
  - Fuel thermal conductivity
  - Fuel thermal expansion
  - Fission gas release
  - Fuel swelling
  - Cladding irradiation creep
  - Cladding thermal expansion
  - Cladding corrosion
  - Cladding hydrogen pickup
- Standard error calculated for each model and included in code so user can perform uncertainty analyses

Evolution of Fuel Thermal Conductivity Modeling

- Prior to 1996: No models contained effect of burnup on fuel thermal conductivity
- 1992: Lucuta et al. publishes data from “Simfuel” (fresh fuel doped with simulated fission products)
  - These data show decreased thermal conductivity with burnup
- 1996: Lucuta et al. publishes revised fuel thermal conductivity model based on 1992 data
- 1997: PNNL released FRAPCON-3.0 with Lucuta model
- 1994-2004: Ronchi and Carrol publish laser flash data from UO_2 disks irradiated at constant temperature
  - These data show more degradation than seen in the Simfuel and than predicted by the Lucuta model

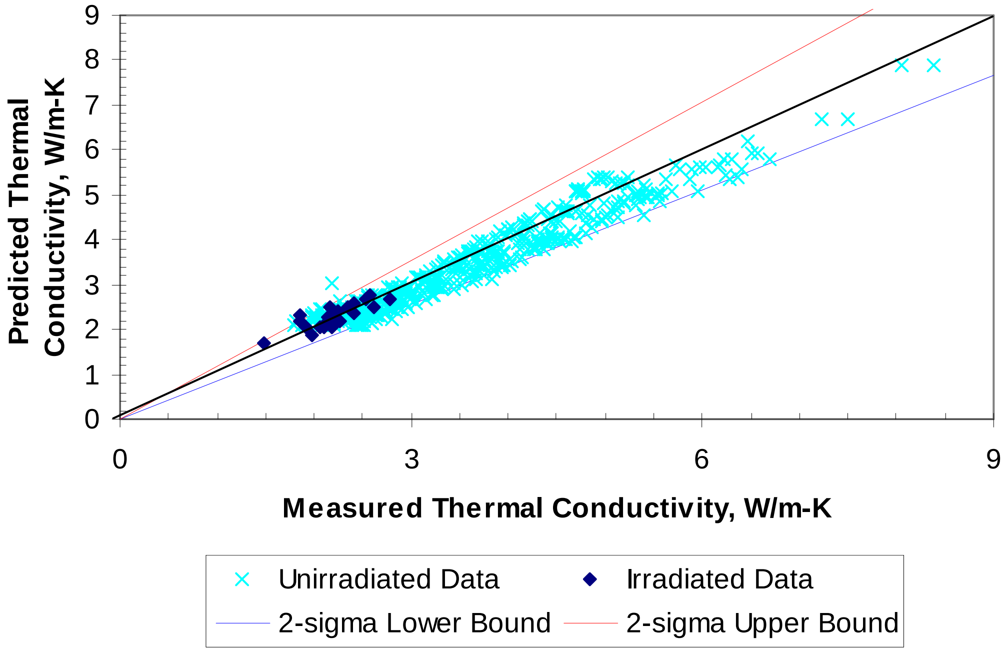
Evolution of Fuel Thermal Conductivity Modeling

- 2003: PNNL releases FRAPCON-3.2 that includes the current thermal conductivity model that matches irradiated data
- Current model:

$$K_{95} = \underbrace{\frac{1}{A + a \cdot gad + BT + f(Bu) + \left(1 - 0.9\exp(-0.04Bu)\right)g(Bu)h(T)}}_{Phonon\ Term} + \underbrace{\frac{E}{T^2}\exp\left(-\frac{F}{T}\right)}_{Electronic\ Term}$$

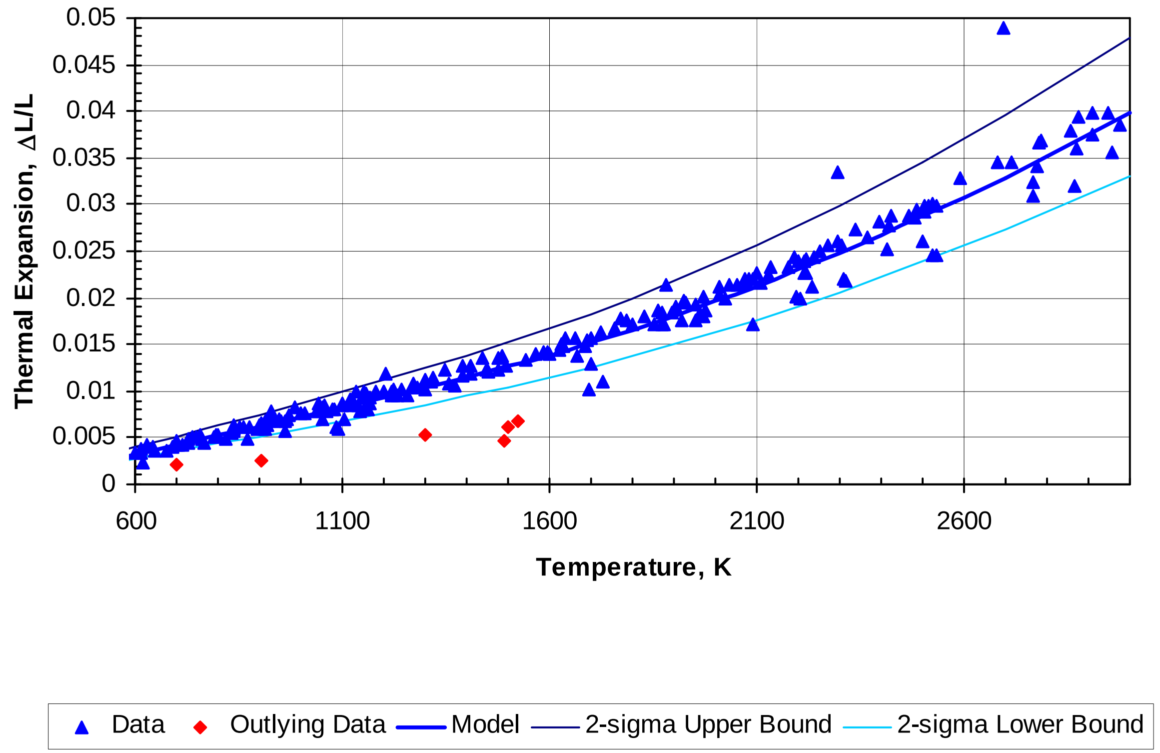
  - Phonon term dominant below 2000K
    - Contains effect of temperature, burnup, and Gd_2O_3
  - Electronic term dominant above 2000K
    - Contains effect of temperature only

Model Validation: Fuel Thermal Conductivity



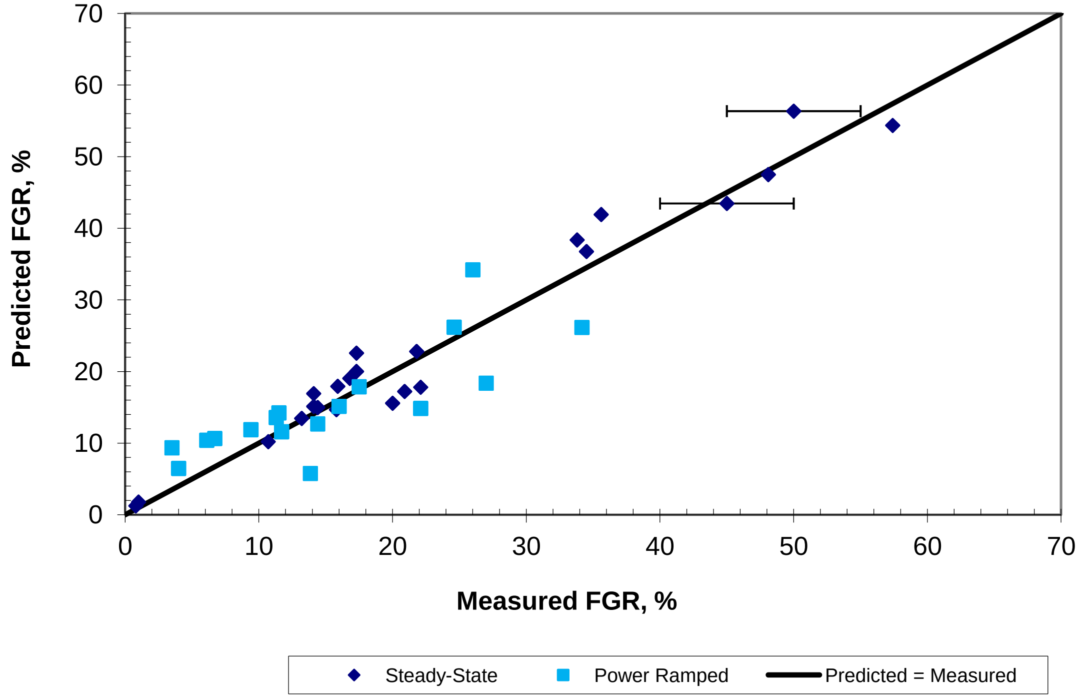
- UO_2 thermal conductivity data, model and upper and lower 2σ predictions
- $\sigma=\pm8.8\%$ (relative)

