

Official Transcript of Proceedings

NUCLEAR REGULATORY COMMISSION

Title: Advisory Committee on Reactor Safeguards
Thermal Hydraulic Phenomena Subcommittee
Material, Metallurgy and Reactor Fuels
Subcommittee: Open Session

Docket Number: (n/a)

Location: Rockville, Maryland

Date: Wednesday, February 20, 2013

Work Order No.: NRC-3095

Pages 1-201

NEAL R. GROSS AND CO., INC.
Court Reporters and Transcribers
1323 Rhode Island Avenue, N.W.
Washington, D.C. 20005
(202) 234-4433

1 UNITED STATES OF AMERICA

2 NUCLEAR REGULATORY COMMISSION

3 + + + + +

4 ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

5 (ACRS)

6 + + + + +

7 THERMAL-HYDRAULIC PHENOMENA SUBCOMMITTEE

8 MATERIAL, METALLURGY, AND REACTOR FUELS SUBCOMMITTEE

9 + + + + +

10 JOINT MEETING: REVIEW OF THERMAL CONDUCTIVITY

11 DEGRADATION

12 + + + + +

13 WEDNESDAY

14 FEBRUARY 20, 2013

15 + + + + +

16 ROCKVILLE, MARYLAND

17 + + + + +

18 OPEN SESSION

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

23
24
25
NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

(202) 234-4433

(202) 234-4433

1 COMMITTEE MEMBERS:

2 SANJOY BANERJEE, Subcommittee Chairman

3 J. SAM ARMIJO, Member

4 MICHAEL L. CORRADINI, Member*

5 JOY REMPE, Member

6 STEPHEN P. SCHULTZ, Member

7 WILLIAM J. SHACK, Member

8 GRAHAM B. WALLIS, Consultant

9
10 NRC STAFF PRESENT:

11 MARK L. BANKS, Designated Federal Official

12 WEIDONG WANG, Designated Federal Official

13 PAUL CLIFFORD, NRR

14 JENNIFER GALL, NRR

15 CHRIS JACKSON, NRR

16 ANTHONY MENDIOLA, NRR

17 BENJAMIN T. PARKS, NRR

18 CHRIS VAN WERT, NRO

19
20 ALSO PRESENT:

21 KEN GEELHOOD, PNNL

22
23 *Present via telephone

A G E N D A

Opening Remarks	4
Introduction	6
Overview of TCD Issue	7
Calibration and Validation of Fuel Models	42
Closed Session	147
Resolution/Future NRC Actions	147
Joint Subcommittee Discussion	188
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

1 public regarding today's meeting. For some items on
2 the agenda, the presentations will be closed in order
3 to discuss information that is proprietary to the fuel
4 vendors and licensees, pursuant to 5 U.S.C.
5 552(b)(C)(4). Attendance at these portions of the
6 meeting dealing with such information will be limited
7 to the NRC staff and its consultants, and to those
8 individuals and organizations who have entered into an
9 appropriate confidentiality agreement with them.

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

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

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

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

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

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

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

17 Introduction

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

23 I want to reiterate, we're not requesting
24 a letter. This is an informational briefing, but we
25 hope we have a frank and open discussion. As you all

1 know, all vendors have taken some action to address
2 the TCD issues. The actions vary among vendors, and
3 we haven't come to a conclusion one way or the other
4 yet.

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

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

14 MR. JACKSON: Yes.

15 CHAIRMAN BANERJEE: All right. Go ahead.

16 Overview of TCD Issue

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

24 Ken Geelhood from PNNL will provide the
25 second presentation. He will describe the algorithms

1 used in the fuel thermal solution, their calibration
2 and validation and the supporting empirical database
3 in more detail.

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

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

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

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

23 At the beginning of 1990's, measurements
24 collected at the Halden research reactor through their
25 instrumented fuel assemblies have provided sufficient

1 evidence to demonstrate the fuel thermal conductivity
2 is in fact a real issue that needs to be addressed.

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

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

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

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

21 MR. CLIFFORD: Well, the short answer is
22 that there are integral tests that are needed to
23 calibrate kind of the overall effects and the feedback
24 effects within the fuel rod. As you mentioned,
25 fission gas release. Yes, there's always been -- I

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 shouldn't say "always been." There has been a good
2 amount of fission gas release data at high burnup
3 fuel.

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

9 MEMBER ARMIJO: So until you could
10 separate the TCD effect by itself, right, you really
11 --

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

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

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

25 MEMBER SCHULTZ: Right.

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

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

11 MR. CLIFFORD: Yes.

12 MEMBER REMPE: So that's --

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

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

22 MR. CLIFFORD: Correct, and further in the
23 presentations, you'll see where vendors have looked at
24 each calculation and found that some remained
25 conservative, in spite of TCD, while other ones needed

1 augmentation factors. That will be clear.

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

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

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

20 They're kind of semi-empirical
21 correlations, in that it's a mathematical form that we
22 -

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

1 MR. CLIFFORD: This is the model --

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

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

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

9 MR. CLIFFORD: Yes.

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

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

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

24 MEMBER CORRADINI: Okay. Okay, thank you.

25 MR. CLIFFORD: Okay, on Slide 5. This is

1 an important slide, because it illustrates the
2 evolution of the Halden fuel temperature database.
3 Each symbol represents in the reactor, online, center
4 line temperature measurements taken over a period of
5 time in the Halden reactor for multiple fuel rod
6 segments within their instrumented test rates.

7 CONSULTANT WALLIS: Does the X axis mean
8 anything?

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

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

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

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

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

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

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

24 MEMBER CORRADINI: If I might just ask,
25 however, ask a question. Also as these tests

1 progress, these are different burnups right? So
2 there's kind of like another axis here that as time
3 progresses, you guys are doing different burnup
4 amounts?

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

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

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

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

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

20 MEMBER ARMIJO: Oh, that's good.

21 MR. CLIFFORD: So this really illustrates
22 what data was available when each code was approved.
23 So just as an example, if you look at GSTRM, which was
24 the legacy GE code, when it was approved, there was
25 very little data. There was no high burnup data

1 available to validate connectivity models within --

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

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

11 MR. CLIFFORD: The only data I'm showing
12 here, this is the UO₂ and gad rods from Halden that
13 are publicly available, that have been used to tune
14 FRAPCON.

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

19 MR. CLIFFORD: Yes.

20 MEMBER REMPE: Are these foreign fuel
21 tests?

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

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

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

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

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

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

23 MR. GEELHOOD: They may do different
24 things like that, or they have gas flow rates and so
25 they can vary the gas in the gap, to change the

1 temperature of the rod. So they can do a lot of those
2 kind of tests, because they're looking at one
3 particular thing, and maybe for one test they're not
4 as interested in gas release.

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

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

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

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

25 MR. GEELHOOD: Well yes. So we get one

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

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

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

18 MEMBER REMPE: It's the gap.

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

25 MEMBER CORRADINI: Okay. But the

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

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

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

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

17 MEMBER CORRADINI: Okay, thank you.

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

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

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

25 MR. GEELHOOD: The last release came out

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

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

4 MR. GEELHOOD: Yes, which was like 2,000
5 --

6 CHAIRMAN BANERJEE: Is that next time?

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

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

16 MALE PARTICIPANT: For PWR, do you have --

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

20 CHAIRMAN BANERJEE: Okay, fine.

21 MEMBER REMPE: Before you leave the Slide
22 2, there's not very much data at 80 gigawatt days per
23 metric ton uranium. Is there a plan for
24 repeatability, additional tests? I've forgotten the
25 numbers, but is it five to seven degrees or something?

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

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

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

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

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

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

24 MEMBER SHACK: But what range of burnups
25 do you think you're covering? You know, FRAPCON is

1 valid now up to what?

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

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

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

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

25 MEMBER SHACK: Up to what burnup?

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

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

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

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

20 MR. GEELHOOD: Right.

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

25 MR. CLIFFORD: Correct. We'll get to that

1 in detail. But to go back to your question, if our
2 predictions of temperature were that far off, then we
3 would see it in other places, such as void volume,
4 such as fission gas release, rod internal pressure.

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

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

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

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

23 MR. GEELHOOD: And so what Paul said too
24 is when you see like one dot there, that's the
25 instrumented fuel assembly, and many times there's

1 many rods in there that are run at different
2 conditions.

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

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

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

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

25 MR. CLIFFORD: Yes, right.

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

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

5 MR. GEELHOOD: Yes. You have one point.

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

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

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

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

21 MR. CLIFFORD: Yes.

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

24 MR. CLIFFORD: Right, right. So you have
25 online temperature measurements periodically every so

1 many minutes --

2 MEMBER ARMIJO: Right.

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

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

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

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

20 MEMBER REMPE: We have some electronic
21 copies too.

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

1 MEMBER REMPE: And things look good, yes.

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

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

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

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

14 (Simultaneous speaking.)

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

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

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

22 MR. GEELHOOD: Oh no. There's two
23 different ways that they can measure. So they can
24 measure the total temperature of the rod using an
25 expansion thermometer, and that's something that just

1 expands. But then most often what they do is they
2 drill out the top and bottom couple pellets, and
3 actually insert a thermocouple in there.

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

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

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

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

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

21 MR. GEELHOOD: Halden definitely has like
22 kind of evolved over time. In some of these earlier
23 ones, there was more thermocouple decalibration, and
24 they've definitely improved on their methods and you
25 may know their methods more than I do. But they're

1 data does seem more reliable with some of the newer
2 tests than it did in the past.

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

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

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

10 MR. CLIFFORD: Yes, we will. Absolutely.

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

16 MR. GEELHOOD: The average of everything.

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

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

23 CONSULTANT WALLIS: It varies a lot.

24 MR. CLIFFORD: It varies a lot.

25 CONSULTANT WALLIS: So there's an average,

1 there's a radial average, and there's also a length
2 average. Is this a length average?

3 MR. GEELHOOD: For the length, yes.

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

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

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

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

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

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

23 CONSULTANT WALLIS: A few points.

24 MR. GEELHOOD: And so where it's measured
25 is where we do the comparison, and so it would be like

1 that, those ends burn up. Or in the case of an
2 expansion thermal --

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

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

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

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

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

23 MR. GEELHOOD: Yes.

24 MEMBER SCHULTZ: Now you've put on here
25 when other code were approved. That doesn't

1 necessarily mean that the vendors used all of this
2 data as a benchmark for their codes or --

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

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

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

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

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

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

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

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

20 MR. GEELHOOD: And the 681 is a uranium
21 and a gadolinium rate. There's the 0₂ rods and the 0₂
22 gadolinium rods, and that is continuing. And so if we
23 were to --

24 MEMBER SCHULTZ: Okay.

25 MR. GEELHOOD: --you know, Paul's going to

1 go this next Halden meeting. He may come back and
2 that point may move up, you know.

3 MEMBER SCHULTZ: Got you.

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

7 MEMBER SCHULTZ: Are still in progress.

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

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

17 MR. GEELHOOD: Right.

18 MEMBER SCHULTZ: Understood. Thank you.

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

23 But in general terms for this
24 introduction, you could say that to grade thermal
25 conductivity results in higher fuel pellet

1 temperatures at a given power level, and that any
2 codes that don't properly account for it will have an
3 artificially low fuel temperature prediction.

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

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

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

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

25 MR. GEELHOOD: There's nothing right now

1 in the --

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

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

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

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

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

21 CONSULTANT WALLIS: That's right.

22 (Simultaneous speaking.)

23 CONSULTANT WALLIS: At the beginning it
24 really matters.

25 Maybe you could take a homework problem

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

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

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

10 CONSULTANT WALLIS: It would be helpful,
11 I think.

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

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

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

22 (Simultaneous speaking.)

23 MR. GEELHOOD: There's a pretty steep
24 temperature gradient. So we have a relocation model,
25 which kind of models this kind of effect of the pellet

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 getting bigger due to cracks and it doesn't fit back
2 together perfectly.

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

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

10 MEMBER SCHULTZ: Sure.

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

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

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

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

25 CHAIRMAN BANERJEE: Paul, I don't mean to

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 be a spoilsport or anything, but are you sort of --
2 how many more slides do you have?

3 (Simultaneous speaking.)

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

6 CHAIRMAN BANERJEE: All right.

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

10 CHAIRMAN BANERJEE: Great. Thanks very
11 much.

12 MR. CLIFFORD: The next presentation.

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

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

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

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

1 CHAIRMAN BANERJEE: All right, okay.

2 MEMBER ARMIJO: We'll speak up.

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

5 Calibration and Validation of Fuel Models

6 MR. GEELHOOD: So my name is Ken Geelhood.
7 I'm a contractor with the Pacific Northwest National
8 Lab, and I maintain a contract with the Office of
9 Research, to continuously update FRAPCON and FRAPTRAN,
10 and then we also have contracts with NRR and NRO to
11 assist them in doing their reviews of vendor fuel
12 performance codes, new cladding alloys, methodologies
13 for doing safety analyses. So I'm going to talk about
14 --

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

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

23 And then so there is kind of parallel
24 development that was being funded, and then the NRC
25 moved it all into one. So that's why FRAPCON came out

1 of FRAP-S and GAPCON, so and then FRAPTRAN similarly.
2 So PNNL since about '95, I think, has been the only
3 contractor doing code development. But the Idaho
4 National Lab definitely laid the groundwork for some
5 of this coding.

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

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

10 MR. GEELHOOD: Gary.

11 MEMBER REMPE: And he's retired.

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

14 MEMBER REMPE: He's also retired.

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

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

20 MEMBER ARMIJO: Okay, okay.

21 CHAIRMAN BANERJEE: Don't get anxious.

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

25 CHAIRMAN BANERJEE: No, no, no. I would

1 never do that. Let's go on.

2 MEMBER ARMIJO: Okay.

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

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

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

22 Corrosion and hydriding; there is a
23 corrosion limits currently in place, and there will
24 probably be hydrogen limits coming down the road; and
25 then fission gas release is a concern, partially for

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 pressure but also for dose calculations.

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

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

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

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

23 Fission gas release. Although it's on the
24 behavior models, it's also in integral effect data,
25 because it can be impacted by the temperature, the

1 size of the gap, all these other things. Then void
2 volume is something that's kind of in integral effect
3 cladding corrosion.

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

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

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

12 CONSULTANT WALLIS: This includes the gap
13 then?

14 MR. CLIFFORD: Gap and the plenum.

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

17 MR. CLIFFORD: Porosity.

18 MR. GEELHOOD: Yes.

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

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

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

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

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

3 CHAIRMAN BANERJEE: Right, right.

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

6 MR. CLIFFORD: I'm just trying to think of
7 --

8 CHAIRMAN BANERJEE: I'm going outside the
9 domain.

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

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

15 MR. CLIFFORD: There's definitely --

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

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

25 MR. GEELHOOD: There's definitely neutron

1 detectors that sometimes get inserted into commercial
2 reactors. But that probably would be more normal
3 operational data than accident data.

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

7 MR. GEELHOOD: That may be, yes.

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

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

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

21 MR. GEELHOOD: Yes.

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

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

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

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

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

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

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

24 MR. GEELHOOD: Model growth?

25 MEMBER ARMIJO: Not growth. Let's say

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

4 MR. GEELHOOD: Cladding hoop strain.

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

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

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

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

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

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

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

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

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

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

1 MEMBER ARMIJO: It does.

2 MR. GEELHOOD: It does? It goes back?

3 MEMBER ARMIJO: Yes.

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

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

11 CONSULTANT WALLIS: It's pretty
12 complicated.

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

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

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

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

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

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

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

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

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

21 We've done, as Steve mentioned,
22 sensitivity analyses on those things before. But we
23 found, you know, it's a 1D solution is appropriate,
24 and then the half dimension is that gas can transport
25 up. So we don't do heat transfer in the axial

1 direction, but we do allow, you know, mixing of the
2 gas and the gap with that in the plenum.

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

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

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

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

21 MEMBER ARMIJO: Okay.

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

1 it. So we define a hard contact and a soft contact.

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

7 MR. GEELHOOD: We could.

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

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

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

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

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

24 MR. GEELHOOD: Yes.

25 CHAIRMAN BANERJEE: If nothing else,

1 somebody in your lab will. All right, okay.

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

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

12 MR. GEELHOOD: I guess this is a cartoon.

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

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

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

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

21 CHAIRMAN BANERJEE: Well, that's artistic
22 license.

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

25 CHAIRMAN BANERJEE: Well, this is

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

3 MR. GEELHOOD: There have been assessments
4 done.

5 CONSULTANT WALLIS: It's a five percent?

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

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

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

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

21 MR. GEELHOOD: Yes.

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

24 CHAIRMAN BANERJEE: But you can certainly
25 assess the effect.

1 CONSULTANT WALLIS: Yes.

2 MR. GEELHOOD: Yes, and these are --

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

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

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

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

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

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

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

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

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

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

22 MR. GEELHOOD: If you're interested in
23 centerline melting, then if one side is touching
24 that's cooler, but the other side is hotter. So it's
25 not going to impact the centerline temperature much,

1 and that's what drives fuel melting, would be the
2 centerline.

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

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

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

16 CHAIRMAN BANERJEE: But do you have the
17 answer?

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

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

24 MEMBER CORRADINI: So let just ask a
25 different question. I'm assuming the NRC is following

1 the big expensive money that DOE is doing for CASL.
2 One of the things CASL is doing is three-dimensional
3 calculations, similar to what's being done at CEA in
4 France, and the effects on fuel behavior.

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

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

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

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

25 MEMBER CORRADINI: I understand. I just

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

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

9 (Laughter.)

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

14 MALE PARTICIPANT: Is it --

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

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

25 MEMBER CORRADINI: I'm not disagreeing

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

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

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

10 MR. GEELHOOD: Yes.

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

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

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

25 CHAIRMAN BANERJEE: In a bundle of cores

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

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

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

15 MR. GEELHOOD: Go

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

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

1 So that's just the mathematical equation.

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

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

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

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

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

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

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

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

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 approach.

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

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

11 MR. GEELHOOD: Yes.

12 CHAIRMAN BANERJEE: Yes.

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

15 CHAIRMAN BANERJEE: They call it the
16 difference intervals.

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

21 CONSULTANT WALLIS: So what is the mesh
22 size here?

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

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

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

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

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

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

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

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

22 CONSULTANT WALLIS: It doesn't adjust the
23 grid.

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

1 CONSULTANT WALLIS: Throughout the life
2 cycle?

3 MR. GEELHOOD: Yes.

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

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

8 (Simultaneous speaking.)

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

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

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

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

20 CHAIRMAN BANERJEE: And do convergence
21 testing?

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

1 CONSULTANT WALLIS: Seventeen is the magic
2 number?

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

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

10 MR. GEELHOOD: Yes, yes.

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

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

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

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

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

22 MR. GEELHOOD: Yes, yes.

23 CHAIRMAN BANERJEE: You sample that
24 history, right?

25 MR. GEELHOOD: Yes.

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

3 MALE PARTICIPANT: History-dependent.

4 CHAIRMAN BANERJEE: That's really what --

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

11 CHAIRMAN BANERJEE: Yes, that's what I was
12 --

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

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

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

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

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

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

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

17 MR. GEELHOOD: Probably temperature is
18 what --

19 (Simultaneous speaking.)

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

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

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

1 MR. GEELHOOD: Yes.

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

6 MR. GEELHOOD: Some of them are, yes.

7 CHAIRMAN BANERJEE: Yes, some of them are.

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

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

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

22 MR. GEELHOOD: So maybe, yes. The
23 integral flux over the time step, which is maybe like
24 10 to 50 days, you know.

25 CHAIRMAN BANERJEE: Yes.

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

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

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

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

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

22 MEMBER SHACK: Impirical.

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

25 MEMBER SHACK: That's okay. The

1 spellchecker was turned off.

2 CHAIRMAN BANERJEE: Okay.

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

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

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

17 MR. GEELHOOD: Yes.

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

24 So you'd have, there would be grain
25 boundaries accessible to fission gas for release. Now

1 does it get that level of detail, or you basically say
2 all the properties, the pellet at this burnup are
3 constant. There's no radial --

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

12 MEMBER ARMIJO: Right.

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

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

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

20 MEMBER ARMIJO: Okay.

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

24 MEMBER ARMIJO: Moving right along.

25 CHAIRMAN BANERJEE: I mean I don't want

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

3 MEMBER ARMIJO: Okay.

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

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

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

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

18 CHAIRMAN BANERJEE: It restores your faith
19 in science.

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

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

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

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

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

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

1 --

2 MR. GEELHOOD: And also burnup.

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

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

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

12 MR. GEELHOOD: Well, it just happens
13 automatically.

14 MEMBER SHACK: It happens automatically.

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

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

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

1 MR. CLIFFORD: That doesn't mean something
2 like MOX wouldn't affect it. That's for _{UO2}.

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

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

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

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

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

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

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

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

18 Prior to 1996, to my knowledge, no models
19 contained the effect of burnup on fuel thermal
20 connectivity. In 1992, Lucuta published data from
21 what he called Simfuel, which was fresh fuel doped
22 with simulated fission products, and that was kind of
23 -- he kind of thought for all these like gases and
24 cesium iodide being jammed in there, it's going to
25 definitely change the thermal conductivity. So those

1 data showed that there was a decrease in thermal
2 conductivity with burnup, and so in 1996, he published
3 his revised thermal conductivity model based on his
4 earlier data, and then in 1997, PNNL released FRAPCON
5 3.0, and that had the Lucuta model.

6 And I guess the Lucuta maybe did about
7 half of what it needed to do, because in between 1994
8 and 2004, Ronchi and Carrol had this laser flash data
9 from actual UO₂ disks that were irradiated. They kind
10 of sandwiched them between metal plates and irradiate
11 them.

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

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

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

25 CHAIRMAN BANERJEE: The surrogates

1 essentially.

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

5 CHAIRMAN BANERJEE: Right.

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

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

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

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

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

22 MR. GEELHOOD: Yes.

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

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

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

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

10 MR. GEELHOOD: Yes. So the laser puts a
11 known quantity of energy in, and you measure how much
12 it goes up. And then if you also measure the density
13 --

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

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

18 MEMBER REMPE: Most of them it's
19 thermocouples.

20 MR. GEELHOOD: Okay.

21 MEMBER REMPE: We have one in my lab.

22 MR. GEELHOOD: If that measures
23 diffusivity, then if you also measure the density and
24 the heat capacity, then you can calculate the thermal
25 conductivity, and the heat capacity's done in a

1 differential scanning calorimetry, where you just keep
2 it up and watch your thermocouples.

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

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

11 MEMBER ARMIJO: Yes.

12 MR. GEELHOOD: So one --

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

17 MEMBER ARMIJO: Temperature.

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

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

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

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

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

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

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

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

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

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

24 MR. GEELHOOD: So that's something that's
25 tough about this, is you can measure high temperature,

1 but really the only thing that's valid is measuring
2 the thermal conductivity at the radiation temperature,
3 because in the reactor, you get kind of like this
4 defect annealing and creation.

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

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

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

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

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

7 MR. GEELHOOD: Phonon.

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

10 CHAIRMAN BANERJEE: At high temperatures.

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

13 MR. GEELHOOD: I'm sorry.

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

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

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

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

23 (Simultaneous speaking.)

24 CHAIRMAN BANERJEE: Maybe the dominant
25 effect, because otherwise it doesn't make that much

1 sense. Okay. Keep going.

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

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

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

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

16 MR. CLIFFORD: Right, that's right.

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

25 MR. CLIFFORD: Given that this has been

1 demonstrated, the root cause.

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

5 But now if we're doing LOCA initialization
6 of fuel melting, we may be way up here. So I think
7 this is continuing on the evolution a bit. So in
8 2003, PNNL released FRAPCON 3.2, and that included the
9 current thermal conductivity model that matched the
10 irradiated data.

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

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

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

22 (Simultaneous speaking.)

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

25 CONSULTANT WALLIS: So A is the dimensions

1 of one over connectivity.

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

6 CONSULTANT WALLIS: Got to get the units
7 right.

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

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

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

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

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

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

1 MR. GEELHOOD: We have a different model
2 for MOX, and we haven't found that the thermal
3 conductivity -- the thermal conductivity of MOX is
4 different, but it's not different with 12 percent MOX
5 or 80 percent MOX. So it's different than UO₂, but it
6 doesn't seem to be a strong function of how much
7 plutonium is in it.

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

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

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

23 (Simultaneous speaking.)

24 MR. GEELHOOD: Yes.

25 CONSULTANT WALLIS: The spectrum you're

1 seeing is similar.

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

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

8 MR. GEELHOOD: Phonon.

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

12 MR. GEELHOOD: Base electronic term.

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

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

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

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

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

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

3 CHAIRMAN BANERJEE: But still --

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

6 CHAIRMAN BANERJEE: But this fits your
7 data.

8 MR. GEELHOOD: Yes. There may be --

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

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

15 CHAIRMAN BANERJEE: See one of the
16 questions that we faced in one of the EPU's, I think it
17 was St. Lucie I --

18 MEMBER REMPE: It was.

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

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

24 CHAIRMAN BANERJEE: Yes.

25 MEMBER SHACK: Right.

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

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

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

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

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

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

20 (Simultaneous speaking.)

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

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

1 first principles.

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

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

12 (Laughter.)

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

15 MR. GEELHOOD: Yes.

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

18 MR. GEELHOOD: Probably just chemistry.
19 You know, an unirradiated model has a different
20 thermal conductivity than a radiated MOX, or an
21 unirradiated UO₂. So --

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

24 MR. GEELHOOD: So it's lower thermal
25 conductivity, because you would expect slightly higher

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 temperatures in MOX at the same power levels of CO₂.

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

5 MEMBER REMPE: I was just curious.

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

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

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

16 MEMBER SHACK: A kind of panoply of
17 regulatory interest.

18 (Laughter; simultaneous speaking.)

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

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

23 MR. GEELHOOD: So this is just predicted
24 -- you want me to go quickly through like the eight
25 models that have been identified, and just kind of

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 show some representative data for this. It's kind of
2 like the data that we have.

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

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

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

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

20 (Simultaneous speaking.)

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

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

25 MR. GEELHOOD: The Ronchi and Carrol are

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

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

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

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

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

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

22 MEMBER SHACK: Okay.

23 (Pause.)

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

25 MEMBER REMPE: But it's all laser flash.

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 Even the irradiated is laser flash.

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

6 MEMBER REMPE: Thanks. Sorry I got you
7 sidetracked.

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

14 CHAIRMAN BANERJEE: What are the red
15 things?

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

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

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

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

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

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

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

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

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

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

1 they did.

2 MR. GEELHOOD: I think yes.

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

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

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

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

15 CHAIRMAN BANERJEE: They probably could
16 have some thermal expansion.

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

20 CHAIRMAN BANERJEE: It is important?

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

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 lot with burnup.

2 MEMBER REMPE: Defects maybe?

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

6 MR. CLIFFORD: Gas expansion.

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

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

14 MR. GEELHOOD: I mean definitely a
15 question.

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

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

21 MEMBER REMPE: Thermal expansion.

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

25 CHAIRMAN BANERJEE: So in transience, the

1 thermal expansion doesn't come into affect the gap?

2 MR. GEELHOOD: Well, it drives the stream.

3 CHAIRMAN BANERJEE: Sorry? It drives

4 what?

5 MR. GEELHOOD: It drives -- so the pellet

6 expands during the transience, and it would drive the

7 cladding stream. So if the swelling --

8 CHAIRMAN BANERJEE: Why isn't it

9 important?

10 MR. GEELHOOD: Well, so then I guess we

11 have like some circumstantial evidence that it's not

12 changing, because we can predict the hoop strains

13 fairly well. So that would tell us probably we're

14 predicting the thermal expansion fairly well.

15 MALE PARTICIPANT: In an integral test?

16 MR. GEELHOOD: But that's more of an

17 integral --

18 MEMBER ARMIJO: You know the temperature.

19 MEMBER SHACK: The hoop strains, you are

20 looking oat that as above the burnup pushing --

21 MR. GEELHOOD: So we look at various ramp

22 tests.

23 MEMBER SCHULTZ: --and that includes the

24 thermal expansion and the swelling and the relocation.

25 MR. GEELHOOD: Well, the swelling and

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

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

4 MEMBER SCHULTZ: But the initial condition
5 incorporates --

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

9 CHAIRMAN BANERJEE: Okay. Let's move on.

10 MR. GEELHOOD: Okay. So this is the
11 fission gas release data we have for UO_2 . So there's
12 power ramped and steady state data in here, and this
13 is just our best estimate model, and then what we did
14 is we biased the gas diffusivity up and down, in such
15 a way that we could over-predict and under-predict all
16 the data.

17 So then rather than putting an uncertainty
18 on our outputted gas release, we put the uncertainty
19 on the diffusivity, that's just actually plus or minus
20 100 percent on diffusivity, and then that gives us a
21 way to bias the gas release that comes down.

22 Fuel swelling. Right now, we predict
23 lower swelling up to about 80 gigawatt-days for time,
24 and then higher swelling above. So what each of these
25 points is, it is an estimate from Halden of what the

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 swelling rate was, because they've got some rates
2 where they can actually measure the length change in
3 the stack, and correlate that to swelling.

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

10 MEMBER REMPE: On your gas release?

11 MR. GEELHOOD: Yes.

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

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

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

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

23 MEMBER REMPE: Of the composition.

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

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

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

4 MR. GEELHOOD: So ANS maintains a standard
5 5.4. It tells you how to calculate radioactive gas
6 release. This is kind of the stable gas release that
7 drives the pressure inside the rod, whereas the
8 radioactive gas release would impact your dose
9 calculation.

10 MEMBER REMPE: Okay.

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

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

23 This is axial growth. Again, you'll see
24 some, I guess we eliminated the B&W data as they
25 didn't fully characterize everything that they needed

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 to, you know. This is axial growth, but we didn't
2 have the actual as-built original lengths, only the
3 final lengths.

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

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

14 MEMBER SHACK: It's deliberate.

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

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

1 I've got 2-sigma upper and lower.

2 CHAIRMAN BANERJEE: Okay. You can just go
3 on.

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

6 MR. GEELHOOD: Yes.

7 MEMBER CORRADINI: Can you hear me?

8 MR. GEELHOOD: Yes.

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

13 MR. GEELHOOD: Yes.

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

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

23 MEMBER CORRADINI: Okay, thank you.

24 MR. GEELHOOD: So I think I had been
25 talking -- axial growth throughout for recrystallized

1 cladding. This is just an example of cladding
2 corrosion. We have a lot of data for different types
3 of alloys, and we have different uncertainties for
4 different alloys that we collected with the presently
5 available data.

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

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

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

21 MR. GEELHOOD: Yes.

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

1 MR. GEELHOOD: Yes.

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

4 MR. GEELHOOD: Sounds good.

5 (Whereupon, a short recess was taken.)

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

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

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

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

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

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

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

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

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

14 CHAIRMAN BANERJEE: Take the temperature.

15 MR. GEELHOOD: Take the temperature, yes.

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

18 MR. GEELHOOD: Yes.

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

21 MR. GEELHOOD: So LHGR is kind of what the
22 NRC staff think about more, because the vendors will
23 propose some sort of envelope that they can operate
24 in, and the staff will decide if that envelope is
25 acceptable. So this plot is more to show this is the

1 envelope that we feel comfortable for FRAPCON.

2 MEMBER REMPE: So if I correlate this with
3 that P graph earlier, where there were like three
4 tests above 50 gigawatt-day per metric ton uranium,
5 how did you decide to plot so many points here? Is it
6 because of different fuel in the tests, or is it every
7 --

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

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

13 (Simultaneous speaking.)

14 MR. GEELHOOD: You know, each IFA can hold
15 6 to 12 test rods in it.

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

19 MR. GEELHOOD: Yes.

20 CHAIRMAN BANERJEE: In terms of what the
21 staff --

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

24 CHAIRMAN BANERJEE: Is there a limit put
25 on the LHGR, based on this data? Like is there sort

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 of an envelope that the staff --

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

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

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

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

23 MR. GEELHOOD: Yes.

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

1 MR. GEELHOOD: This is only Halden data.

2 CONSULTANT WALLIS: All Halden data.

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

6 CONSULTANT WALLIS: But it's all Halden.

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

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

12 MR. GEELHOOD: Not so much, no.

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

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

20 CHAIRMAN BANERJEE: Okay.

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

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 90's data, you can hardly see it because it seems to
2 be predicted fairly well.

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

8 CHAIRMAN BANERJEE: Is that little --

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

13 MEMBER ARMIJO: This was for gad?

14 MR. GEELHOOD: Oh, good one. This is for
15 gad. So all the gad data has come since the year
16 2000, so there's not really an animation like the last
17 one, and we calculated again about five percent
18 uncertainty on that, for a 1-sigma. Then there's a
19 the predicted minus measured over measured. So again,
20 the relative under/over prediction as a function of
21 burnup.

22 What this demonstrates to us is we're not
23 kind of developing any sorts of bias as burnup
24 progresses. So now this is the range of our fission
25 gas release data, and so this comes from more than

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 just Halden. This comes from some commercial plants,
2 other test reactors.

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

7 MR. GEELHOOD: Yes, yes.

8 CHAIRMAN BANERJEE: And which you use and
9 --

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

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

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

25 CONSULTANT WALLIS: It's a funny plot,

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

6 MEMBER SCHULTZ: Yes, they can't.

7 CONSULTANT WALLIS: So this is a better
8 plot really.

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

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

17 MR. GEELHOOD: Yes.

18 CHAIRMAN BANERJEE: So those brown points
19 up there --

20 MR. GEELHOOD: Yes.

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

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

25 MALE PARTICIPANT: Back one slide.

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

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

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

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

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

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

1 and they --

2 CHAIRMAN BANERJEE: Did they predict this
3 as well?

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

7 CHAIRMAN BANERJEE: In terms of what,
8 material properties?

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

16 CHAIRMAN BANERJEE: Thanks.

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

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

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 the direct temperature measurement.

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

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

7 CHAIRMAN BANERJEE: Tuned it, right.

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

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

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

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

25 MR. GEELHOOD: So this one there was a

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

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

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

10 CHAIRMAN BANERJEE: That's pretty
11 impressive.

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

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

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

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

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

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

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

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

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

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

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

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

16 MR. GEELHOOD: Yes.

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

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

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

24 MR. GEELHOOD: No, I understand. I mean
25 we -- so I mean it's easier to describe, than to like

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 put it in terms of equations.