Model Validation: Fuel Thermal Expansion



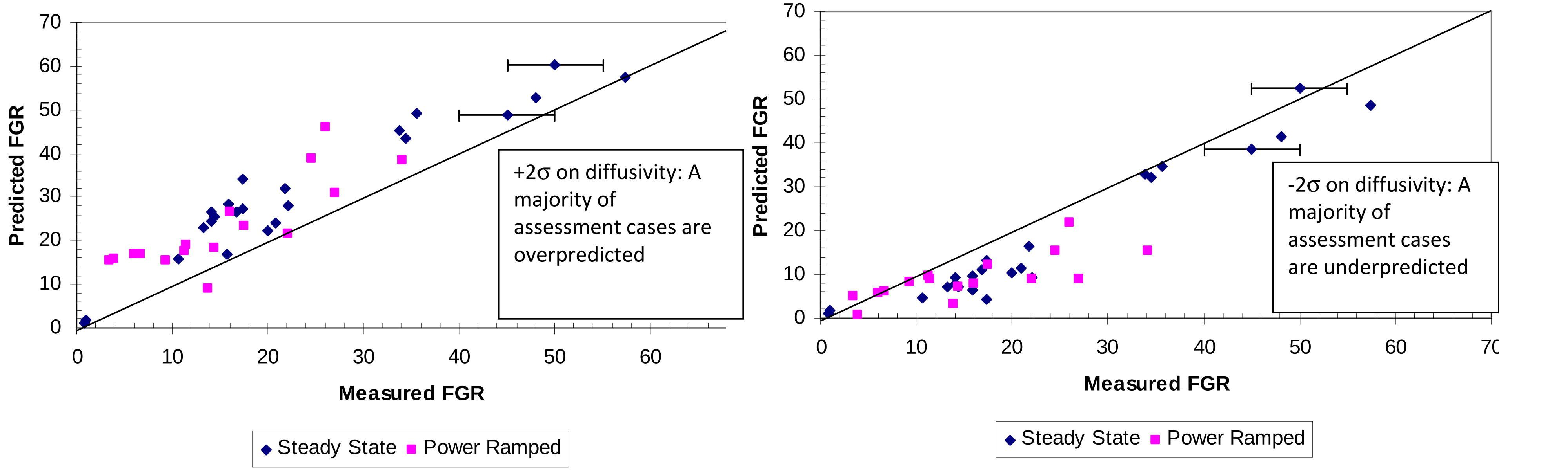
- UO_2 thermal expansion data, model and upper and lower 2σ predictions
- $\sigma = \pm 10.3\%$ (relative)

Model Validation: Fission Gas Release



- Nominal predictions shown (error bars represent known measurement error)

Model Validation: Fission Gas Release



- Fission gas release data, model with upper 2σ and lower 2σ model predictions (error bars represent known measurement error)
- σ=±100% on gas diffusivity

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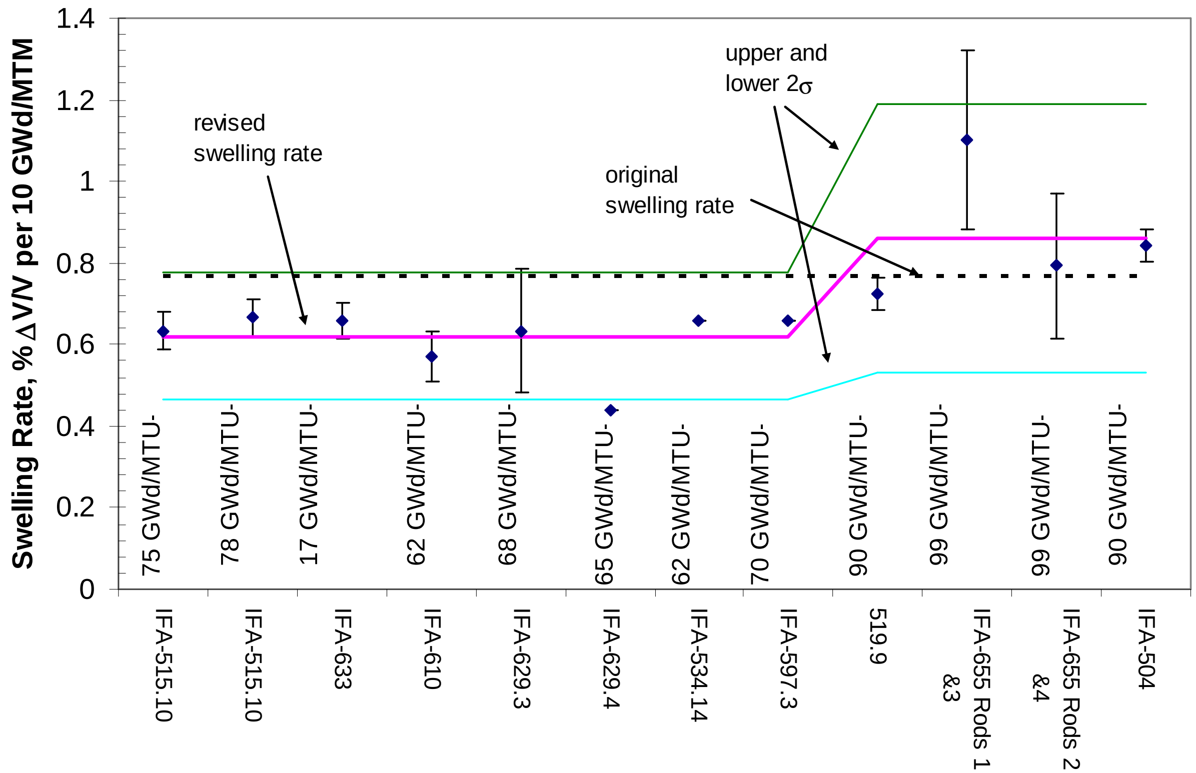
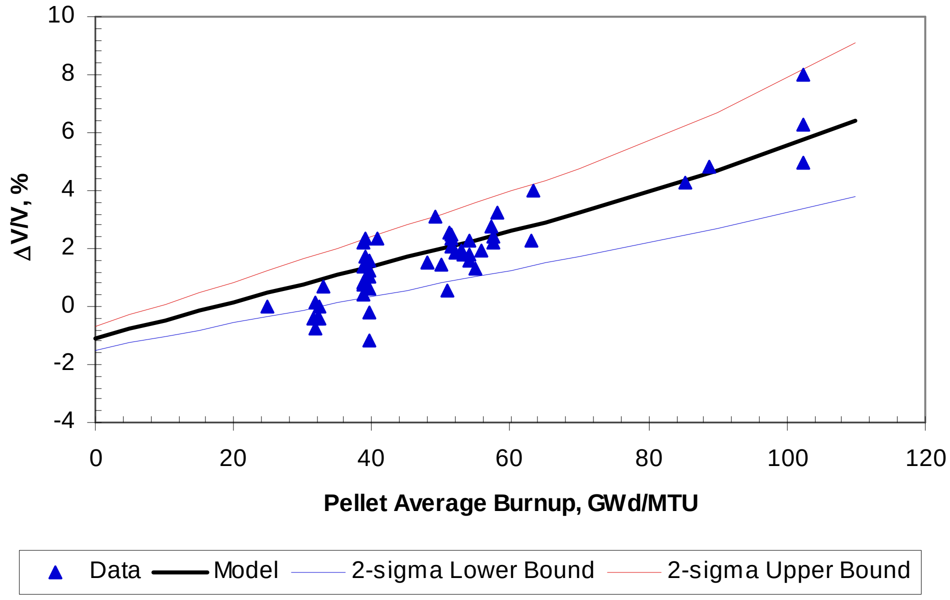
Model Validation: Fuel Swelling