2 CHAIRMAN BANERJEE: All right.

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

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

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

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

22 CHAIRMAN BANERJEE: So how do you
23 calculate saturation?

24 MR. GEELHOOD: So that's another. It's an
25 empirical fitting parameter, but it's a function of

1 the gas pressure or the cladding pressure pushing back
2 on the pellet. So it's kind of how much that holds
3 in, and then also the temperature and also the grain
4 size. So a smaller grain would have more room for --

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

9 MR. GEELHOOD: So there's --

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

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

14 CHAIRMAN BANERJEE: Adjust.

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

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

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

1 yes.

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

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

8 CHAIRMAN BANERJEE: Who wrote that paper?

9 MR. GEELHOOD: Messi.

10 CHAIRMAN BANERJEE: Werner.

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

12 CHAIRMAN BANERJEE: Okay.

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

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

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

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

5 CHAIRMAN BANERJEE: Test.

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

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

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

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

21 MR. GEELHOOD: Yes.

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

24 MR. GEELHOOD: Maybe yes.

25 CHAIRMAN BANERJEE: Maybe.

1 MR. GEELHOOD: But then --

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

4 MR. GEELHOOD: Yes.

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

7 (Simultaneous speaking.)

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

10 CHAIRMAN BANERJEE: Right.

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

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

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

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

23 (Laughter.)

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

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

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

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

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

15 MEMBER SCHULTZ: There was no changes at
16 that point?

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

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

21 MR. GEELHOOD: Yes.

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

24 CHAIRMAN BANERJEE: Diffusion through a
25 sphere --

1 CONSULTANT WALLIS: There's no sphere
2 there.

3 CHAIRMAN BANERJEE: --is a 1D problem.

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

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

8 VOICES: No, the grain.

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

11 MEMBER ARMIJO: No.

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

14 (Simultaneous speaking.)

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

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

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

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

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

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

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

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

15 MR. GEELHOOD: Yes, I'm sorry.

16 CHAIRMAN BANERJEE: Due to the fluence,
17 right?

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

21 CHAIRMAN BANERJEE: Yes. Standard store
22 stuff.

23 MEMBER ARMIJO: Yes.

24 MR. GEELHOOD: And this, they call it a
25 two-stage diffusion problem, and it's fairly typical

1 among handling of fission gas release.

2 MR. CLIFFORD: About the athermal term?

3 MR. GEELHOOD: In the diffusivity?

4 MR. CLIFFORD: Yes.

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

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

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

22 So what it allows us to do is to run many
23 realizations or instances of FRAPCON-3, by varying the
24 manufacturing uncertainties, the model uncertainties
25 and the power uncertainties. So this package then

1 reads data from each realization, compiles
2 distribution throughout each output of interest.

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

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

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

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

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

25 MR. GEELHOOD: So when you get your

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

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

5 MR. GEELHOOD: Yes. Then you'll get your
6 200 realizations, and it looks at those outputs and
7 says "Okay, your upper 95/95 is X." So it's a more
8 straightforward thing, rather than relying on various
9 assumptions that are kind of buried in more simplistic
10 ways. It's just kind of --

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

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

15 MR. CLIFFORD: It depends on the --

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

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

25 But you can do these log normals or

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

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

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

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

14 CONSULTANT WALLIS: What's the resintered
15 density then?

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

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

22 MR. GEELHOOD: Yes, yes.

23 CONSULTANT WALLIS: Oh, it's a change?

24 MR. GEELHOOD: So what they do is they put
25 an as-manufactured pellet in a furnace of 1,700 K I

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 think. I can't remember the unit.

2 MEMBER ARMIJO: Very high.

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

8 CONSULTANT WALLIS: It's a very small
9 change.

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

13 CONSULTANT WALLIS: Right.

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

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

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 CHAIRMAN BANERJEE: A lot of user input,
2 right?

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

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

9 MR. GEELHOOD: Yes.

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

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

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

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

23 MR. GEELHOOD: So we did a study earlier
24 for the Office of Research, and it kind of drove our
25 selection of these eight parameters, that we varied

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 like all kinds of things, you know, inputs and model
2 parameters, and kind of see which ones had more or
3 less of an impact. I think that's NUREG/CR-7001.

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

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

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

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

23 MR. GEELHOOD: So then this is just some
24 examples of the output. So we get these
25 distributions, you know, and you can decide oh maybe

1 this internal pressure is not, the output distribution
2 is not normal. You know, at some point you can't get
3 to any lower pressure. But maybe it's this kind of T
4 distribution.

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

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

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

13 CONSULTANT WALLIS: .99 percent with .001,
14 99.9, 99.9 percent, 9.9 percent.

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

16 CONSULTANT WALLIS: But the thing that's
17 so strange is that there's a lot of tail, because
18 that's a much higher value for internal pressure than
19 95/95. It means there's a huge tail going on.

20 MR. GEELHOOD: Yes, yes. This isn't like
21 the answer. This is just kind of a sample case we
22 ran. But you're right. In general, like some of
23 these things have like a significant tail, because you
24 know, if you do a worse case analysis, these are your
25 worse case thermal conductivity and worse case gas

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 release, you can get really high pressure in these
2 things.

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

5 (Simultaneous speaking.)

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

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

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

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

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

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

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

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

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

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

9 MR. GEELHOOD: All what?

10 CONSULTANT WALLIS: The temperature.

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

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

16 MR. GEELHOOD: Oh yes, yes.

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

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

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 CONSULTANT WALLIS: Just when I was going
2 to get into it, and some of this, some of the material
3 we read did show some Studsig data and so on, and
4 there was -- it was different from other data. You're
5 not going to get into that, though?

6 MR. GEELHOOD: A lot of this data was ramp
7 test data, and so, you know, when I showed gas release
8 predictions, I showed steady state and ramp test. A
9 lot of that ramp test data came from Studsig. I
10 didn't show the predictions of strain, predicting and
11 measured. But a lot of that also comes from various
12 ramp tests, Studsig included.

13 MEMBER ARMIJO: I was going to ask a
14 question. When you found that the thermal
15 conductivity in the old codes that's non-conservative
16 at high burnups, and then you made, you adjusted your
17 codes and you wound up with much higher temperatures.

18 MR. GEELHOOD: Yes.

19 MEMBER ARMIJO: You know, what other parts
20 of the code were overly-conservative? You know, the
21 other -- because of the fission gas release is the
22 finger you're nailing all your analyses to. So if you
23 raise the fuel temperature to account for thermal
24 conductivity degradation, there must have been
25 something else that was predicting the fission gas

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 releases that was overly-conservative?

2 MR. GEELHOOD: Yes, like the four or five
3 tuning parameters in the gas release model had to be
4 changed.

5 MEMBER ARMIJO: Okay. What were they?

6 MR. GEELHOOD: Well like the multiplier on
7 the diffusion, the diffusivity.

8 CHAIRMAN BANERJEE: The pellets, I mean
9 the grain size?

10 MR. GEELHOOD: What the grain -- well, the
11 grain size we pretty much just -- it's pretty
12 standard.

13 MEMBER SHACK: That's a real parameter.

14 MEMBER ARMIJO: Yes. That you can
15 measure.

16 MR. GEELHOOD: That's something you can
17 measure. But then what the resolution rate is, how
18 much saturation on the grain boundary there could be.
19 And so, so we have these like parameters that have
20 been kind of empirically derived, and so you know, if
21 in the future we decided at really high burnup there's
22 even more, then we would have to go and somehow adjust
23 --

24 MEMBER ARMIJO: But it wasn't any one
25 particular parameter that was way out of line --

1 MR. GEELHOOD: I mean it's kind of a
2 balance between like all three or four of them, to get
3 them to like predict our, you know, fairly. Even
4 though it doesn't look like a lot of data, it comes
5 from a lot of different conditions. So to get one
6 model that predicts all that, you know, is kind of a
7 little bit of a balancing act.

8 MEMBER SHACK: It takes Von Carmen's three
9 point numbers.

10 MEMBER SCHULTZ: So you adjust everything
11 that you can, in order to get the best answer for all
12 the set.

13 MR. GEELHOOD: Luckily, we have more data
14 --

15 (Simultaneous speaking.)

16 MEMBER ARMIJO: Well sometimes you can't,
17 you can't -- you have data, and so those are fixed,
18 and then little by little, you get to the things that
19 are just guesses, and then those are the ones you mess
20 with.

21 MR. GEELHOOD: Yes. I mean a lot of these
22 like kind of more fundamental parameters, it's either
23 difficult or impossible to make a measurement, I mean
24 to do a diffusion experiment in reactors. It would be
25 an engineering, you know, feat to design that

1 experiment.

2 CONSULTANT WALLIS: You didn't say
3 anything about MOX.

4 MR. GEELHOOD: And I wasn't asked to say
5 much about MOX, but I could say more about MOX if you
6 had --

7 CHAIRMAN BANERJEE: I'm going to have to
8 interrupt this, because we're already --

9 MEMBER ARMIJO: Way too interesting.

10 CHAIRMAN BANERJEE: 45 minutes, actually
11 50 minutes behind schedule. So that means that of
12 course we'll have to reduce our lunch break. But
13 before we do that, we really do need to close the
14 session now.

15 So I think if we could just make sure that
16 everybody is, who should be here is here, and who
17 shouldn't be here is not here, and we will go into
18 closed transcripts now.

19 (Whereupon, at 11:19 a.m., the meeting
20 adjourned to closed session.)

21

22

23

24

25

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

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

(202) 234-4433

(202) 234-4433

1 they're being used very reload, and the hurdles that
2 are introduced because of 51.09.

3 MEMBER REMPE: So you're approving new
4 codes, and what if there's another issue that's not
5 defined yet, that crops up because of new data --

6 MR. CLIFFORD: We'll get there, we'll get
7 there.

8 MEMBER REMPE: Do you have a conditional
9 approval now or what?

10 MR. CLIFFORD: We'll get there.

11 MEMBER REMPE: Cool.

12 (Laughter.)

13 MEMBER REMPE: I didn't look ahead, okay.

14 MR. CLIFFORD: I'm glad we did.

15 Corrective actions. We should be scrutinizing any
16 future changes in fuel design or operating limits,
17 along with the supporting empirical data, to ensure a
18 high level of confidence in model predictions, and
19 this would be applicable to any future license burnup
20 limit extensions beyond 62, the introduction of pellet
21 additives or changes in the physile content of the
22 pellets.

23 I mean you could argue that a lesson
24 learned would be that we shouldn't have allowed 62
25 gigawatt-days when we did, if in fact we only had data

1 up to 40 at the time. Maybe that's a lesson learned.
2 But going forward, I think the best corrective action
3 would be to require periodic requalification of
4 analytical models, or to institute a sunset clause and
5 the staff's approval of future models.

6 MALE PARTICIPANT: What does OGC think of
7 that?

8 MEMBER ARMIJO: Paul, do you really mean
9 requalification or rejustification in a sense, without
10 -- I don't know what requalification means, but I
11 suspect it means a huge effort versus a defense of the
12 adequacy of the existing model, you know, like no new
13 phenomenon discovered in the last five years, that
14 sort of stuff, more qualitative arguments.

15 MR. CLIFFORD: It's all explained here.
16 This was our first attempt.

17 (Simultaneous speaking.)

18 MR. CLIFFORD: When we approved PRIME a
19 couple of years back, you know, we were in the midst
20 of identifying TCD, and we were recognizing that we
21 had these legacy codes, and something needed to be
22 done. So we introduced condition of approval in the
23 safety evaluation.

24 I mean you can read the whole thing, but
25 essentially every five years, GE will have to submit

1 a letter identifying any new data, and showing that
2 that data does not change the best estimate predicted
3 capabilities of their tools, nor does it change the
4 uncertainties they're assuming in their safety
5 analysis.

6 CONSULTANT WALLIS: Do you think this is
7 a template for future codes?

8 MR. CLIFFORD: I think this a template.
9 Right now, our strategy is that a very similar
10 condition would be put on all future approvals.
11 We're looking at a new version of RODEX for AREVA.
12 It's RODEX4, but applicable to recrystallized
13 cladding. The previous approval of RODEX -- this is
14 the type of condition we would put in that SE.

15 So this approach requires action on the
16 part of the industry to keep track of information, and
17 to continuously demonstrate to themselves that their
18 codes remain applicable. It also gives the staff a
19 vehicle to then open up that review.

20 When they submit this letter and it shows
21 up to say their biases and uncertainties have changed
22 because there's more data now, then that gives us a
23 vehicle for then opening up that review and demanding
24 action.

25 MEMBER CORRADINI: Paul, can I ask a

1 question? You're using the PRIME example, right, on
2 Slide 24?

3 MR. CLIFFORD: Yes, correct.

4 MEMBER CORRADINI: Okay. So has the staff
5 gone further to lay out a time line about their
6 review, so that you don't get in this bollix again,
7 that let's say there's new data that shows, because of
8 cladding or fuel, that some sort of condition requires
9 a reanalysis.

10 They now have a new model. They give it
11 to you and it's years before they get it, and then
12 they have, they're in a situation where there would be
13 -- the licensee is going to use something in that
14 process.

15 So this sounds good, but what's the time
16 line for the complete eventual issuance of the
17 licensee being blessed with a new technique? This is
18 only part of the puzzle.

19 MR. CLIFFORD: No, I agree. But this
20 solves half the problem.

21 MEMBER CORRADINI: Well, let me -- maybe,
22 because unless I see the full picture, I'm not sure
23 what problem it solves at all. I want to be a little
24 bit pretending to be, if I happen to be, let me pick
25 one. Dominion and Kewaunee, since that's now

1 officially irrelevant.

2 Why would I agree or not fight about all
3 this, unless I saw the end game making sense? That
4 is, you can't just think about the applicability or
5 the first part of the problem. You have to lay out
6 the time line of the whole problem.

7 Otherwise, you could just make a mess
8 later on from all of this. I guess this sounds like
9 a good step, but unless you lay out now that they,
10 every five years they look for some new evidence that
11 requires them to change the model, then staff has got
12 to, in some sense, also put a way out in their time
13 line for review, so that then the licensees can now
14 use the model, or I should say develop a process to
15 use the new model. You guys then have to approve
16 that.

17 MEMBER SCHULTZ: Mike, doesn't that
18 follow the last bullet? The vendor is going to be
19 identifying and dispositioning any bias on model
20 predictions, or any increase on uncertainty, and the
21 next step would be for the staff to review that letter
22 and get back to the vendor, as to what needs to happen
23 next.

24 MR. CLIFFORD: Yes. It's kind of
25 difficult to do that.

1 MEMBER CORRADINI: Well, but if I only see
2 a part of the solution here, I worry that the other
3 piece of the solution could be more complicated than
4 we first suspect, or we just speeded up one part of
5 this, but the rest of the process still takes 10 to 15
6 years.

7 So I guess what I'm curious about is how
8 this all lays out, given that there's so many moving
9 parts.

10 MR. CLIFFORD: You make a good point.
11 That's something we can think about. But it is
12 difficult, without having an idea of what the error or
13 what the impact is for future change or a future
14 problem, and how we would go about --

15 MEMBER CORRADINI: But now I'll just make
16 even a more provocative statement. It seems to me if
17 you want to do this to the license or to the vendors,
18 and the technology, something comes up in the
19 technology, then staff has got to come up with some
20 sort of review process that's a bit more expeditious,
21 not only for the --

22 Let's just take an example. There's some
23 sort of change or some sort of knowledge about a new
24 material or something that creates a difference, that
25 you've got to contend with. Now the next step would

1 be staff would then, depending upon the severity or
2 the degree of change, staff's going to have to come up
3 with a different review process, not views.

4 Otherwise, you're going to get in this
5 process the licensee is never going to adopt any of
6 this, because they just see this endless set of steps.
7 So we could just come back to where we are now. I
8 mean I can't remember which of the presenters it was,
9 Ben was trying to explain all this thing.

10 It muddles the mind on all the
11 possibilities, simply because it takes so long.

12 MEMBER SCHULTZ: Well, also what you're
13 pointing out Mike is that, and I look forward in the
14 slides, I don't see a solution to the problem that we
15 did describe, which was licensees aren't adopting, or
16 in a position to need to adopt, the new models as they
17 are approved by the staff.

18 MEMBER CORRADINI: Yes, and I betcha
19 that's a business decision. It's a time and business
20 decision.

21 MEMBER SCHULTZ: It is.

22 MR. CLIFFORD: And we've had dialogues
23 with the vendors, and we've talked openly about okay,
24 when you submit PAD5, we want you to submit a
25 retirement plan for PAD4, and put it right in the --

1 put it right in the topical report so we can approve
2 it.

3 MEMBER SCHULTZ: And the other codes
4 that they have.

5 MR. CLIFFORD: And the other codes.

6 MR. JACKSON: In terms of regulatory
7 response or regulatory action, if the five-year look
8 under this condition, under the PRIME SE should
9 uncover something large, I mean I think we would take
10 immediate action or more dramatic action, versus
11 something that's very minor, and we could deal with
12 that.

13 MEMBER ARMIJO: You know, that's what
14 worries me about this thing. If you found a large
15 effect like TCD, then I could see this as very
16 valuable. But you know, the amount of data we have
17 today as opposed to the data that was available when
18 these old codes were approved, it's a lot more and a
19 lot better.

20 So unless you find something really
21 significant, this process should be very simple and
22 straightforward.

23 (Simultaneous speaking.)

24 MEMBER CORRADINI: --to what I'm saying.
25 The staff, I think it's commendable the staff has come

1 up with a way to try to, you know, come up with the
2 time windows that the vendors have to report on stuff.
3 But on the other hand, there ought to be, instead of
4 using the term severity, I'll just use it as a change
5 in the prediction.

6 If the change in prediction is five
7 percent or pick some number, then the review process
8 and the recalibration for all parties, including the
9 licensee, ought to be fast. If it's ten percent of 15
10 or something that's really major, then you're going to
11 have to go through a serious review.

12 So it's not just the time, but it's also
13 the level of change that to have to deal with.

14 MEMBER SHACK: Yes, but I don't see that
15 this does anything. I mean this just tells them they
16 have to inform the staff. The staff then has to make
17 a decision as to whether some real severe regulatory
18 action is warranted, or that's very nice. We file
19 this letter and it's --

20 MEMBER CORRADINI: Okay. Well, that's
21 fine, but then it really --

22 MEMBER SHACK: At least you have the
23 information and it's been considered. I mean the
24 prime responsibility is always on these people for
25 safety, not the staff. It puts the responsibility

1 where it belongs, and gets them involved. I think
2 it's a great idea.

3 MEMBER ARMIJO: I guess I'd have a lawyer
4 look at this, because the word "may augment the
5 existing PRIME qualification," you know, I'd be more
6 concerned if its "may degrade or undermine." You can
7 always augment a qualification by new data, a little
8 more data.

9 But it seems like you really want to avoid
10 the problem we have right now, that TCD wasn't
11 implemented in a timely way, and we've known about
12 this for how many years, 10, 15 years?

13 MEMBER SHACK: Yes. The "which may"
14 should be "which may affect" existing PRIME
15 qualification.

16 MEMBER ARMIJO: Well, I wouldn't care. I
17 wouldn't care if we found things that showed that
18 PRIME was very conservative, and it was -- that's up
19 to them if they want to come back to you and say we'd
20 like to get some benefit. But I would care if they
21 found out that hey, this new data on fission gas
22 release is really something's changed, and it's
23 degrading our --

24 CHAIRMAN BANERJEE: But this is early
25 information though, right?

1 MEMBER ARMIJO: Well no.

2 (Simultaneous speaking.)

3 MEMBER ARMIJO: This is a big deal. It
4 depends how it's done.

5 CHAIRMAN BANERJEE: Imagine that you were
6 doing some work in any field. You'd be expected to
7 stay up on the development and what's going on.

8 MEMBER ARMIJO: Of course, of course.

9 CHAIRMAN BANERJEE: And then just an
10 informational letter. They're asking you to write a
11 letter to inform them of new sources of data, whatever
12 uncertainties arise with your model against this new
13 data, if there's any, and how you're going to deal
14 with it or what you plan to do. I mean this is not
15 taking any action whatsoever.

16 MEMBER ARMIJO: This could be like
17 perpetual requalification, even if there's no safety
18 impact.

19 CHAIRMAN BANERJEE: They say there is no
20 safety significance and the staff throws up, what does
21 it matter.

22 MEMBER ARMIJO: Okay.

23 CHAIRMAN BANERJEE: They don't have to do
24 anything with it.

25 MEMBER SHACK: The staff, then, sort of

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 has to decide when this done whether some action is
2 required. But I mean most of these, I suspect, will
3 end up --

4 CHAIRMAN BANERJEE: Like if we change one
5 correlation in a code or something, I mean we're not
6 going to ask for that code to be requalified.

7 MEMBER ARMIJO: That's what it says.

8 CHAIRMAN BANERJEE: No, it doesn't say
9 that.

10 MR. CLIFFORD: Well, they can't change any
11 correlations.

12 MEMBER SCHULTZ: They can't change the
13 correlations without approval of the staff.

14 MR. CLIFFORD: Right.

15 CHAIRMAN BANERJEE: Well, in general
16 imagine that you have a code called NOTRUMP or
17 something, which I know more about all this stuff.
18 You change DNB correlation or something in that, you
19 know, you have to qualify that. You give the database
20 to the staff. We do it all the time. Every time we
21 have a new fuel, we change the DNB correlation.
22 What's the big deal?

23 CONSULTANT WALLIS: It reminds of certain
24 GSI, where the new data comes in faster than any kind
25 of reaction --

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 CHAIRMAN BANERJEE: That's a completely
2 different --

3 MEMBER SHACK: But this is clearly
4 different. I mean this is not, you know, if they want
5 to propose a change in a correlation, that's one
6 thing. But in this one, we'd say when those new
7 Halden data come out, you have to go back and look and
8 see if in fact it changed your model --

9 MR. CLIFFORD: It won't affect your model.

10 MEMBER SHACK: It changed your model.

11 CHAIRMAN BANERJEE: Doesn't change it.

12 MEMBER SHACK: If it doesn't change it,
13 it's fine. If it somehow changes it, you have to
14 change and disposition that. I mean but I would
15 think, you know, it's very different from introducing
16 a new correlation.

17 CHAIRMAN BANERJEE: No. I misspoke about
18 the DNB, because you'd still show that the W-3 or
19 whatever it is works on your new data, that's all.

20 MEMBER ARMIJO: Well, augmented database
21 means a bigger database, and the database is always
22 going to get bigger. If it doesn't change the answer,
23 why are you going through this exercise?

24 (Simultaneous speaking.)

25 MEMBER SHACK: --to find out if it does

1 change the answer.

2 MEMBER ARMIJO: Well, you'll know pretty
3 well, pretty quickly when you take the data, you know.
4 The fission gas release numbers are consistent with
5 the original database. Why mess around? You'll have
6 the staff and everybody else churning perpetually,
7 depending upon how this is managed.

8 MEMBER SHACK: They'll just write the
9 letter saying that this is consistent with the
10 existing database.

11 CONSULTANT WALLIS: Well, there's a
12 problem --

13 MEMBER ARMIJO: That's what I would -- if
14 it was done that way, Bill, I wouldn't be so worried.
15 But I just, the way it reads, it sounds like it's
16 going to --

17 CONSULTANT WALLIS: Well, it discourages
18 investigation, because every time you discover
19 something new, you have to go through this.

20 MEMBER ARMIJO: That's part of the
21 negative, yes.

22 (Simultaneous speaking.)

23 MR. CLIFFORD: Every five years they have
24 to submit a letter.

25 CHAIRMAN BANERJEE: You assess your

1 database.

2 MEMBER SCHULTZ: So this is in place --
3 (Simultaneous speaking.)

4 MEMBER ARMIJO: They've cut a deal on
5 PRIME already.

6 MEMBER SCHULTZ: This is in place?

7 MR. CLIFFORD: For PRIME.

8 MEMBER SCHULTZ: And so did you have to
9 ask if this was going to be applied retroactively to
10 everyone, or to the other codes?

11 MR. CLIFFORD: No.

12 MEMBER SCHULTZ: They didn't ask that?

13 MR. CLIFFORD: We haven't made that
14 decision. We're going to --

15 (Simultaneous speaking.)

16 MR. JACKSON: This is just the type of
17 thing we're thinking about, you know, having been
18 through this experience with --

19 (Simultaneous speaking.)

20 MEMBER ARMIJO: You'd pretty much need to
21 do this with any new code, right?

22 MR. CLIFFORD: Oh, absolutely.

23 MEMBER ARMIJO: I mean it wouldn't be fair
24 to --

25 MR. CLIFFORD: It's our first attempt to

1 ensure that the industry is staying on top of the
2 data, and at least recognizing in a public letter that
3 their codes are becoming outdated.

4 MEMBER SHACK: Or not.

5 MR. CLIFFORD: Or not.

6 CHAIRMAN BANERJEE: We have made this
7 comment on the reactor physics codes.

8 MEMBER SCHULTZ: Well, I think this is
9 a good idea. I'm just concerned that the other part
10 of the problem needs to be addressed, and that is that
11 movement to new methodologies needs to happen.

12 MR. CLIFFORD: Right, and that gets us to
13 our next slide.

14 MEMBER REMPE: Before you leave this,
15 though, I guess I'm so curious about a point I think
16 Steve raised earlier, about how the licensees are
17 impacted by this. Just because the vendor says okay,
18 my code has to change, will there be -- I mean
19 earlier, you said that the licensee has it in their
20 tech specs.

21 Will they have PRIME approved in 2010, and
22 then can they continue using PRIME approved 2010 or
23 will PRIME need to be updated automatically, because
24 I caught the vendor.

25 MR. PARKS: Those tech spec COLA

1 references for GE plants only reference NEDE-24011,
2 which is GESTAR. So GESTAR is a motherhood document
3 that's updated on a regular basis. Amendments are
4 submitted to the staff for review.

5 One could conceive this SE condition in
6 such a way as if they write a negative report that
7 says their model's impacted, we would expect to see a
8 revision to adjust that in an upcoming GESTAR
9 revision, which we would then review.

10 But no licensee needs a licensing action
11 to adopt, because once the latest revision of GESTAR
12 is approved, licensees can use this.

13 MEMBER REMPE: Automatically, licensees
14 will update it.

15 MR. PARKS: So for this framework, it
16 works, right.

17 MEMBER REMPE: And what if they say "we
18 think it's still fine, it works fine," but you guys
19 say "no, we don't think it's fine."

20 MR. CLIFFORD: At least we had that
21 dialogue.

22 MEMBER REMPE: Okay.

23 MR. CLIFFORD: At least we had that
24 dialogue. Right now, we don't have that dialogue.

25 MR. JACKSON: So the regulatory process is

1 in place, you know. For Westinghouse, Part 21
2 applies. So if they find an error that's important to
3 safety, they're required to report it, and you know,
4 there's a couple of words in there important to safety
5 and error, and these are interpreted different ways.

6 The 5046 requirements apply to licensees,
7 and if it's an error that affects temperature, you
8 have annual reporting, you have reported if it exceeds
9 50 degrees. So that's, you know, that's the situation
10 we have now, and you know, we've addressed the TCD
11 issues through that way.

12 But what Paul's saying is we could do
13 better perhaps, and this would lower the threshold a
14 little bit on topical reports, for when we would get
15 the information. Obviously, whenever we get the
16 information, if we find a plant that's in non-
17 compliance or that there's a safety factor, we'd have
18 to take action.

19 This would just give us the information to
20 make that decision. The decisions would still be just
21 as difficult. So the situation we have now --

22 (Laughter.)

23 MR. JACKSON: This situation we have now
24 is there's plants that are, you know, that are taking
25 the RAC up, and this affects my PCT by 20 degrees.

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 Well, that doesn't merit regulatory action on my part,
2 to tell them to do something before 2016 or 2017.

3 But if it's 200 degrees or more, I might
4 take a more dramatic regulatory action. This is just
5 a way to get the information, so that we can get it
6 into our regulatory processes and start working them
7 through.

8 MEMBER SCHULTZ: I think this approach
9 is very valuable, and it will be even more valuable,
10 if like in this case, GE and it goes into the GE
11 licensing methodology and GESTAR, and all licensees
12 are going to be affected by or be using that
13 methodology, if GE does the analysis, all GE fuel
14 users.

15 MR. CLIFFORD: Right.

16 MEMBER SCHULTZ: So that's a good thing,
17 and if that can be done also for Westinghouse and
18 AREVA plants, that would be great. Because the
19 licensees will read this. Those that are using GE
20 fuel are going to be paying attention to this five
21 year report in 2015, and they'll be looking to see
22 whether it's going to change or not, and they'll be
23 involved in the decision to some degree, at least
24 they'll be aware of the decision.

25 MEMBER CORRADINI: So Steve, can I follow

1 that up? I mean so you've been on the other side of
2 this. So if they see this, are they going to then be
3 more apt to want to learn the new technology or be
4 part of it, so that they use it, or are they going to
5 be apt, from a business decision standpoint, to stand
6 back and watch everybody say "Okay, who's first, but
7 not me"?

8 MEMBER SCHULTZ: No. Everybody is going
9 to pretty much go through it together, and here, what
10 I see is that in 2015, all GE fuel users are going to
11 be very interested in this report, and be asking GE,
12 through the Owners Group most likely, so what happens
13 next, now that you've evaluated the new data and
14 discarded some, and they'll be following the NRC
15 reaction to that, and what happens next as to whether
16 there's going to be any model changes or not.

17 There's nothing in here that says model
18 change is what'll happen. It's more likely to be, as
19 Ken was mentioning with FRAPCON, where they got new
20 data, they put it into their model and put it on the
21 chart, looked really good, fit real fine, no changes
22 were required.

23 MEMBER CORRADINI: Okay, okay.

24 CHAIRMAN BANERJEE: What does
25 "demonstrate" mean here? "GNF must demonstrate." I

1 mean that's in the fourth line there. I mean that can
2 be a pretty broad term.

3 MR. CLIFFORD: Well, "demonstrate" would
4 mean if there's a new Halden rod, then they would have
5 to use PRIME to simulate the burnup profile in the
6 Halden reactor, compared against the measured data, as
7 an example.

8 MEMBER ARMIJO: Well, but you can apply it
9 to every new, every experiment that comes out, and it
10 may not change the story at all, you know. All the
11 fission gas release data that comes out, the database
12 is big already. You add more stuff, but you go
13 through another complete analysis.

14 I don't know what you're going to -- I
15 don't know where you're going with this Paul, but I
16 think it could turn into a nightmare, or maybe I'm
17 just reading it the wrong way. But I know what you're
18 trying to do, and I wish something like this had been
19 there when there was no data.

20 But now we've got a lot of data, fuel
21 swelling, cladding creep, fission -- we have tons of
22 data on that. TCD, we weren't so rich, but we are
23 now, and you know --

24 MR. JACKSON: When we imposed this license
25 condition, GNF was notified. I mean there was some

1 dialogue with GNF.

2 MEMBER ARMIJO: Well, that's their
3 problem. They signed up for it, you know. It's going
4 to work, you know, it will come back to the staff.

5 MEMBER SHACK: If Sam was still in charge,
6 it would have been a different story.

7 (Laughter.)

8 MEMBER ARMIJO: I wish Harold was here,
9 because like he says, he's an amateur lawyer. But I
10 would say the staff should be very careful too,
11 because if this comes back, you'll have every five
12 years mountains of stuff coming back for your review,
13 and it could be trivial stuff, and you will have to
14 set up some process that says "Hey, this is true, but
15 this is not nothing, worth doing this much work.
16 There's nothing new here." And then every five years,
17 there's not going to be a hell of a lot of new stuff
18 coming out.

19 MEMBER SHACK: Oh yes, there's no doubt.
20 You put a test rod in Halden and it takes you seven or
21 eight years to irradiate it.

22 MEMBER ARMIJO: You know, it's just --

23 MR. JACKSON: Well, we receive data on the
24 annual 50.46 reports, the large change 50.46 reports,
25 the Part 21 reports. We have a system that when the

1 reports come in, we can deal with them.

2 MEMBER ARMIJO: I can see a situation
3 where some Russian guy publishes some stuff from a
4 PWR, and he's got some unusually high fission gas
5 release data and everything else. New data, everybody
6 knows about it.

7 The Westinghouse guys and the AREVA guys
8 are going to be sweating blood, of how first either
9 say it's valid or it's not valid or justifying that,
10 and you know --

11 MALE PARTICIPANT: They have an
12 opportunity --

13 MEMBER SHACK: Well, they'd be doing that
14 anyway, Sam. If they see data that doesn't look
15 right, they're going to ask whether it's right or you
16 know --

17 MEMBER ARMIJO: Well obviously. But you
18 know, you have your own database.

19 MEMBER SHACK: I don't see anything wrong
20 with just having people look at the data.

21 MEMBER ARMIJO: It depends how you handle
22 it, how you manage it.

23 MR. CLIFFORD: The other option would be
24 essentially a sunset clause, and surprisingly
25 independent from us developing this PRIME SE

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 condition, the IAE had conducted a periodic review of
2 the NRC, and one of their recommendations was that we
3 should consider limiting the approval of codes to
4 specific periods of time.

5 MEMBER ARMIJO: I don't have a problem
6 with a sunset clause, but it's got to -- it can't be
7 every five years, you know. There is a time when all
8 codes may need to be.

9 MR. JACKSON: You know, what is it, every
10 ten years they perform a --

11 MR. CLIFFORD: Safety review. Periodic
12 safety review.

13 MR. JACKSON: What's the name they use?

14 MR. CLIFFORD: That's right.

15 MEMBER CORRADINI: That's for the plant.

16 MR. CLIFFORD: That's for the plant,
17 correct.

18 MEMBER SHACK: Right. The periodic safety
19 review is used around the world. They don't go to the
20 level of detail that would actually go in and look at
21 the data for the codes. They do look at that broadly,
22 though. Periodic safety review.

23 MR. CLIFFORD: So we've gotten at least
24 one recommendation from the IAE, that says we should
25 limit the duration of which codes are approved.

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 MEMBER SHACK: You know what that letter's
2 saying. This is a hell of a lot bigger club.

3 MR. CLIFFORD: Well yes, but --

4 (Laughter.)

5 MEMBER ARMIJO: This is a, you know, you
6 wouldn't do this every five years. You would put a
7 much longer sunset period, I would think.

8 CONSULTANT WALLIS: Twenty years?

9 MEMBER ARMIJO: Yes.

10 MR. JACKSON: Well, it's a good point.

11 MEMBER ARMIJO: In this case, you know, it
12 takes time to get enough data, unless there's
13 something really bad that happens, and something comes
14 out that's a new finding that you've got to deal with
15 right away. You know, with enough time, yes, you
16 should modernize all your codes.