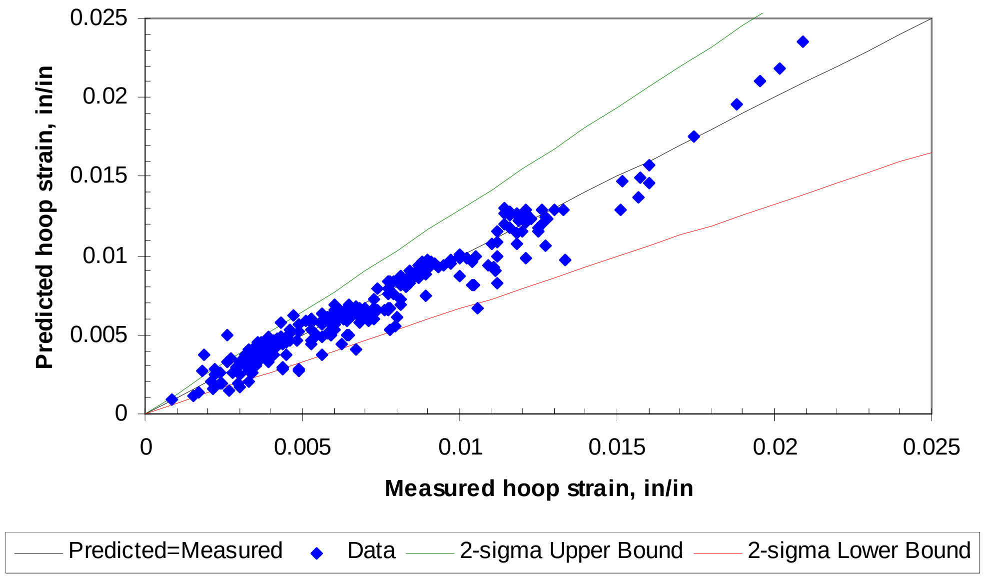
- Swelling rates from twelve Halden tests and FRAPCON-3.4 model predictions with uncertianties
- σ=± 0.08% ΔV/V per 10 GWd/MTU below 80 GWd/MTU
- σ=± 0.16% ΔV/V per 10 GWd/MTU above 80 GWd/MTU

Model Validation: Fuel Swelling (cont.)



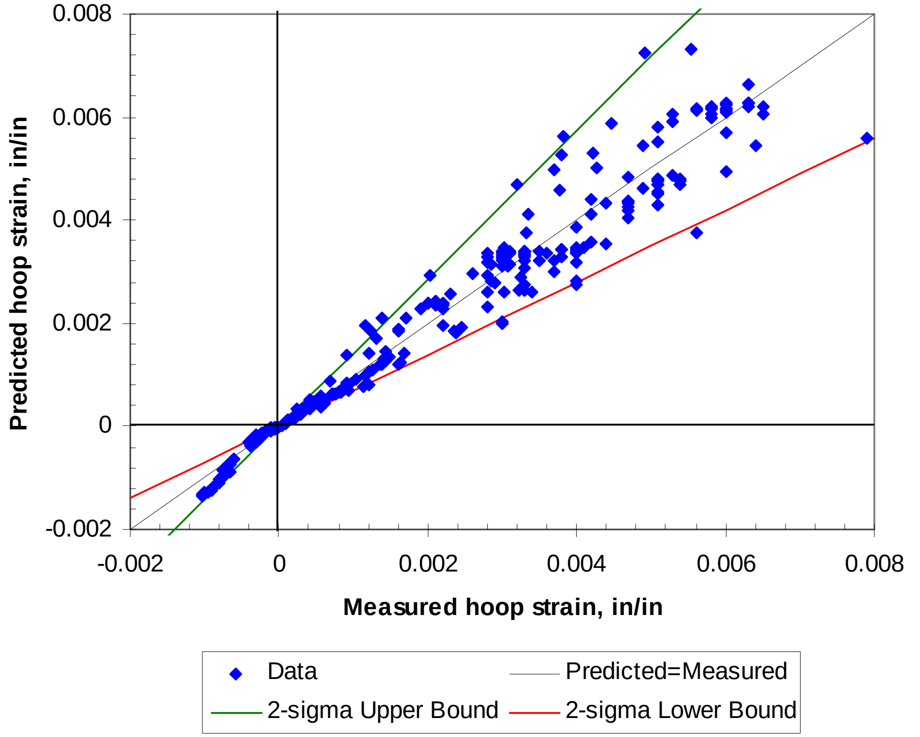
- UO_2 swelling data, model and upper and lower 2σ predictions
- σ=± 0.08% ΔV/V per 10 GWd/MTU below 80 GWd/MTU
- σ=± 0.16% ΔV/V per 10 GWd/MTU above 80 GWd/MTU

Model Validation: Cladding Irradiation Creep, SRA Cladding



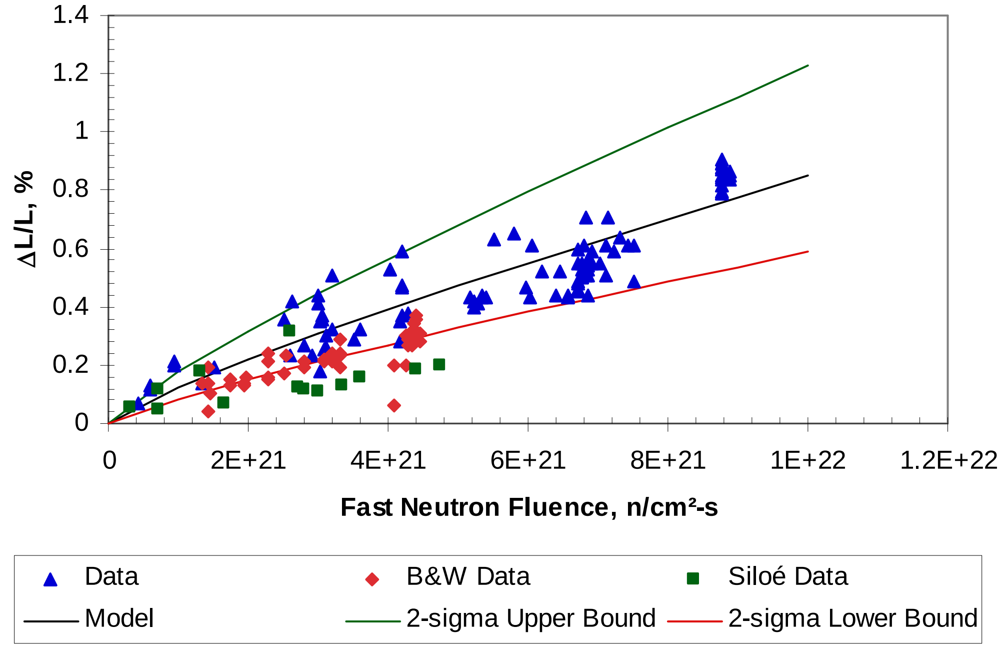
- SRA (Zircaloy-4, ZIRLO™) cladding creep data, model and upper and lower 2σ predictions
- σ=±14.5% (relative)

Model Validation: Cladding Irradiation Creep, RXA Cladding



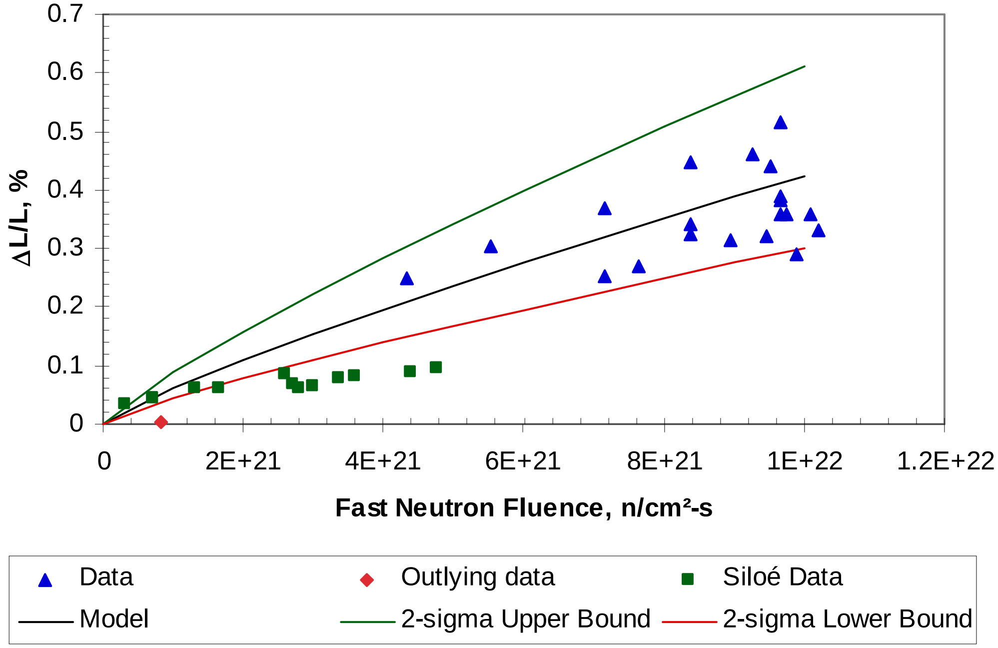
- RXA (Zircaloy-2, M5™) cladding creep data, model and upper and lower 2σ predictions
- σ=±21.6% (relative)