17 CONSULTANT WALLIS: I think I see one good
18 thing out of this, is that, you know, if we have a new
19 generation of regulators. If we say every 20 years,
20 then the new people will wonder what's in the code and
21 why it's there. They're going to have to, they have
22 to look at it.

23 MEMBER ARMIJO: Okay, well --

24 MR. CLIFFORD: Okay. So that would be
25 another approach we would consider.

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 MEMBER SHACK: Or an additional approach.

2 MR. CLIFFORD: Or an additional approach.

3 This is the last slide, Conclusions. All the fuel
4 vendors recognize the need to address TCD in fuel
5 performance models and downstream safety analysis. I
6 guess in summary, the BWR fuel performance methods are
7 the effects of TCD.

8 GE and Westinghouse have fully implemented
9 corrections via new codes. AREVA has RODEX4 and
10 hopefully will be transitioning their fleet from
11 RODEX2A to RODEX4. The story is not as
12 straightforward in the PWR world, as we spent most of
13 the afternoon talking about.

14 With respect to fuel mechanical design
15 explicitly, and not downstream analysis, AREVA has
16 migrated or will be migrating to COPERNIC, or is
17 applying penalty factors, and Westinghouse is awaiting
18 new methods.

19 The last bullet is what we just talked
20 about. We are considering implementing safety
21 evaluation conditions, which would mandate periodic
22 requalification or notification with respect to the
23 future use of fuel performance models.

24 CHAIRMAN BANERJEE: Why are BWRs so much
25 more advanced than PWRs with regard to this? Is there

1 any reason?

2 MEMBER CORRADINI: Well, they're better,
3 right?

4 (Simultaneous speaking; laughter.)

5 MALE PARTICIPANT: They boil.

6 MEMBER CORRADINI: I was trying to help
7 Sam out.

8 CHAIRMAN BANERJEE: It seems a lot more
9 complex, but --

10 MEMBER ARMIJO: They boil, boiling water.

11 MEMBER SCHULTZ: Not in terms of fuel.

12 MR. CLIFFORD: I can't answer that. I
13 can't answer why certain vendors are ahead of other
14 vendors in addressing this issue.

15 MEMBER SCHULTZ: Just for clarity, Paul,
16 is AREVA migrating to COPENIC, or are they going --

17 MR. CLIFFORD: For their B&W plants,
18 they're migrating off of TACO3 to COPENIC. But their
19 longer-term strategy is to migrate to GALILEO, once
20 it's approved.

21 MEMBER CORRADINI: And now it's been
22 almost a whole two hours, so I don't remember. But is
23 GALILEO supposed to be both a B and a P friendly
24 approach?

25 MR. CLIFFORD: That's our understanding.

1 CHAIRMAN BANERJEE: And probably in HTGR
2 as well.

3 (Laughter.)

4 MEMBER ARMIJO: I suspect that we won't
5 see that for a long, long time.

6 MEMBER SHACK: Right after 50.46(c) is
7 finished.

8 MEMBER CORRADINI: Yes, but it's still B
9 so it's checked.

10 CHAIRMAN BANERJEE: But the more acute
11 problem is PAD5, which is there right now. PAD5 has
12 been submitted or --

13 MR. CLIFFORD: No.

14 CHAIRMAN BANERJEE: --or shortly will be
15 submitted?

16 MR. CLIFFORD: Shortly will be submitted,
17 which means it's already been developed in the final
18 documentation.

19 CHAIRMAN BANERJEE: Do you -- I saw
20 somewhere that you'd review hopefully and get it all,
21 if it's all fine, out by 2015?

22 MR. CLIFFORD: Correct.

23 CHAIRMAN BANERJEE: Right, and then what
24 happens is really the question? 2015, imagine PAD5 is
25 now approved. Will they have to go back and look at

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 any of these plants with PAD5?

2 MR. CLIFFORD: I think what you'll see is
3 with 50.46(c) looming, which is going to cause a lot
4 of plants to reanalyze LOCA, I think you'll see a
5 consolidation in the LOCA methods. I think when
6 plants are told they have to spend the money and redo
7 their LOCA, they're going to say okay, well I'm going
8 to get off this Appendix K. What's the latest and
9 greatest realistic model you have? Use PAD5, use the
10 latest and greatest.

11 If the vendors were smart, they wouldn't
12 offer all of these methods, because they've got to
13 maintain these codes. Would you prefer to have one
14 code or ten codes that do the same thing?

15 MEMBER CORRADINI: Paul, can I ask a
16 question about that? But we're still in the middle of
17 rulemaking for C, right?

18 MR. CLIFFORD: Yes, we are.

19 MEMBER CORRADINI: So will that even be
20 done in five years?

21 MR. CLIFFORD: The original schedule was
22 it would be done next year.

23 MEMBER CORRADINI: Okay. Well, that's not
24 what I was asking.

25 (Laughter.)

1 MR. CLIFFORD: Well, but there's been a
2 slight change in direction. So I really can't tell
3 you what the schedule is. Right now --

4 MEMBER ARMIJO: We're going to review that
5 pretty soon, right?

6 MR. CLIFFORD: Right. We're going to be
7 talking about it next week.

8 MEMBER CORRADINI: Okay. Well then never
9 mind. We'll wait until Sam brings it up in his
10 Subcommittee.

11 MR. JACKSON: In addition to the 50.46(c)
12 though, we've had several utilities commit to redoing
13 their analysis, reanalysis for their commitments under
14 50.46 letters in the 2015, '16 and '17 time frame.

15 MR. PARKS: Right. But it's important to
16 remember that regulatory commitments can change, per
17 the 50.59 regulations that apply.

18 MR. JACKSON: Oh yes.

19 MR. PARKS: So if they decide that their
20 conditions aren't satisfied or the climate isn't
21 amenable to them redoing an analysis, because the rule
22 hasn't been revised or because the methods haven't
23 been approved, they may push back that date.

24 MR. JACKSON: Right. My expectation is if
25 PAD5 is approved in 2015, they would use that

1 reanalysis they committed to in reporting this error.
2 But once again, that's just speculative, because they
3 can change commitments. 50.46(c) may exist, and who
4 knows what it will be?

5 MEMBER SHACK: Do you know whether PAD5 is
6 a major redo of PAD 4.0, or is it PAD 4.0 TCD with
7 some quality control?

8 MR. PARKS: That may be proprietary.

9 MEMBER SHACK: That may be proprietary.

10 MR. JACKSON: I mean we've had several
11 meetings with them, and I don't know, we're not --

12 (Simultaneous speaking.)

13 MR. JACKSON: We don't expect surprises,
14 I guess, is the way I would characterize it.

15 MEMBER SHACK: So there's the provisions
16 here that focus on TCD. Ben, in your presentation,
17 the issue of thermal conductivity degradation has
18 caused, of course, the additional reviews of the LOCA
19 methodology and results.

20 We talked in some detail, but not great
21 detail, about the ASTRUM methodology and its
22 application, and some surprises, I'd call them
23 surprises, that have come about with regard to the
24 plant analyses that you -- some of which -- that you
25 look at in detail, and it's causing you to look at

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 those that have been submitted in more detail.

2 Is there something else that ought to be
3 a follow-on with regard to the best estimate LOCA
4 methodologies that is being learned here, that we
5 haven't focused on completely?

6 MR. PARKS: I would say that when I
7 presented my conclusions, I included recommendations.
8 I wouldn't say that they're recommendations, so much
9 as areas I plan to investigate further and sort of my
10 thinking on the priorities, given the way my data is
11 aggregating or data are aggregated.

12 I guess having said that, to go too much
13 more into what we need to do with respect to the best
14 estimate methods, it depends on the method and whether
15 it's being revised or whether we expect to be in use
16 for a long time, and you know, we're not looking at a
17 static picture, because we are changing our review
18 practices for implementations of those methods, and
19 the vendors know that.

20 We've discussed how our reviews have
21 changed over the years with the different vendors. So
22 it's just a very fluid situation in some respects that
23 continues to change. It's hard to say, you know,
24 there's a specific recommendation here or a specific
25 finding at this point.

1 But the way we review the information that
2 we gather certainly always factors into how we conduct
3 ourselves going forward. I'm sorry it wasn't a simple
4 answer to the question, but it's very complicated.

5 MEMBER SHACK: It's not a simple question.
6 I didn't expect a simple answer.

7 MR. CLIFFORD: But we are in the midst of
8 reviewing the Westinghouse full spectrum LOCA topical
9 report, and we're dealing with some of these issues,
10 with sampling fuel rods and the effect of thermal
11 conductivity degradation, and also remember that
12 50.46(c) is going to put a kind of a spin on all these
13 calculations too, because instead of having a burnup-
14 independent acceptance criteria like 17 percent,
15 you're going to have an acceptance criteria that goes
16 from 17 or 18 percent down to six percent.

17 So they're going to have the sample rods,
18 because the acceptance criteria for which they're
19 demonstrating compliance to is changing. So all these
20 issues are going to be addressed as part of full
21 spectrum LOCA, and you guys will have the opportunity
22 to review that, right?

23 MEMBER ARMIJO: We're looking forward to
24 it.

25 MEMBER CORRADINI: But the question, I

1 guess Paul, I think what you're saying, I can see how
2 it consolidates. But in some sense, that a lot of
3 these things are happening together, and there's
4 inter-X, I'll use the term "system interactions."

5 So it seems that as the staff develops
6 some sort of thinking process as to what comes first,
7 what comes second, so that -- you don't do something,
8 then it's just redone because of another issue?

9 MEMBER SCHULTZ: Is the timing -- let me
10 ask it maybe little differently. Is the timing right
11 with regard to thermal conductivity degradation, so
12 you feel comfortable that that will be in its proper
13 place as you're going forward with these improvements
14 to the BE LOCA?

15 MEMBER CORRADINI: Yes, because if they're
16 linked, in some sense they've got to be phasing away,
17 that they all make sense. Because I agree with you.
18 50.46(b) or (c) whatever which one it is, it will
19 essentially force people to pull together and try to
20 improve their whole methodology for analysis.

21 MR. PARKS: I would say that given that
22 there is going to be some number of years before all
23 of these things come together, and so we've got a
24 rulemaking activity and a methodology revision, and a
25 bunch of commitments in 50.46 letters to reanalyze,

1 all of those things coming together in a couple of
2 years.

3 We know that it's going to be a while
4 before this thing is resolved fully. So in terms of
5 estimating the effects of errors in ECCS evaluation,
6 it's appropriate that they apply a lot of rigor and
7 they think very hard about how they estimate these
8 effects.

9 So I think that are we in the right place,
10 and is this coming together at the right time? With
11 respect to TCD and LOCA analyses, I think we're going
12 to be in the right place in a few years, and I think
13 that the various people who have reported the effects
14 of TCD are good to sit for a while.

15 And we're also being a little bit
16 indefinitely in our closure evaluations for these
17 things, that when we open TACs and review them, we say
18 "Should another report or error be, you know, brought
19 to our attention, we intend to revisit this
20 conclusion."

21 So we're kind of keeping track of what
22 happens in the future too.

23 MR. JACKSON: If I can add on, I mean
24 there's a lot of things going on. So we're reviewing
25 full spectrum LOCA, and because I think we understand

1 enough about TCD now to be able to --

2 MEMBER ARMIJO: Make sure it's done
3 correctly.

4 MR. JACKSON: Convince ourselves that
5 that's fully addressed. So you know, we have the
6 knowledge base to review that acceptably. Now we have
7 a new rulemaking that may or may not go into effect,
8 and what's in there is, you know, subject to change.
9 So you know, I think that we have enough knowledge
10 about TCD to implement the new rule, should it go into
11 effect or should it go into effect in a similar way.

12 So the rule is kind of a question mark.
13 It's not clear when it's going to come. You know, I
14 expect it to come and I think we know enough about TCD
15 to implement that. Now in this interim period, we're
16 evaluating the reports. We're moving forward. We've
17 addressed the high priority plants and we're moving on
18 to the next one. Since we've learned more, we go back
19 and revisit.

20 So in terms of looking forward, I think
21 we're in a good spot. We're closing out the issues
22 that we have in front of us as well, and --

23 MR. PARKS: Now Dr. Corradini, I think to
24 get back to your original question, I guess by virtue
25 of the fact that the various fuel vendors are making

1 the best decisions they can to phasing various methods
2 over certain points of time, and develop a unified
3 analytic framework that applies to many plants that
4 are only maintaining one code, that's one way to make
5 sure that it's all coming together at the right time
6 and right place.

7 And then the other thing is, you know,
8 with respect to these methods, it's a group of 20 NRC
9 staff and/or contractors, and we all work on the same
10 floor. So you know, we closely interact with one
11 another, and we track and talk about what we're doing,
12 so that we're not stovepiping ourselves.

13 We also reach out to our other colleagues
14 in Research and New Reactors, to make sure that we're,
15 you know, keeping track of what's going on there with
16 respect to the latest data that might be coming in, or
17 what's happening on the new reactor licensing front.

18 MEMBER CORRADINI: Okay, that helps.
19 Thank you.

20 CHAIRMAN BANERJEE: So you did your audit
21 at Westinghouse, the group of four or five people on
22 roughly what? Five calculations or five submittals
23 that went through?

24 MR. PARKS: I can say that there were five
25 submittals, but to go into too much more detail than

1 that, it's proprietary.

2 CHAIRMAN BANERJEE: We're in open
3 session, okay. I keep forgetting, we're not in closed
4 session. All right. But do you plan any more audits?
5 I mean there are some curious results.

6 MR. PARKS: Sure. I wouldn't exactly call
7 it an invitation, but for lack of a better word, the
8 invitation's been extended. In other words, we
9 wouldn't oppose if you need more information, that you
10 call us up and ask us questions, have an audit, do as
11 you need.

12 We've actually taken, in terms of 50.46
13 report reviews, when we get a whole bunch of reports
14 that come in and document the same change or the same
15 error, we're trying to make sure that we're getting to
16 the vendor as efficiently as possible, so that we
17 don't have to ask five licensees five questions, and
18 get five of the same answer.

19 So we don't have anything on the calendar
20 or planned or approved at this point, but the
21 possibility is always there. It's always considered,
22 and it's nothing we rule out.

23 MR. JACKSON: Right. So we're planning on
24 pursuing those issues that have been brought up, and
25 when we present those issues to the licensees and then

1 the vendors, we'll have to decide what the most
2 efficient way is. Many times, we choose an audit
3 because --

4 CHAIRMAN BANERJEE: More compact.

5 MR. JACKSON: It's more compact. Other
6 times you choose not to, because you'd like to see the
7 RAI responses formally responded to on the docket. So
8 typically, we take the combination of the two. But
9 we'll make that decision and whatever we base our
10 safety planning on will be on the docket at the end.
11 But it's certainly on the table.

12 CHAIRMAN BANERJEE: Okay. Well, are
13 there any other questions? Would you like to make
14 some closing remarks?

15 MR. JACKSON: I would.

16 CHAIRMAN BANERJEE: Then we just caucus
17 as a Subcommittee after that.

18 MR. JACKSON: Okay, thank you. First of
19 all, I'd like to thank the ACRS members, the
20 consultants and the staff. This has been a good
21 meeting. I appreciate all the support, particularly
22 before. In terms of proprietary information, that was
23 a challenge.

24 So I think it's a good meeting. I think
25 your insights and views are important to us as we

1 proceed forward. I want to congratulate Paul and Ben
2 and Ken for the good presentations. It's been a long
3 day, but they did a very good job.

4 I'd also like to thank the staff who
5 worked with Ben and Paul, and many of which are
6 sitting behind us right now, who have all contributed
7 to this. So I'm proud of their efforts as well. So
8 that's really all I wanted to say. Thank you.

9 CHAIRMAN BANERJEE: First of all, let me
10 thank all of you and particularly Paul and Ben. Very
11 interesting presentations, and your colleague from --

12 MR. CLIFFORD: Behind the pillar.

13 CHAIRMAN BANERJEE: Ken, thank you as
14 well. It was a great presentation. I enjoyed it very
15 much. We still have to decide as a Subcommittee what
16 we want to do, in terms of should we have a brief
17 presentation to the full Committee or how we feel.

18 What I'll do is I'll go around the
19 Subcommittee, and ask for any remarks, and you can
20 have some feedback at that time. Okay. So I think
21 with that, thanks very much. We look forward to
22 hearing more. This is a story which is ongoing, and
23 both on the fuel and on the safety analysis side.

24 MEMBER ARMIJO: Did I miss my opportunity
25 to make a comment?

1 CHAIRMAN BANERJEE: No, no, of course
2 not. We haven't actually --

3 MEMBER ARMIJO: Oh, we haven't started
4 that?

5 CHAIRMAN BANERJEE: --started that
6 process yet.

7 MEMBER ARMIJO: My mind was wandering.

8 Joint Subcommittee Discussion

9 CHAIRMAN BANERJEE: Let's start with
10 Graham and we'll get his comments, and then we'll move
11 --

12 CONSULTANT WALLIS: I'm not sure your
13 consultant should go first. FRAPCON, I liked the
14 presentation. It's a huge task, and you've got 15
15 phenomenon, 200 subroutines, all this stuff put
16 together. So there's no way we can review all the
17 details.

18 The overall picture is that you put
19 together an evolving and improving code and it works
20 with reasonable and probably adequate accuracies. So
21 that's about all I need to say. I think it's very
22 good that the NRC does this, because in some other
23 areas, we tend sometimes to see the NRC having no way
24 to fall back on a confirmatory analysis by its own
25 people, or its own people who really understand the

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 phenomena so they can really understand what is being
2 submitted.

3 This is an area where I think you really
4 are ahead of the game. That's great. TCD, there's
5 clearly a transition period between the old codes and
6 new codes. The most satisfactory thing would be to
7 bring in the new codes that fully account for the
8 farm.

9 So I sympathize with your struggles. I'm
10 not sure I can advise you what to do, except keep on
11 working through the woods until you come out the other
12 side. I know it's not always easy. On the issue of
13 how new information gets incorporated into codes, this
14 is something that many of us have thought about for
15 years.

16 I think it's a big issue, and I don't want
17 to wade into it myself. But I think it's an area
18 where your discussions with the ACRS in the future
19 could be very useful. It's one of the functions of
20 the ACRS, to sort of help in these sort of major
21 decisions about how do you handle this issue, which is
22 going across the board. So I think that ACRS should
23 be able to help you in that area.

24 CHAIRMAN BANERJEE: Thanks, Graham.
25 Steve.

1 MEMBER SCHULTZ: A couple of general
2 comments. One, on the technical side, just to
3 reemphasize. I think we have identified, as a result
4 of the thermal conductivity degradation investigation,
5 that in terms of the application to analysis and all
6 the 50.46 related reports that have come in, that it
7 does raise some additional questions associated with
8 the methodology.

9 It could raise them, and so that
10 investigation that you had indicated, Ben, that you're
11 going to continue, and I'm using you. Hopefully in
12 the context of you plus other staff, that in fact that
13 is carried through to a full conclusion, that you keep
14 investigating it until you understand what's driving
15 the changes, and you know the staff understands it as
16 well as the vendors, that they understand how these
17 differences are coming to affect the result.

18 In that regard, in terms of the staff
19 contributing to this, on occasions like this, thermal
20 conductivity degradation, you mentioned the numbers of
21 staff. I'm not going to get into resources, but these
22 issues come to be every once in a while, and this is
23 an important one, and the investigation, as we've seen
24 over the last few years, is very intricate and
25 detailed, and involves lots of different issues.

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 It's a real opportunity for knowledge
2 development, and for training and learning for a new
3 generation into the business, as it were, and Graham
4 mentioned this previously, and I hope the staff is
5 gaining fully from this opportunity to investigate a
6 problem. A problem of this type doesn't come up very
7 often, and to be involved in its investigation and
8 solution is very important.

9 So I'd encourage management of the staff
10 to be sure that the work gets spread around, so that
11 knowledge management and learning goes hand in hand,
12 as well as resolving the problem. And I, with Graham,
13 I certainly hope that this is an opportunity.

14 I was glad to see that, in moving forward,
15 you're looking at ways in which to incorporate
16 learning within the industry, and applications where
17 new data will be examined thoroughly by vendors and
18 licensees and the NRC on a periodic basis, not just
19 National Labs and others. So that'll be the
20 development integrated into the regulatory process.

21 CHAIRMAN BANERJEE: Thank you, Steve.
22 Mike?

23 MEMBER SCHULTZ: I'm sorry. In terms of
24 full Committee --

25 CHAIRMAN BANERJEE: Yes.

1 MEMBER SCHULTZ: I think it would be
2 good to have a short summary for the full Committee at
3 this point in time. I think it's been three-quarters
4 of year.

5 CHAIRMAN BANERJEE: The last, yes, the
6 last EPU, St. Lucie 2.

7 MEMBER SCHULTZ: It came up in the
8 context of that. A lot of good work has been done.
9 It's not, we can present it not as a closure
10 discussion, but certainly an hour presentation as an
11 update would be appropriate.

12 CHAIRMAN BANERJEE: Okay. Mike, I wanted
13 to give you a chance before everybody else.

14 MEMBER CORRADINI: You do? Thank you. I
15 guess I wanted to thank the staff. I think this is a
16 nice summary. Sanjoy had told us that the whole point
17 of today's Subcommittee meeting was really to try to
18 get at least the Thermohydraulics Subcommittee and
19 interested other members up to speed as to where all
20 things sit, and how they fit together. So I think the
21 staff did a very nice job in putting that together for
22 us.

23 In terms of what to present to the full
24 Committee, I would agree with Steve's last comment.
25 I think it's important that we have some sort of

1 informational briefing. I think the initial set of
2 slides that Paul put together would be the source of
3 that.

4 I think details about FRAPCON and details
5 about how this is all sorting out relative to your
6 analysis and the staff's analysis are interesting, but
7 they might take us away from kind of the big picture,
8 and I think that's important that the full Committee
9 gets an idea of the big picture.

10 I guess my only other comment was that I'm
11 still struggling with how this forest of things comes
12 together and how the licensees adopt, as appropriate,
13 these new techniques. That's why I was asking Paul at
14 the end about the five-year notification as a good
15 start.

16 But I'm still struggling with how
17 eventually the licensees are going to be able to, with
18 some obviously expeditious time table, adopt
19 appropriate new methodologies, because they're going
20 to be looking for higher, they're going to be looking
21 for new fuel types or new cladding types, and all this
22 kind of rolls together.

23 So I think that's a good start. I just
24 would ask the staff to kind of think about that, and
25 how it fits together in terms of levels of importance

1 and timing. Other than that, Sanjoy, did you want
2 anything else from us?

3 CHAIRMAN BANERJEE: No. I think from
4 you, that's fine. Thanks, Mike. I'm going to give
5 Sam a chance to speak.

6 MEMBER ARMIJO: Thank you. Thank you, Mr.
7 Chairman. First of all, I'd like to thank the staff.
8 This was, the presentations were very well prepared,
9 and they addressed the things I really wanted to
10 learn. They put everything in perspective, because
11 we've been looking at TCD effects under EPUs one at a
12 time, and we didn't know where everything was coming
13 together, whether the problems had been resolved,
14 where problems remained, and how big these problems
15 are.

16 I think you did a very good job of that.
17 I really like your charts, Paul, on the code by code,
18 of where it stands and what needs to be done to make
19 those work. I think these are the sorts of things
20 you'd want to present in a full Committee briefing for
21 information.

22 I think some stuff on FRAPCON, showing
23 that it's really in pretty good shape. Because
24 without it, I'd really be nervous that we could rely
25 on these numerous codes to tell us what is really

1 going on. So I think a little bit of that would be
2 worthwhile in a full Committee briefing.

3 I'm still trying to understand myself why
4 TCD is turning out to be such a big deal in the ECTS
5 BWRs. I don't know whether it's physics, I don't know
6 whether it's statistics methodology or what. I'll
7 have to talk to my colleagues on that, and see if they
8 can help me out.

9 If I looked at your Chart 4, that chart of
10 thermal conductivity as a function of temperature, I
11 just conclude that we're running too much of our cores
12 at low temperatures, and if we just heated them up, we
13 would get rid of this problem.

14 But I'm not kidding too either, because it
15 seems -- well, you know, all the stored energy that's
16 going to be giving us more problems as a result of
17 this stuff is coming from low temperature fuel, and
18 you know, a lot of things I've seen, as people are
19 getting more and more conservative, putting more fuel
20 in, particularly the EPU guys operating at lower and
21 lower temperatures, and they may just be building up
22 a bigger problem for themselves from a certain
23 standpoint.

24 But that's just something for you to think
25 about. Overall, I was really happy. I learned a lot

1 and I appreciate the effort the staff put into
2 preparing this material.

3 MEMBER SHACK: I haven't got much to add.
4 You know, it was a very good presentation. I think it
5 really -- it's been a long time since we talked about
6 this, and I think the overall view is much improved
7 while we're looking at this EPU by EPU.

8 I really do like the idea of the license
9 condition or the conditions that you put on the SE,
10 that they come back and they review this. I think
11 that's a good idea, and it should be pursued, you
12 know, with other kinds of modeling efforts. I think
13 it's a plus.

14 I agree. I think the Committee, the full
15 Committee would like to hear about this. Sort of
16 basically a pared-down version of Paul's presentation,
17 I think, is probably all we could possibly get in.

18 CHAIRMAN BANERJEE: Joy?

19 MEMBER REMPE: I guess again, to be
20 repetitive, I really appreciated the education you
21 provided today and the summary. With respect to the
22 EPUs, I think that if you hadn't had FRAPCON to come
23 in and try and explain all the different factors that
24 the various vendors and licensees were trying to
25 explain to us, we wouldn't have had much confidence.

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS
1323 RHODE ISLAND AVE., N.W.
WASHINGTON, D.C. 20005-3701

1 So I guess that's where I'd like to make
2 a plea to the NRC, that they continue allocating bucks
3 to review additional data that comes from Halden, and
4 incorporate it and keep FRAPCON up to date, and
5 monitor it, not just rely on the licensee to notify
6 you of new data that's coming out.

7 Again, I kept emphasizing those
8 uncertainties, and I would like to make sure we have
9 lots of confidence in what we're doing here. So
10 that's one thing. An off the wall comment is what
11 about severe accidents in MELCOR? Are you going to
12 put thermal conductivity degradation into MELCOR? Is
13 there a need to?

14 MEMBER CORRADINI: Do you want five
15 degrees or 500 degrees?

16 MEMBER REMPE: Well, at some point, it
17 seems like it might be important to think about it.

18 MEMBER SHACK: They get to such high
19 temperatures that the problem is solved.

20 (Simultaneous speaking.)

21 MEMBER REMPE: I don't know, but it's just
22 something I was wondering about, and then again, I
23 agree with my colleagues about, that we really should
24 have this brought to the full Committee, not only
25 because of the work that's being done, about the

1 proposal to have the recertification, because it's
2 something that ought to be in evaluation every five
3 years. But maybe that's a lesson that should be
4 expanded to other areas.

5 CHAIRMAN BANERJEE: Great. Thanks, Joy.
6 So I think you've got fairly clear feedback from the
7 Subcommittee, that we do want to have maybe an hour's
8 presentation to the full Committee.

9 MEMBER SHACK: Give them more than that.
10 I mean an hour is --

11 CHAIRMAN BANERJEE: Okay. I think we'll
12 work with P&P and give you a little bit more. I agree
13 with Bill, because I was just going to say that like
14 Sam, I personally, and I think it would be great to
15 have, would like to see at least a brief presentation
16 on FRAPCON, because I feel that that's been very
17 helpful in finding our way through the EPU's that we
18 have to do.

19 So it would be worthwhile, not going
20 through all the details and so on, but at least
21 establishing that FRAPCON is a well-validated code,
22 which takes into account these TCD effects, and
23 reassuring the Committee that in the future, whatever
24 the vendors put up, if you have something which is in
25 the nature of confirmatory calculations, that we can

1 rely on FRAPCON giving an assessment of these TCD
2 effects. So I think that would be valuable itself to
3 present.

4 And also, of course, we would like to see
5 Sam and others have pointed out, an overview like Paul
6 did of the codes and what their status is and what's
7 under development, keep it, you know, relatively
8 short. But at least it gives you a bird's eye view of
9 the situation.

10 MR. CLIFFORD: Is one of our ground rules
11 that it's open?

12 CHAIRMAN BANERJEE: We can close it.
13 That's not a problem.

14 MR. CLIFFORD: I mean FRAPCONs are open.
15 My presentation was, most of it was open. But the
16 table by table stuff was closed.

17 MEMBER ARMIJO: Yes.

18 CHAIRMAN BANERJEE: Sam, I mean what's
19 your sense of that? We can always close the full
20 Committee meeting, but you're the boss of the full
21 Committee meeting.

22 MEMBER SHACK: We dislike closing full
23 Committee meetings if we can avoid it.

24 CHAIRMAN BANERJEE: We have often.

25 MEMBER SHACK: We have, and you know,

1 certainly, you know, we need --

2 MEMBER ARMIJO: And it's these tables that
3 are the ones that --

4 CHAIRMAN BANERJEE: Well, you know, I
5 think also some of Ben's conclusions need to be
6 presented, because there's some curious effects there.
7 So that we would need to close it for anyway.

8 MEMBER ARMIJO: We should because, you
9 know, there are some problem areas, and you ought to
10 be able to speak frankly to the Committee on the
11 problem areas, and if we don't close it, you may have
12 to be so diplomatic that they mistake medicine for
13 candy.

14 (Simultaneous speaking.)

15 CHAIRMAN BANERJEE: I mean we have closed
16 it.

17 MEMBER SHACK: Parts of it could be.

18 MEMBER ARMIJO: And then you might a part
19 of it that's open.

20 CHAIRMAN BANERJEE: May I suggest, then,
21 that we perhaps have about half of the briefing open,
22 and half of it closed. We'll try to arrange it in our
23 unusual fashion, so that it's not too disruptive, and
24 we've done it often before.

25 I think in the closed part, it would be

1 useful to have some of this proprietary information,
2 and also I think present at least an overview of the
3 issues that you see occurring with regard to the
4 safety, downstream safety analysis, primarily if it's
5 LOCA-focused. I think that's what we'd like to see.

6 That's probably the area that has caused
7 us some concern with the EPU's. So it would be worth
8 just revisiting that, and giving us an overview of the
9 status. So this is essentially a status. We're not
10 looking for any sort of decisional process at all,
11 just information.

12 MR. JACKSON: Okay. We can support that.

13 CHAIRMAN BANERJEE: Yes. So the staff
14 will get in touch with you, because we have to
15 schedule it and see what needs to be done, okay. So
16 I'd just like to close by thanking all of you all over
17 again, and look forward to seeing you again at the
18 full Committee.

19 MR. JACKSON: Thank you.

20 CHAIRMAN BANERJEE: Okay. Oh. I keep
21 forgetting my duties. I've been chairman for too
22 long.

23 (Whereupon, at 4:11 p.m., the meeting was
24 adjourned.)

25

Calibration and Validation of NRC Fuel Performance Models

FRAPCON-3.4

Ken Geelhood

Pacific Northwest National Laboratory

February 20, 2013

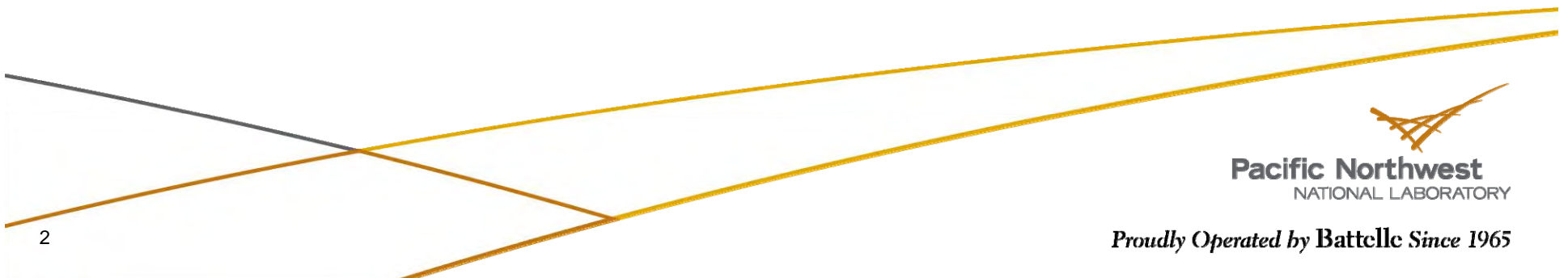


Pacific Northwest
NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

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

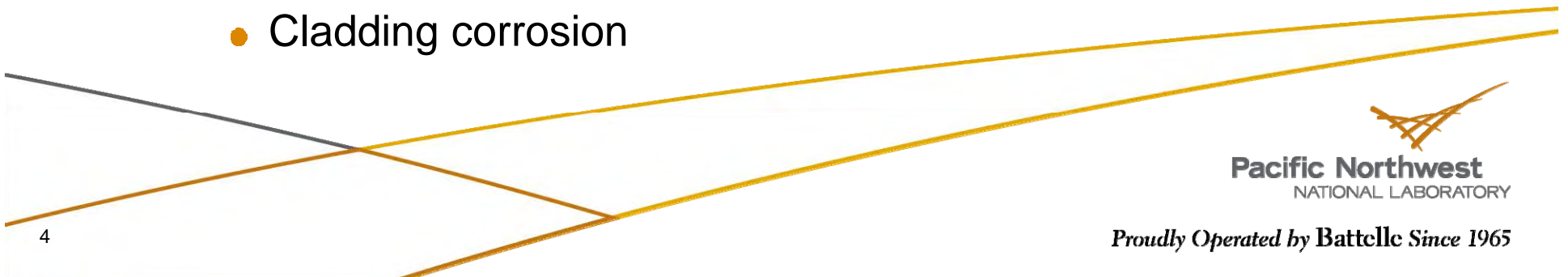
- Thermal conductivity
- Heat capacity
- Thermal expansion
- Mechanical properties