Model Validation: Cladding Axial Growth, SRA Cladding



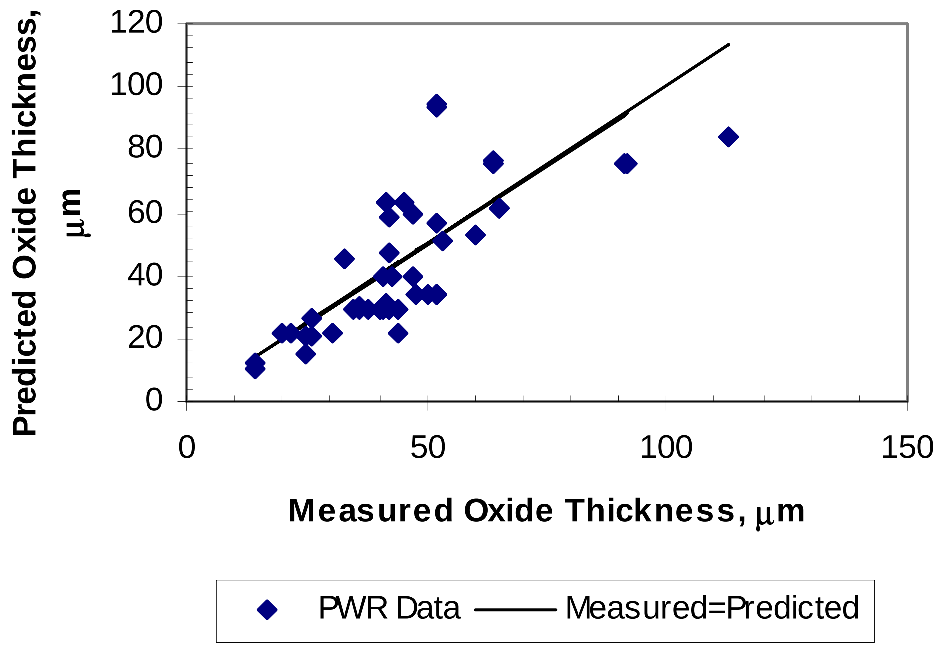
- SRA (Zircaloy-4, ZIRLO™) cladding axial growth data, model and upper and lower 2σ predictions
- σ=±22.3% (relative)

Model Validation: Cladding Axial Growth, RXA Cladding



- RXA (Zircaloy-2, M5™) cladding axial growth data, model and upper and lower 2σ predictions
- σ=±20.3% (relative)

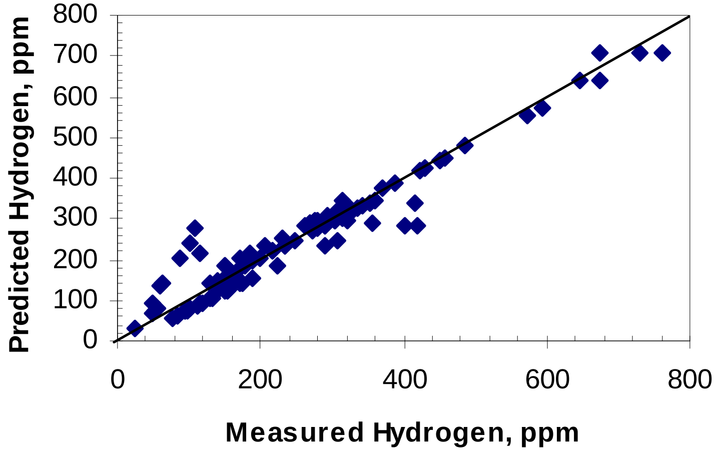
Model Validation: Cladding Corrosion



Example for Zircaloy-4

- Zircaloy-2 (BWR) σ=±7.6μm (absolute)
- Zircaloy-4 (PWR) σ=±15.3μm (absolute)
- ZIRLO™ (PWR) σ=±15μm (absolute)
- M5™ (PWR) σ=±5μm (absolute)

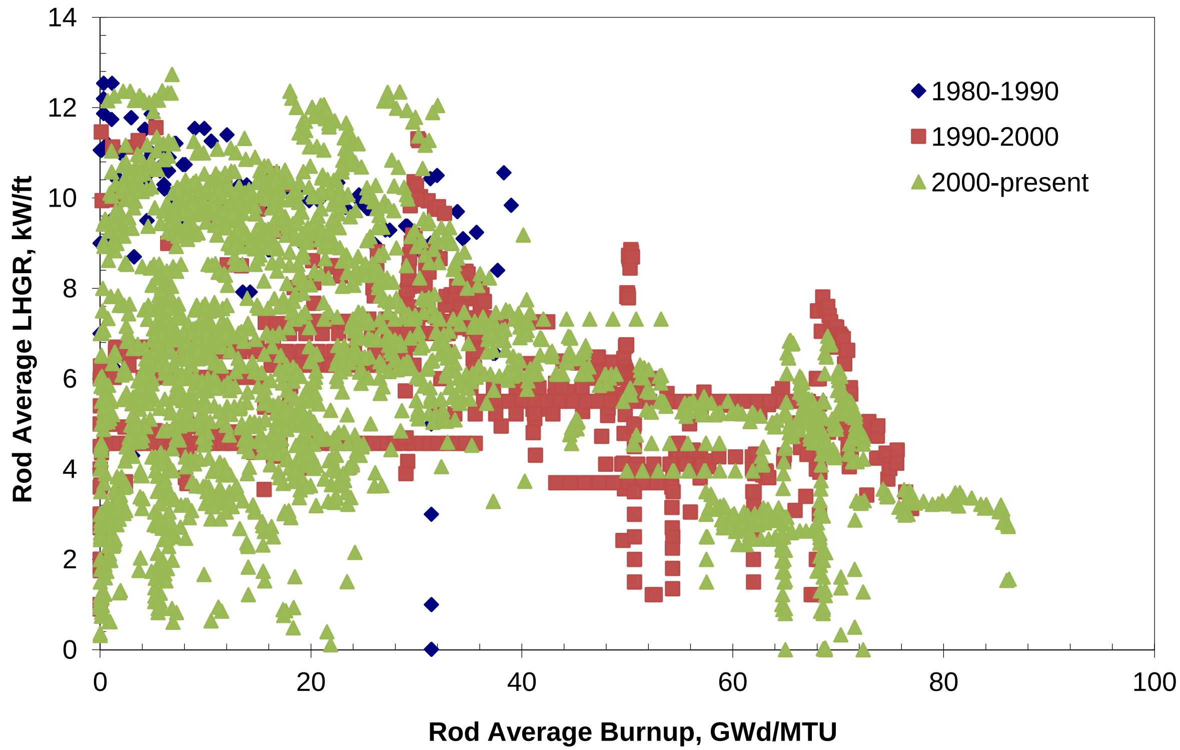
Model Validation: Cladding Hydrogen Pickup



Example for Zircaloy-4

- Zircaloy-2 prior to 1998 (BWR) σ=±10 ppm (<45 GWd/MTU)
- Zircaloy-2 since 1998 (BWR) σ=±11 ppm (<49 GWd/MTU)
- Zircaloy-2 since 1998 (BWR) σ=±61 ppm (>49 GWd/MTU)
- Zircaloy-4 (PWR) σ=±40 ppm
- ZIRLO™ (PWR) σ=±45 ppm
- M5™ (PWR) σ=±20 ppm