■ Behavior models

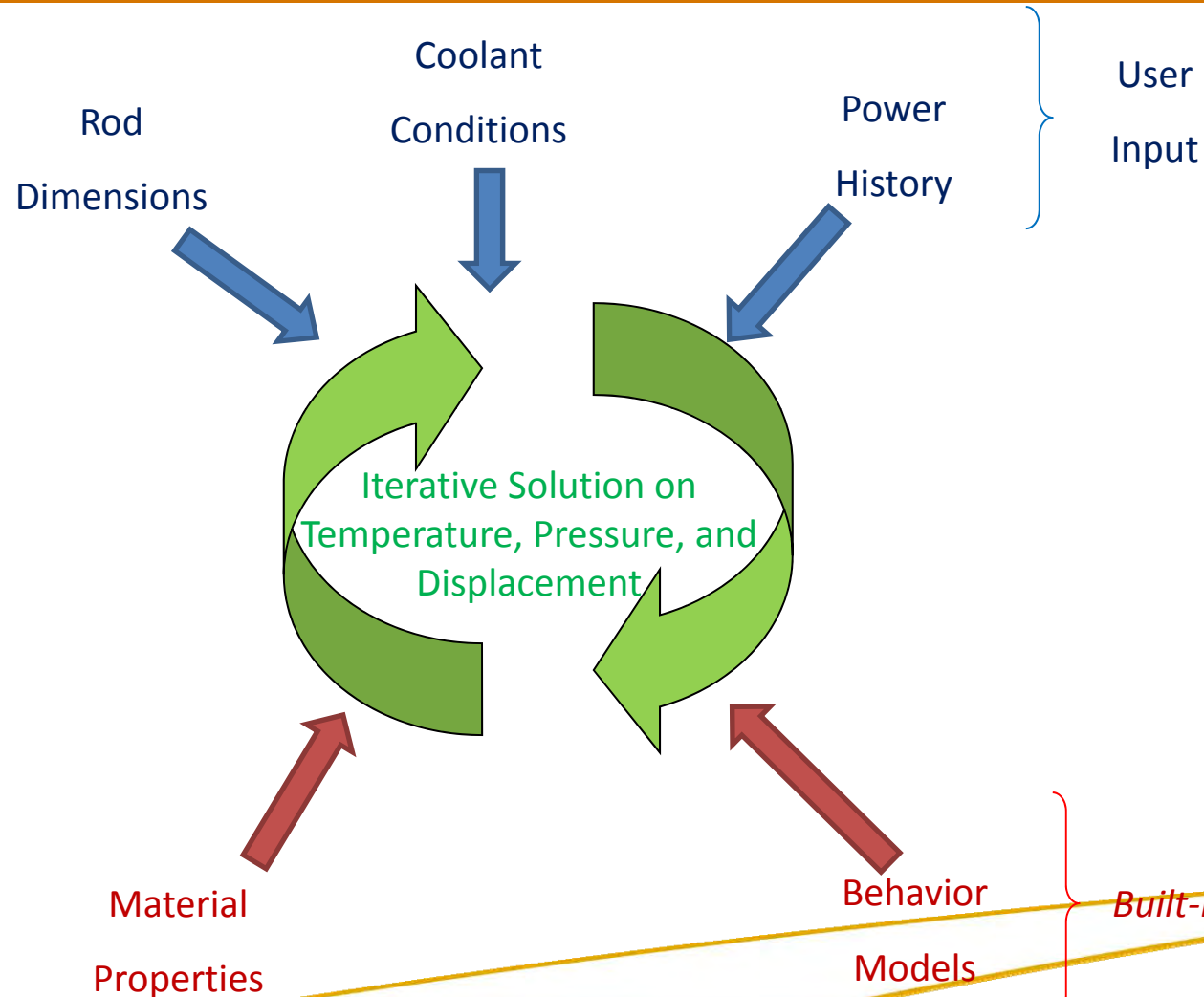
- Cladding creep
- Fuel pellet densification and swelling
- Fuel relocation
- Fission gas release
- Cladding corrosion

▶ Integral effects data

- Centerline temperature
- Fission gas release
- Void volume
- Cladding corrosion
- Cladding hoop strain



Nature of FRAPCON-3.4 and FRAPTRAN 1.4



Pacific Northwest
NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

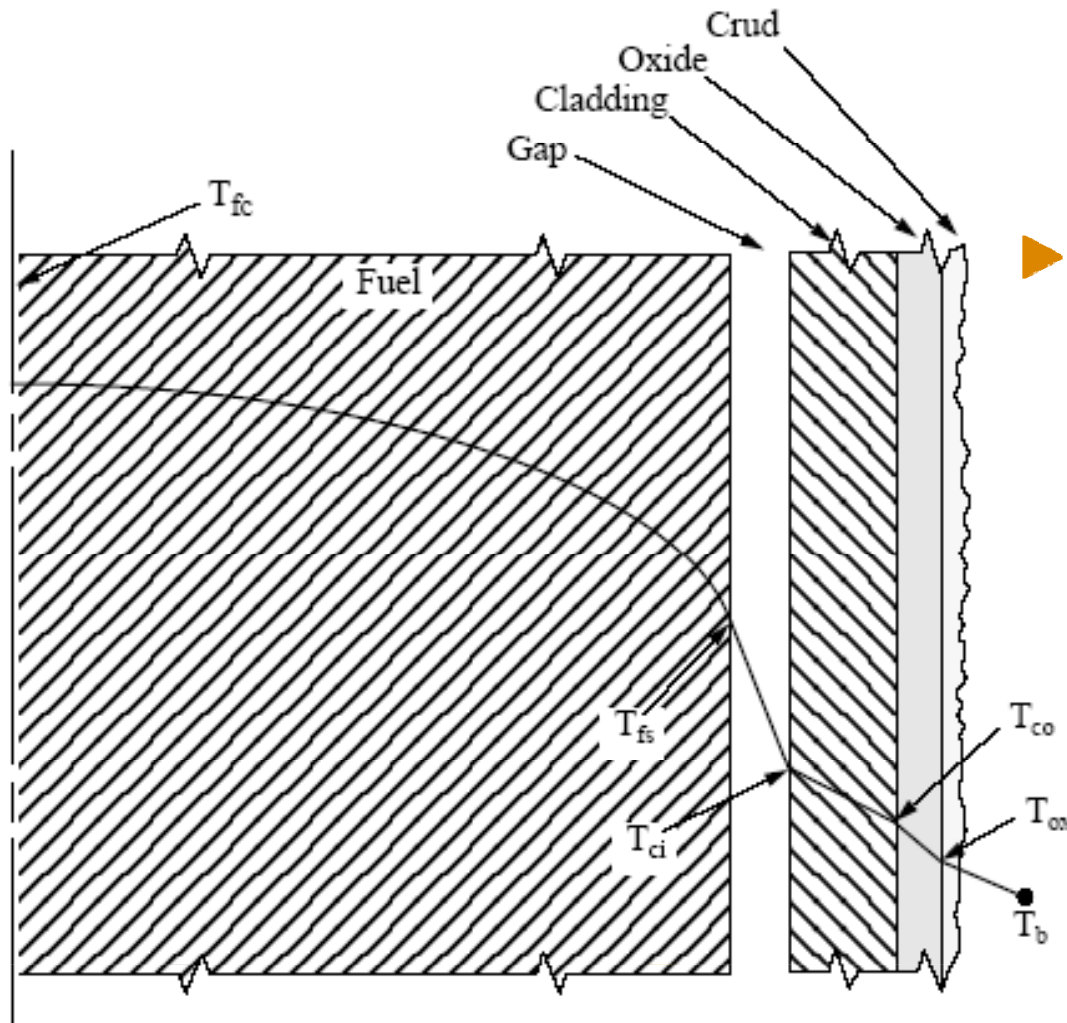
Main Solution



- ▶ 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

$$T_w(z) = T_b(z) + \Delta T_f(z) + \Delta T_{cr}(z) + \Delta T_{ox}(z) \quad \text{forced convection}$$

-or-

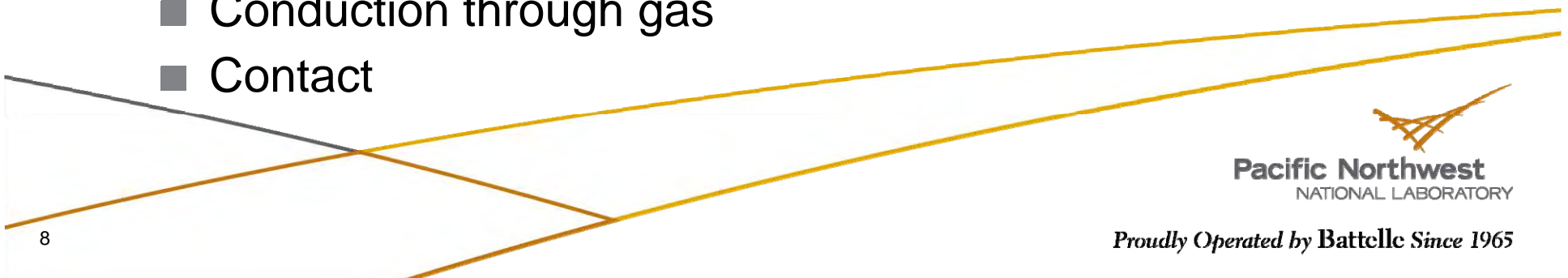
$$T_w(z) = T_{sat} + \Delta T_{JL} + \Delta T_{ox}(z) \quad \text{nucleate boiling}$$

- ▶ 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

$$\iint_S k(T, \bar{x}) \vec{\nabla} T(\bar{x}) \cdot \vec{n} ds = \iiint_V S(\bar{x}) dV$$

- The terms of this equation are approximated for each radial node

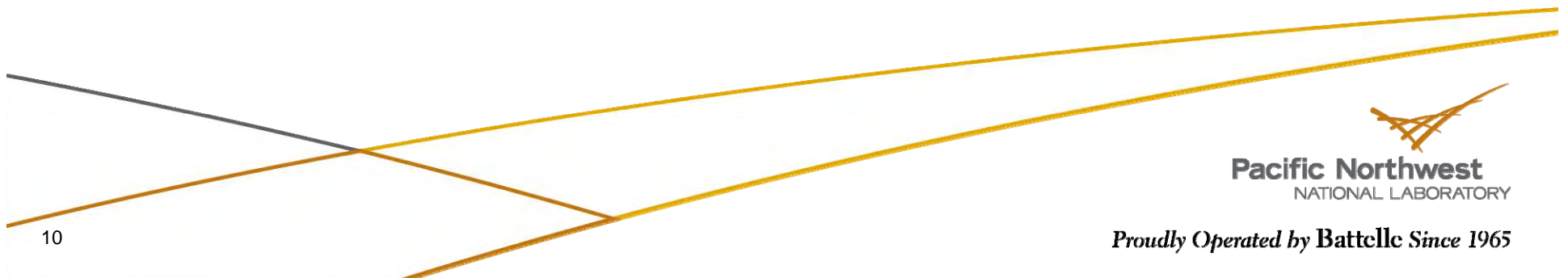
$$\iint_S k(T, \bar{x}) \vec{\nabla} T(\bar{x}) \cdot \vec{n} ds \approx (T_m - T_{m-1}) k_{lm} \delta_{lm}^s + (T_m - T_{m+1}) k_{rm} \delta_{rm}^s$$

$$\iiint_V S(\bar{x}, t) dV \approx P_f P (Q_{lm} \delta_{lm}^v + Q_{rm} \delta_{rm}^v)$$

- Solution solved using matrix algebra to solve the equations for each node simultaneously

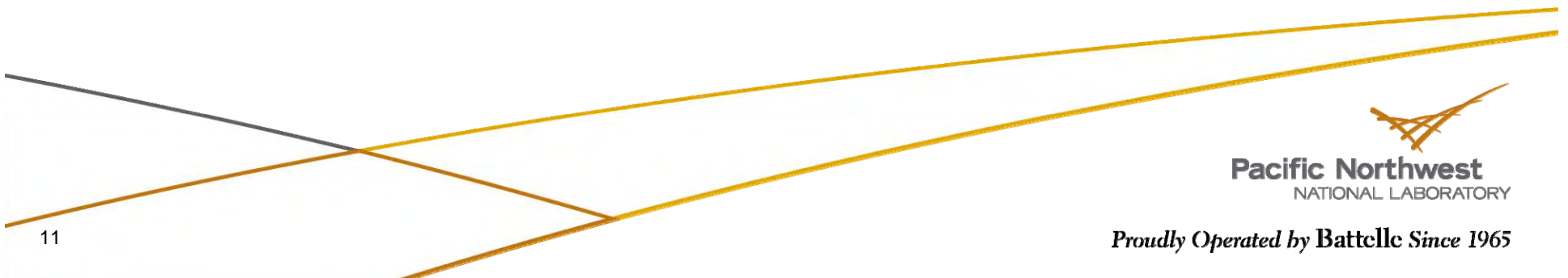
Material Properties Models

- ▶ Semi-empirical
- ▶ 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



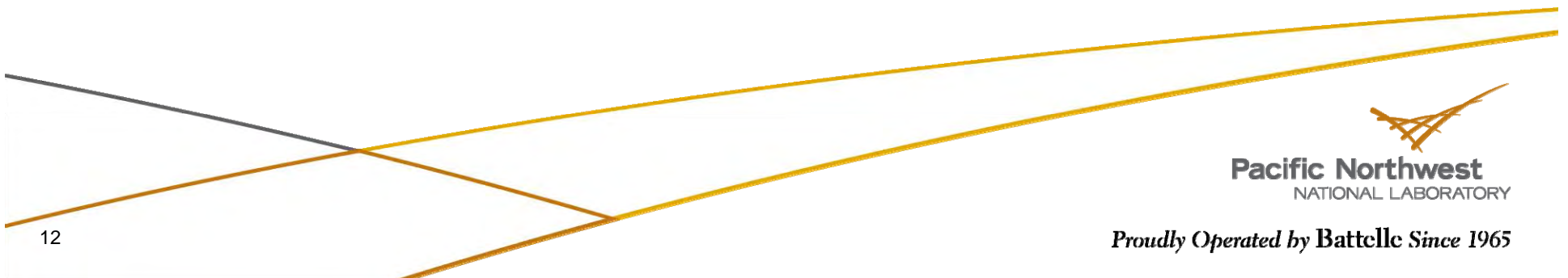
Behavior Models

- ▶ Semi-emperical
- ▶ Mathematical form of each model based accepted mechanisms that control behavior of interest
- ▶ Fitting parameters based on fit to data



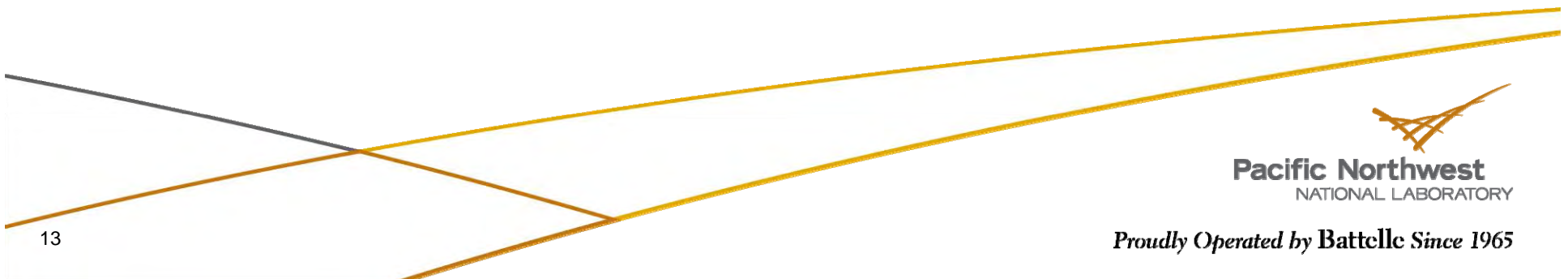
Calibration Parameters

- ▶ All parameters are in material property models or behavior models based on fits to separate effect data
- ▶ No further tuning parameters have been added