Integral Assessment: Temperature Range of data



- Rod-average LHGR vs. rod-average burnup for temperature assessment cases

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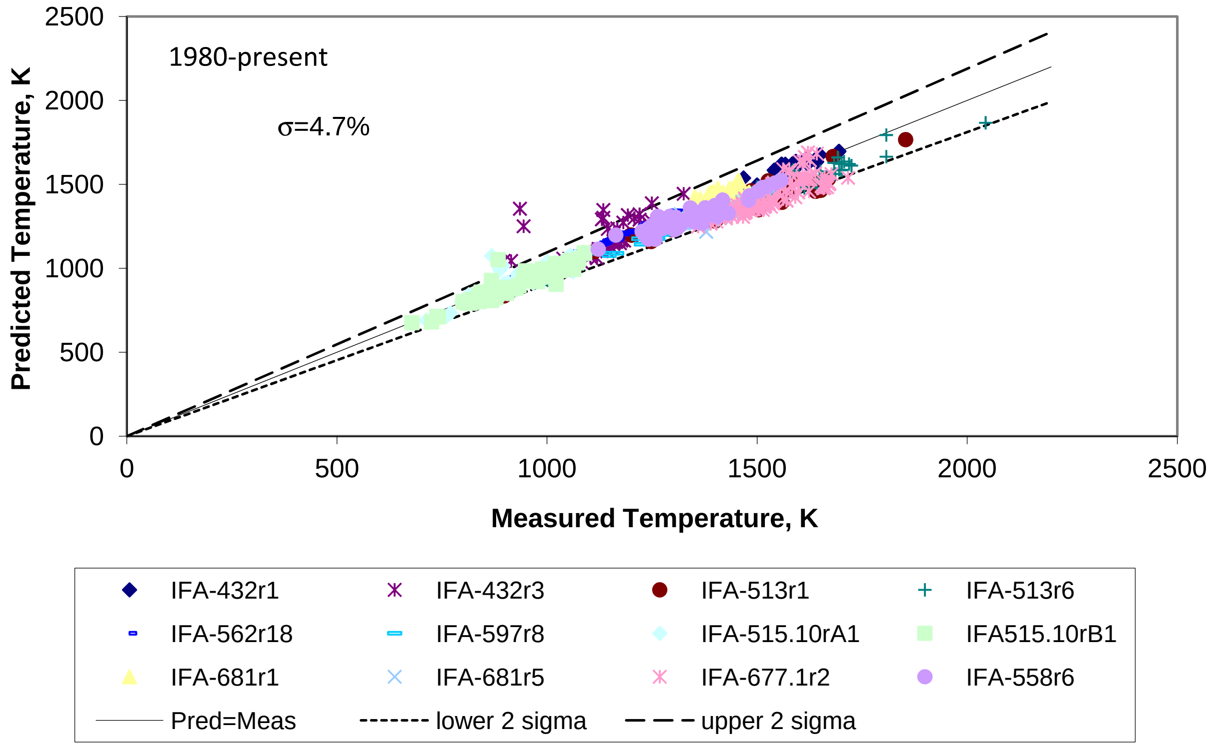
Integral Assessment: Temperature Predicted vs. Measured



- Measured and predicted centerline temperature for the UO_2 assessment cases throughout life
- σ=±4.7% (relative)

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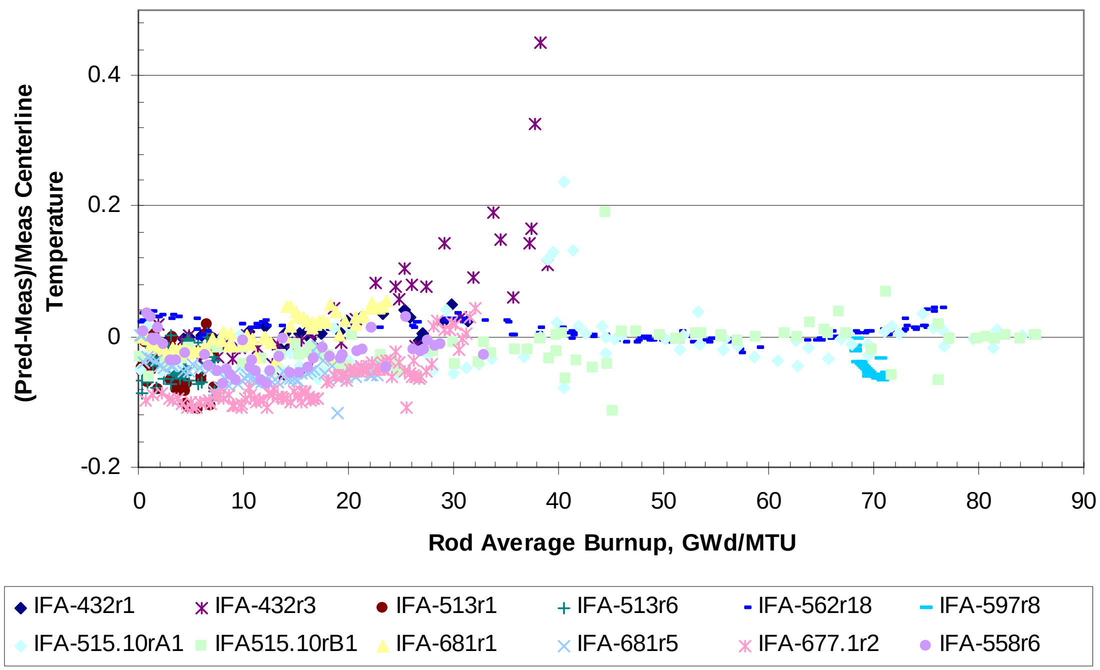
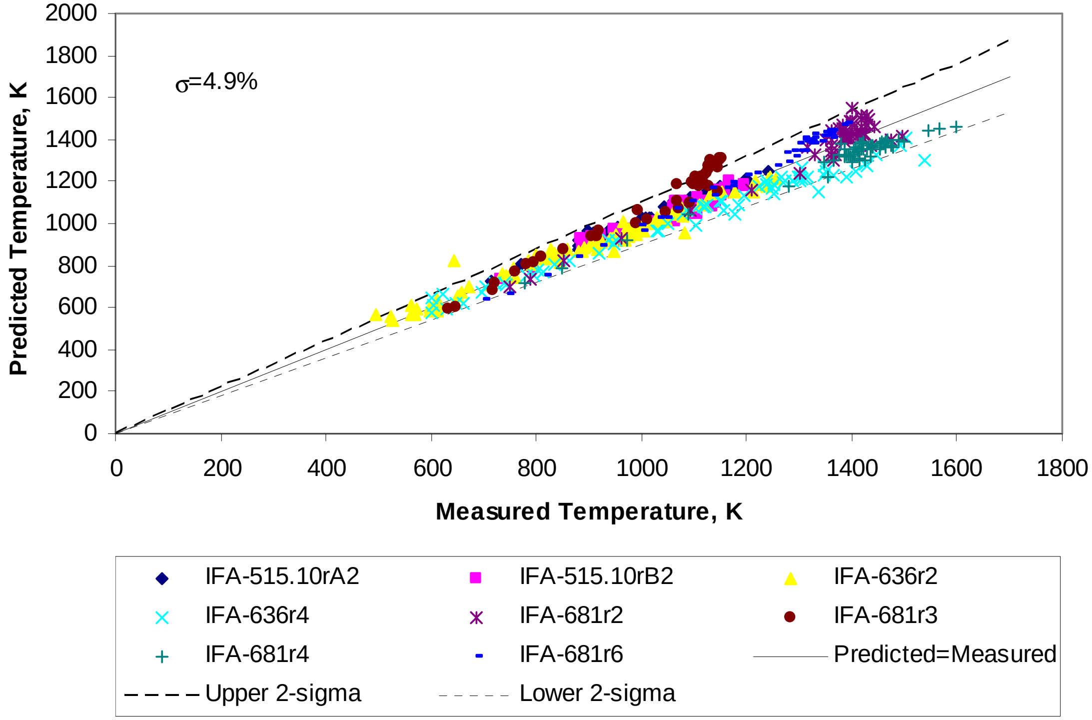
Integral Assessment: Temperature (Predicted – Measured)/Measured vs. Burnup



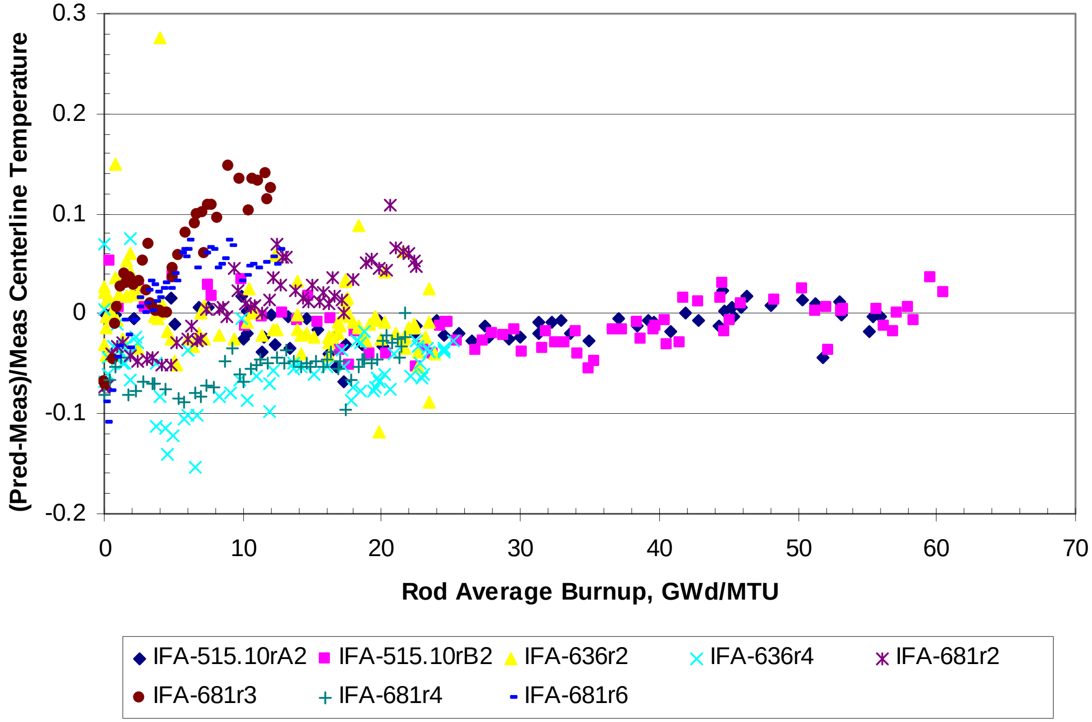
- Measured and predicted centerline temperature for the UO_2 assessment cases throughout life
- $\sigma=\pm4.7\%$ (relative)

Integral Assessment: Temperature Predicted vs. Measured



- Measured and predicted centerline temperature for the UO_2-Gd_2O_3 assessment cases throughout life (all since 2000)
- σ=±4.9% (relative)

Integral Assessment: Temperature (Predicted – Measured)/Measured vs. Burnup



- Measured and predicted centerline temperature for the UO_2-Gd_2O_3 assessment cases throughout life
- σ=±4.9% (relative)

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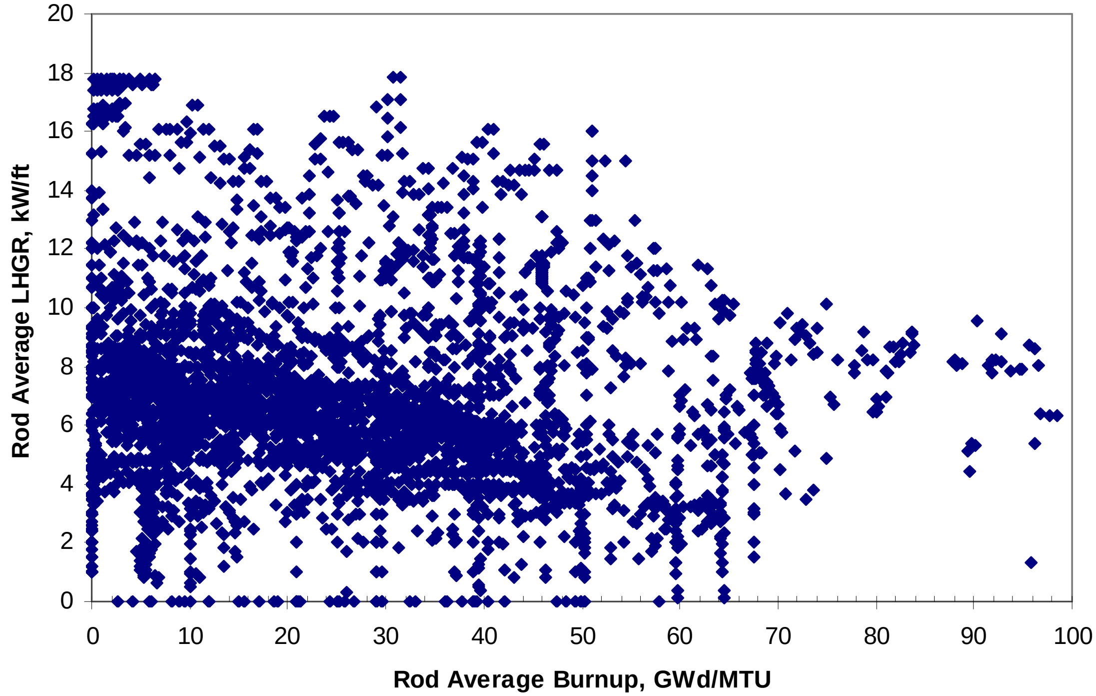
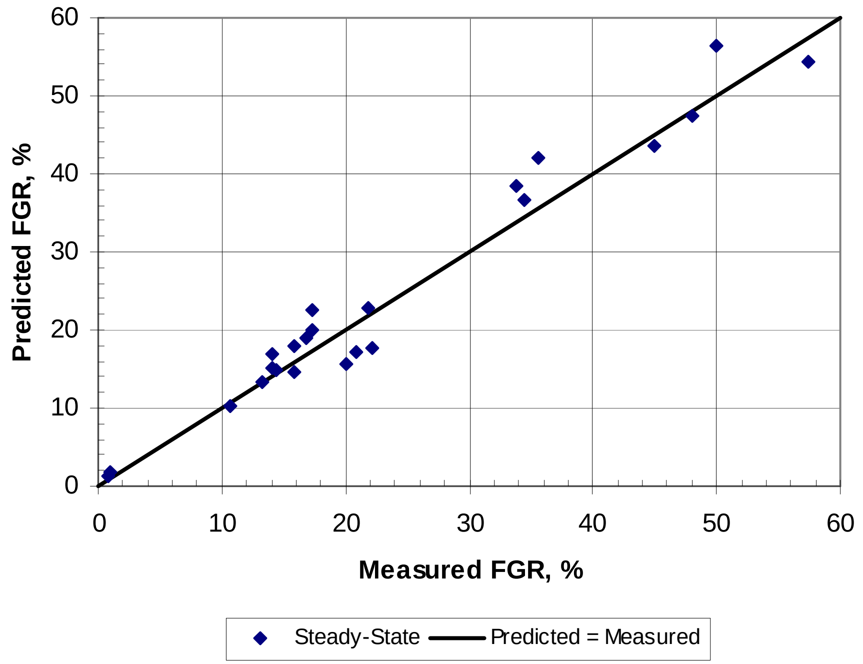
Integral Assessment: Fission Gas Release Range of data



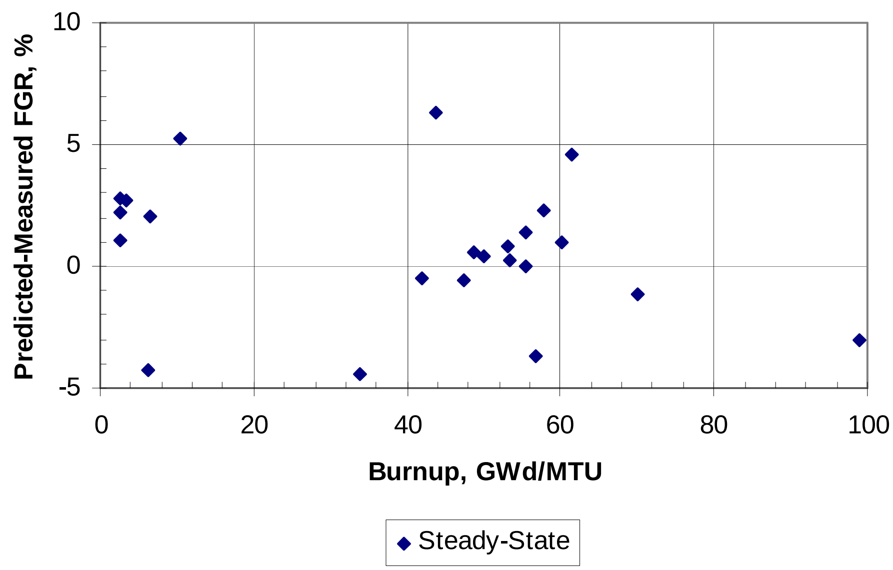
- Rod-average LHGR vs. rod-average burnup for fission gas release assessment cases

Integral Assessment: Fission Gas Release Predicted vs. Measured



- Comparison of FRAPCON-3.4 predictions to measured FGR data for the UO_2 steady-state assessment cases
- $\sigma = \pm 2.6\%$ (absolue)

Integral Assessment: Fission Gas Release Predicted – Measured vs. Burnup

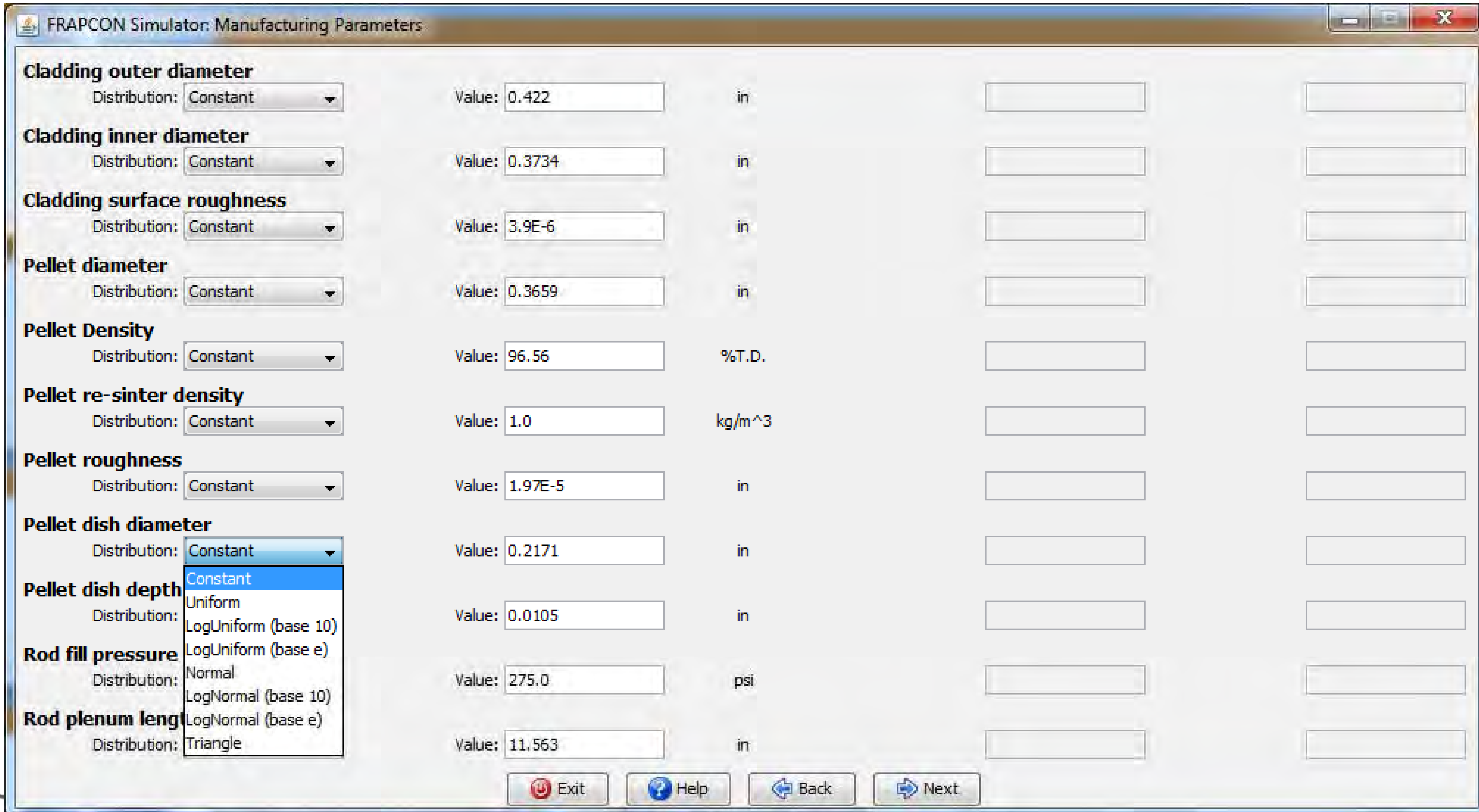


- Predicted minus measured FGR versus rod-average burnup for the UO_2 steady-state assessment cases
- σ=±2.6% (absolute)

Uncertainty Analysis with FRAPCON-3.4

- Stochastic framework capable of running many realizations of FRAPCON-3.4 varying:
  - Manufacturing uncertainties
  - Model uncertainties
  - Power uncertainties
- Package reads data from each realization and compiles distributions for each output of interest.
- Allows staff to validate vendor predictions of nominal and upper tolerance limit for various code outputs.
- Methodology does not rely on assumptions of normality for input or output distributions as the RMS methods typically used in industry do.

Uncertainty Analysis with FRAPCON-3.4 Input



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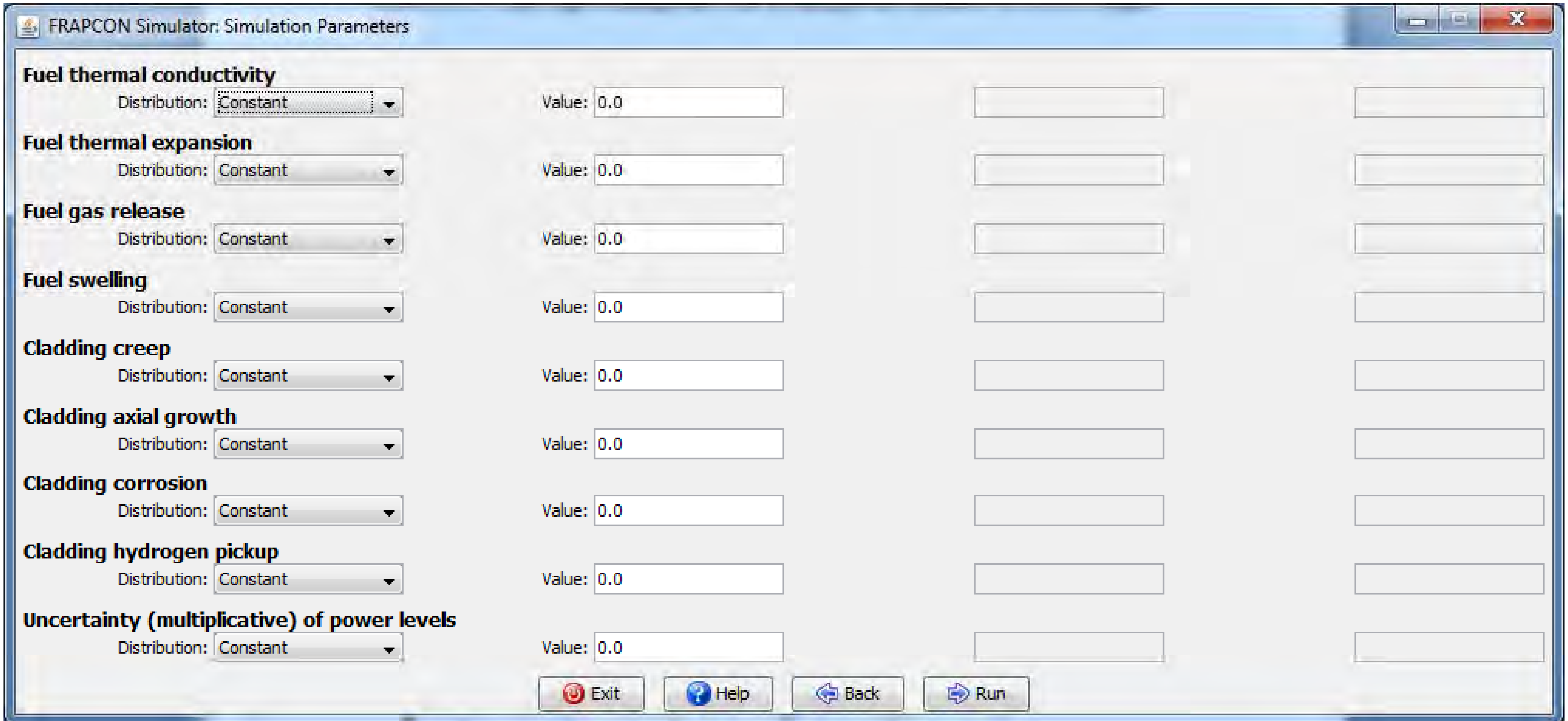
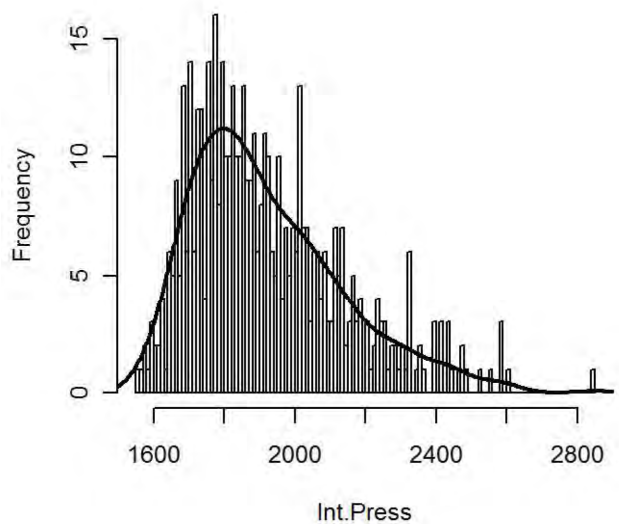
Uncertainty Analysis with FRAPCON-3.4 Input



Uncertainty Analysis with FRAPCON-3.4 Output

- Output distributions



- Inputs and outputs for each realization

Results.dat - Notepad

File Edit Format View Help

Real,	Int.Press,	Cnt.Temp,	Strain,	FGR,	DCO,	DCI,	ROUGHC,	POD,	DEN,	RSNT
1,	1.78952E+03,	2.62999E+03,	4.52323E-01,	1.50300E+01,	4.22000E-01,	3.73400E-01,	3.90000E-0			
2,	1.65482E+03,	2.68428E+03,	5.95411E-01,	1.16100E+01,	4.22000E-01,	3.73400E-01,	3.90000E-0			
3,	2.16289E+03,	2.82969E+03,	5.51791E-01,	1.98700E+01,	4.22000E-01,	3.73400E-01,	3.90000E-0			
4,	2.10606E+03,	2.82276E+03,	5.46886E-01,	1.84400E+01,	4.22000E-01,	3.73400E-01,	3.90000E-0			
5,	2.53833E+03,	2.81593E+03,	1.05104E+00,	2.25600E+01,	4.22000E-01,	3.73400E-01,	3.90000E-0			
6,	1.39913E+03,	2.51920E+03,	6.45997E-01,	7.86000E+00,	4.22000E-01,	3.73400E-01,	3.90000E-0			
7,	1.19533E+03,	2.33894E+03,	3.80605E-01,	6.41000E+00,	4.22000E-01,	3.73400E-01,	3.90000E-0			
8,	0.00000E+00,	0.00000E+00,	0.00000E+00,	0.00000E+00,	4.22000E-01,	3.73400E-01,	3.90000E-0			
9,	0.00000E+00,	0.00000E+00,	0.00000E+00,	0.00000E+00,	4.22000E-01,	3.73400E-01,	3.90000E-0			
10,	2.18889E+03,	2.90831E+03,	3.83521E-01,	2.01000E+01,	4.22000E-01,	3.73400E-01,	3.90000E-0			
11,	1.17435E+03,	2.45758E+03,	4.17531E-01,	5.24000E+00,	4.22000E-01,	3.73400E-01,	3.90000E-0			
12,	2.63451E+03,	3.08784E+03,	3.79090E-01,	2.78400E+01,	4.22000E-01,	3.73400E-01,	3.90000E-0			
13,	2.06329E+03,	2.94862E+03,	4.66872E-01,	2.00100E+01,	4.22000E-01,	3.73400E-01,	3.90000E-0			
14,	1.84756E+03,	2.68775E+03,	5.21069E-01,	1.57100E+01,	4.22000E-01,	3.73400E-01,	3.90000E-0			
15,	1.52357E+03,	2.51963E+03,	4.97465E-01,	1.20100E+01,	4.22000E-01,	3.73400E-01,	3.90000E-0			
16,	1.20363E+03,	2.42023E+03,	2.59632E-01,	5.31000E+00,	4.22000E-01,	3.73400E-01,	3.90000E-0			
17,	1.77857E+03,	2.70365E+03,	4.25561E-01,	1.40500E+01,	4.22000E-01,	3.73400E-01,	3.90000E-0			
18,	2.45844E+03,	2.85759E+03,	5.45986E-01,	2.45800E+01,	4.22000E-01,	3.73400E-01,	3.90000E-0			
19,	2.35549E+03,	2.81102E+03,	7.05168E-01,	2.22200E+01,	4.22000E-01,	3.73400E-01,	3.90000E-0			

- Calculated Upper Tolerance Limits

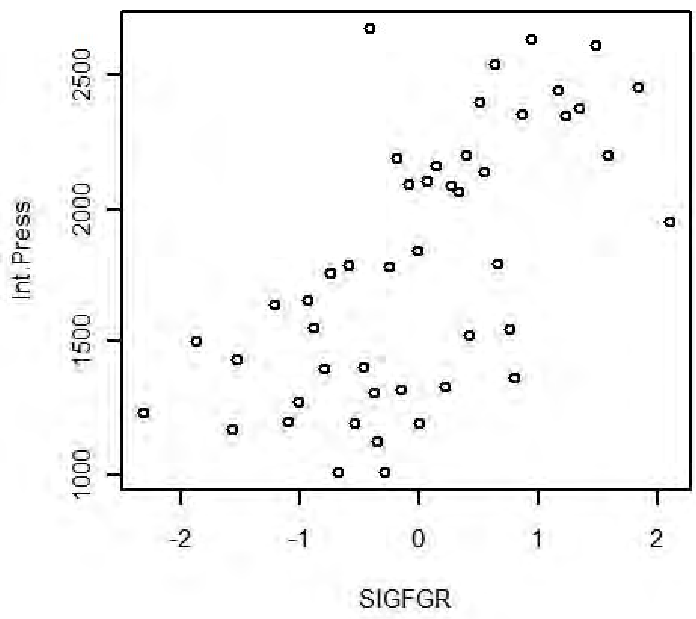
UTL.txt - Notepad

File Edit Format View Help

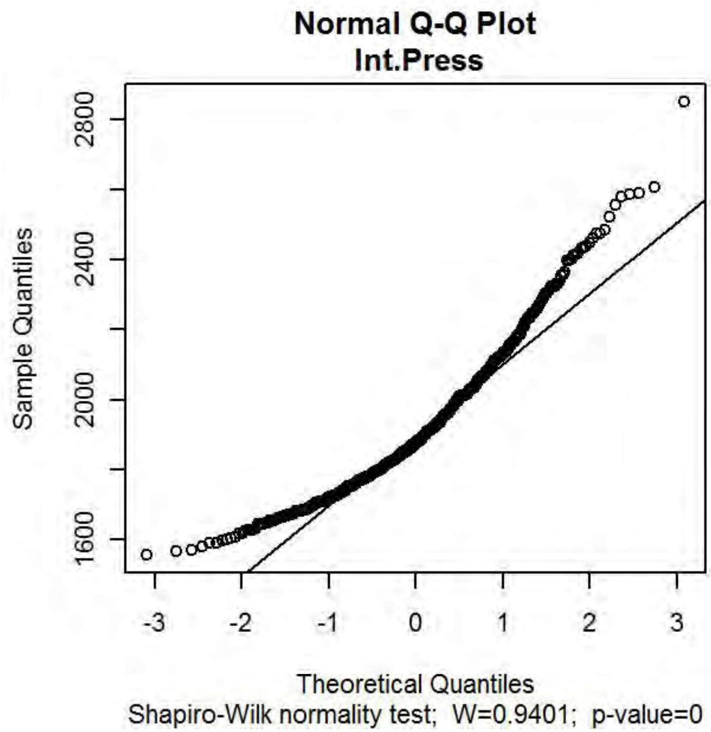
alpha	gamma	n	Int.Press	Cnt.Temp	Strain	FGR
0.1	0.9	47	2576.107	3037.06	0.745293	25.97670
0.1	0.95	47	2621.872	3058.25	0.760819	26.63641
0.1	0.99	47	2717.15	3102.366	0.7931427	28.00987
0.1	0.999	47	2842.729	3160.512	0.8357464	29.82013
0.05	0.9	47	2778.895	3130.956	0.8140901	28.89994
0.05	0.95	47	2832.344	3155.704	0.8322232	29.67043
0.05	0.99	47	2944.567	3207.666	0.8702958	31.28816
0.05	0.999	47	3094.15	3276.926	0.9210428	33.44444
0.01	0.9	47	3163.442	3309.01	0.9445508	34.44331
0.01	0.95	47	3232.56	3341.013	0.9679994	35.43966
0.01	0.99	47	3379.006	3408.821	1.017682	37.55072
0.01	0.999	47	3576.533	3500.281	1.084695	40.39815
0.001	0.9	47	3598.048	3510.243	1.091994	40.70829
0.001	0.95	47	3685.796	3550.872	1.121763	41.9732
0.001	0.99	47	3872.653	3637.391	1.185156	44.6668
0.001	0.999	47	4126.329	3754.85	1.271217	48.32362

Uncertainty Analysis with FRAPCON-3.4 Output

- Output vs. Input



- Test for Normality



Conclusions

- Fuel performance codes such as FRAPCON-3.4 are used to demonstrate compliance with a large number of SAFDL's
- Two kinds of validation data
  - Separate effects data
  - Integral assessment data
- All property and behavior models validated to be best-estimate vs. data
- 8 property and behavior models identified to have a significant impact on outputs of interest
  - σ calculated for each
  - These uncertainties are built in to the code

Conclusions

- Large database of integral assessment data used to validate FRAPCON-3.4
  - FRAPCON-3.4 provide a best-estimate prediction of fuel temperature
  - σ calculated for predictions
- Capability recently added to perform stochastic uncertainty analyses with FRAPCON-3.4
  - Allows staff to validate vendor predictions of nominal and upper tolerance limit for various code outputs.