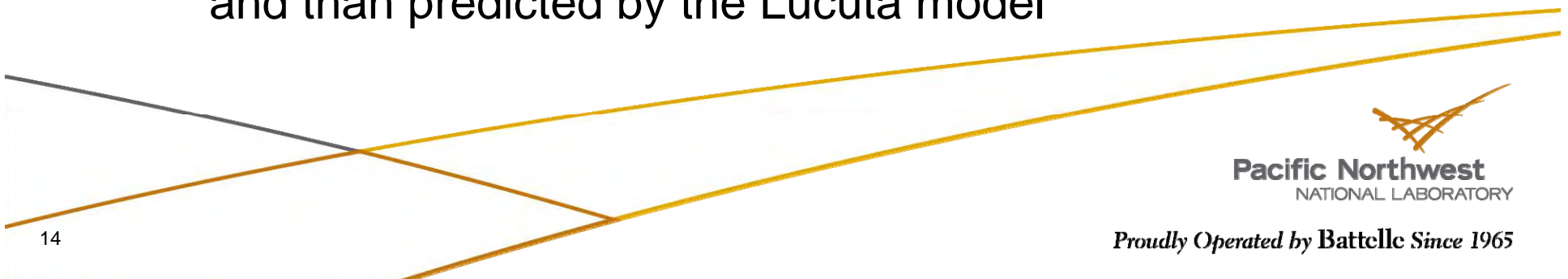
Impact of Calibration Parameters

- ▶ 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

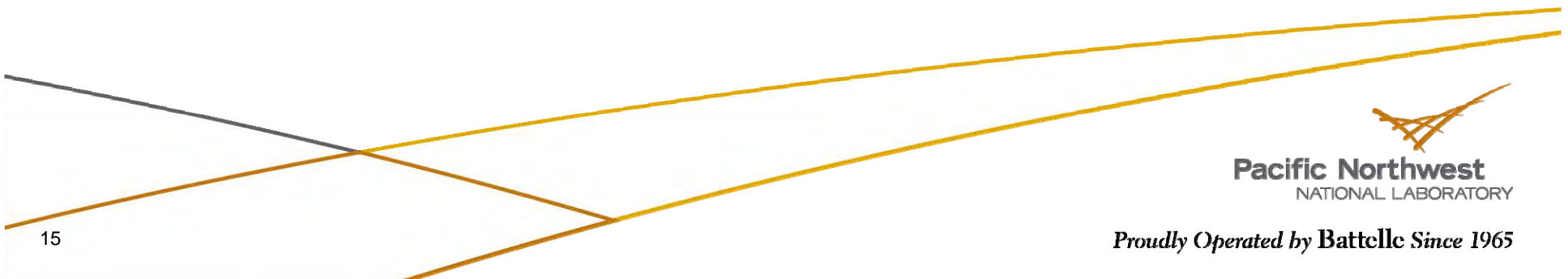


Evolution of Fuel Thermal Conductivity Modeling

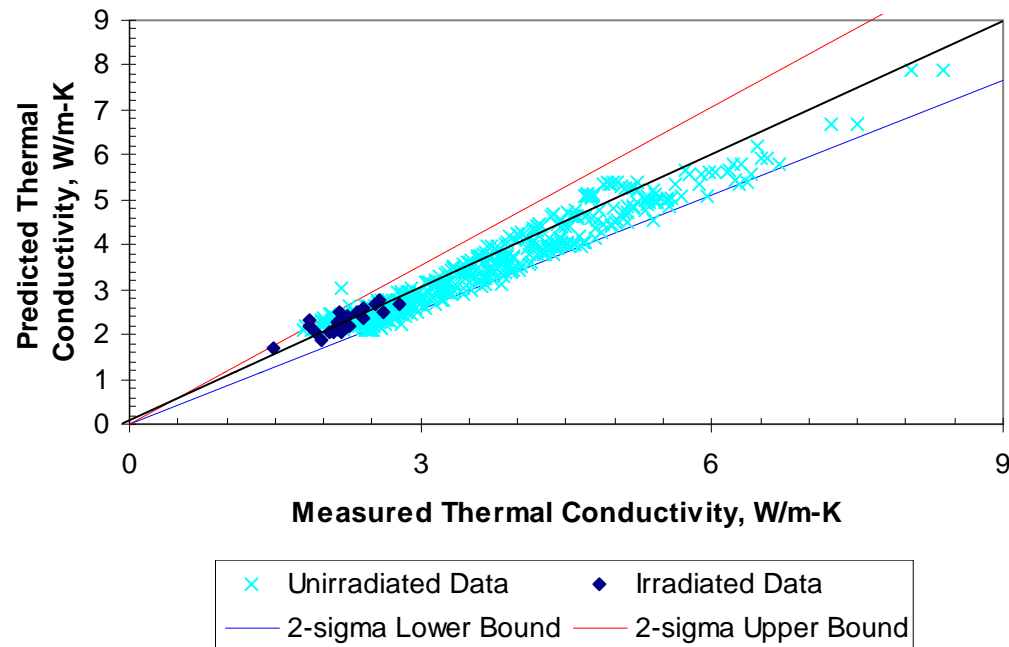
- ▶ 2003: PNNL releases FRAPCON-3.2 that includes the current thermal conductivity model that matches irradiated data
- ▶ Current model:

$$K_{95} = \underbrace{\frac{1}{A + a \cdot gad + BT + f(Bu) + (1 - 0.9 \exp(-0.04Bu))g(Bu)h(T)}}_{\text{Phonon Term}} + \underbrace{\frac{E}{T^2} \exp\left(-\frac{F}{T}\right)}_{\text{Electronic Term}}$$

- Phonon term dominant below 2000K
 - Contains effect of temperature, burnup, and Gd_2O_3
- Electronic term dominant above 2000K
 - Contains effect of temperature only

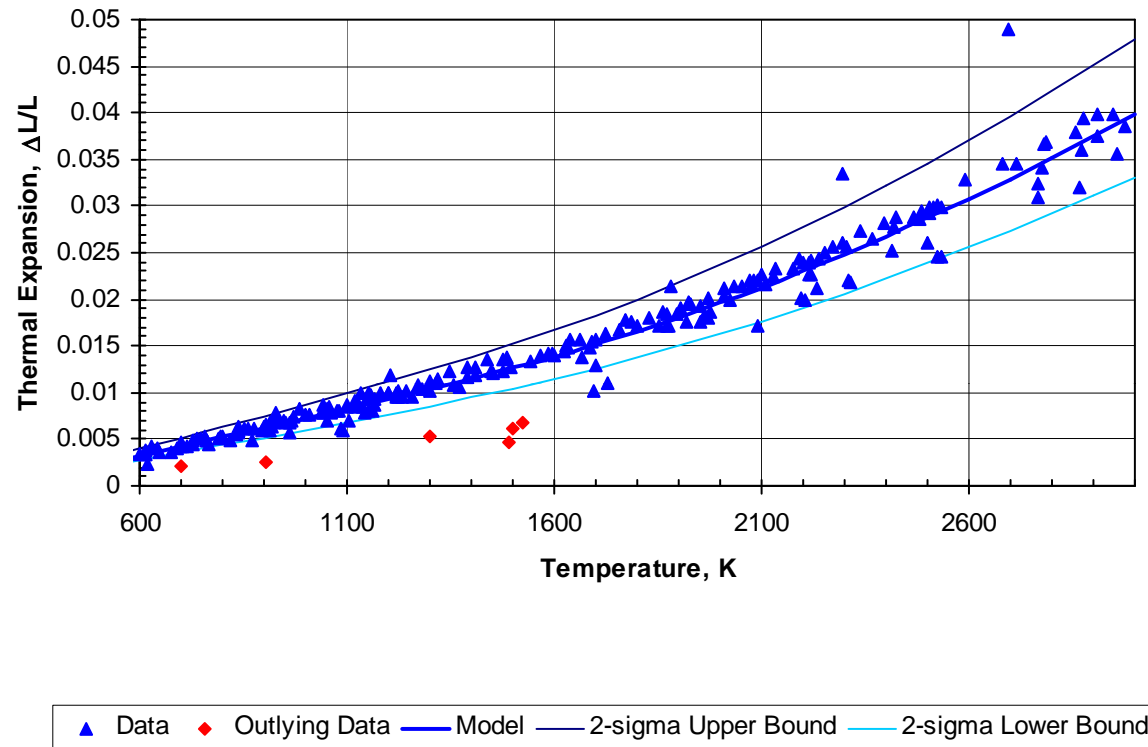


Model Validation: Fuel Thermal Conductivity



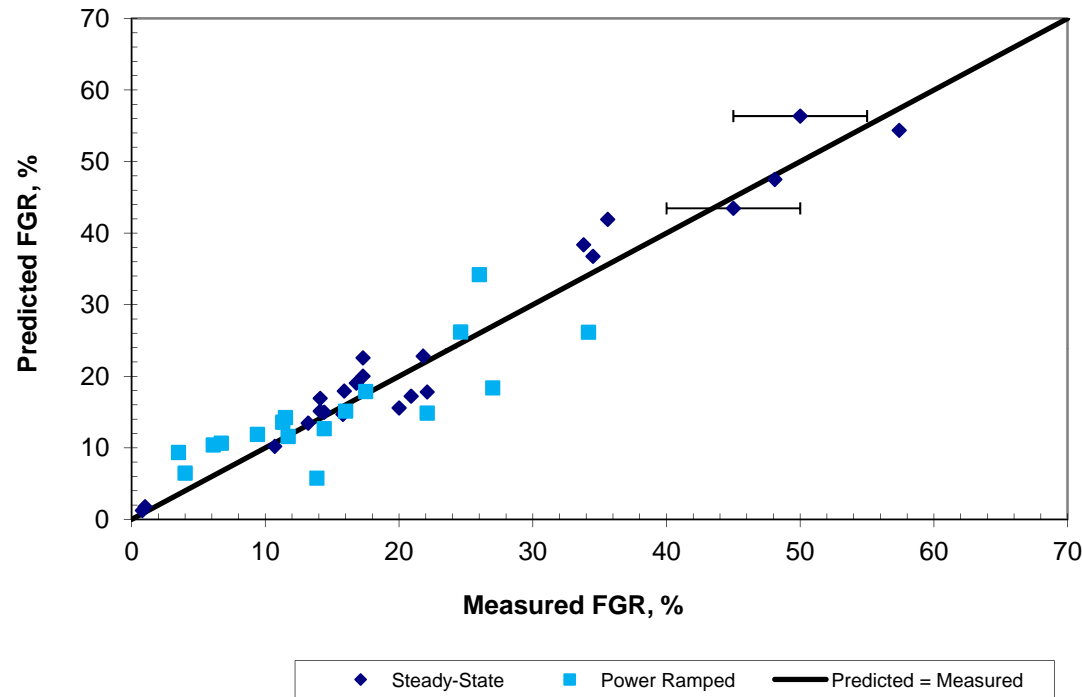
- UO_2 thermal conductivity data, model and upper and lower 2σ predictions
- $\sigma = \pm 8.8\%$ (relative)

Model Validation: Fuel Thermal Expansion



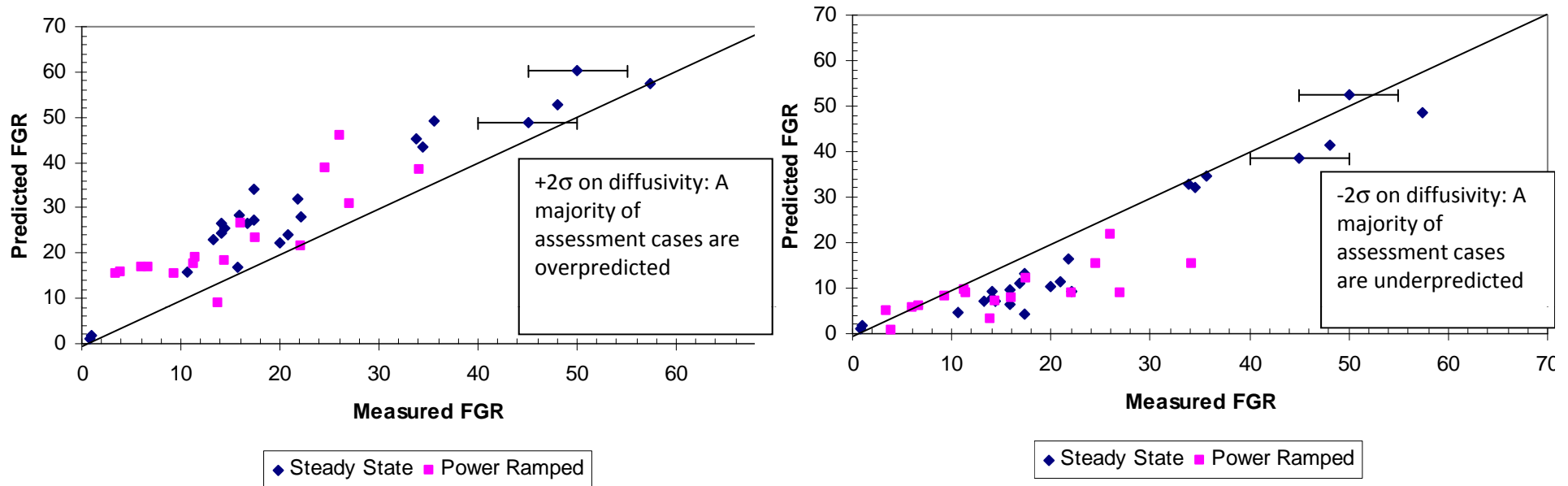
- UO_2 thermal expansion data, model and upper and lower 2σ predictions
- $\sigma = \pm 10.3\%$ (relative)

Model Validation: Fission Gas Release



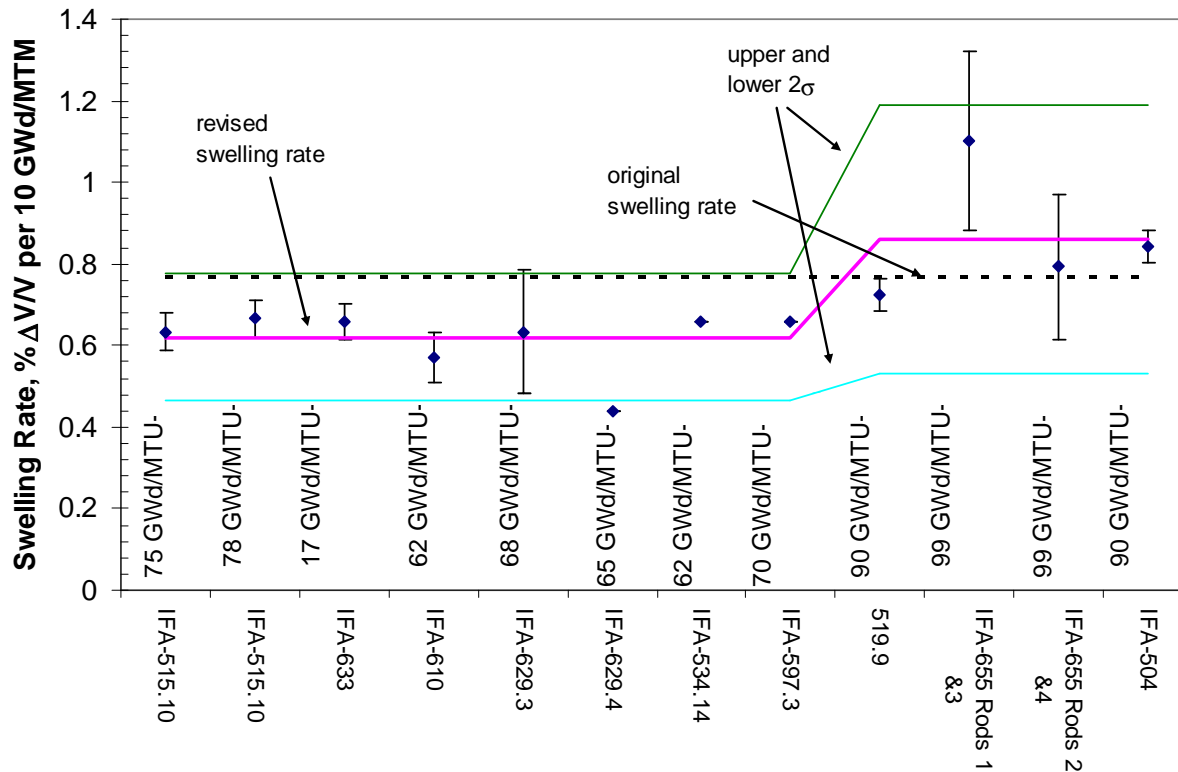
- Nominal predictions shown (error bars represent known measurement error)

Model Validation: Fission Gas Release



- Fission gas release data, model with upper 2σ and lower 2σ model predictions (error bars represent known measurement error)
- $\sigma = \pm 100\%$ on gas diffusivity

Model Validation: Fuel Swelling

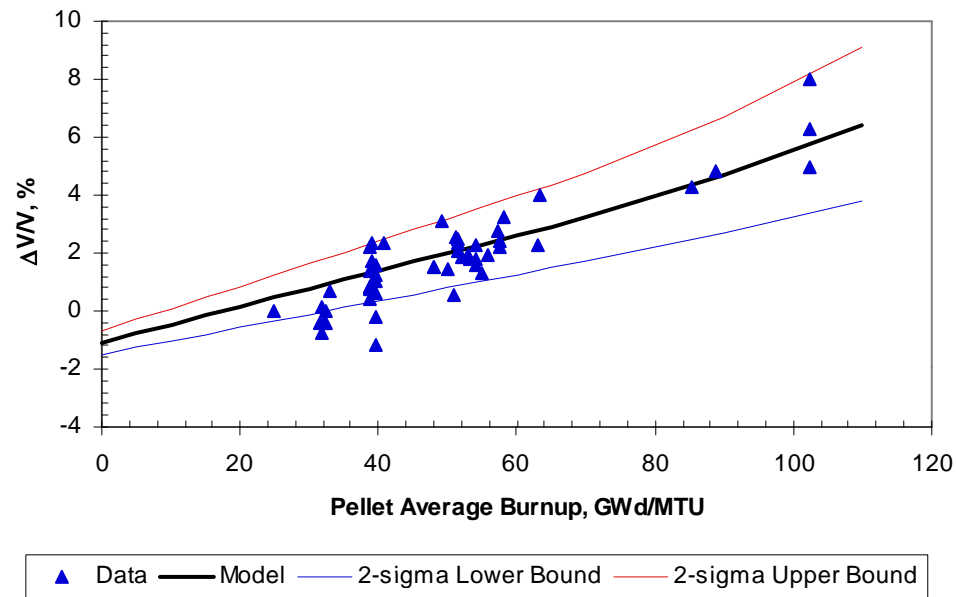


- Swelling rates from twelve Halden tests and FRAPCON-3.4 model predictions with uncertainties
- $\sigma = \pm 0.08\% \Delta V/V$ per 10 GWd/MTU below 80 GWd/MTU
- $\sigma = \pm 0.16\% \Delta V/V$ per 10 GWd/MTU above 80 GWd/MTU

Pacific Northwest
NATIONAL LABORATORY

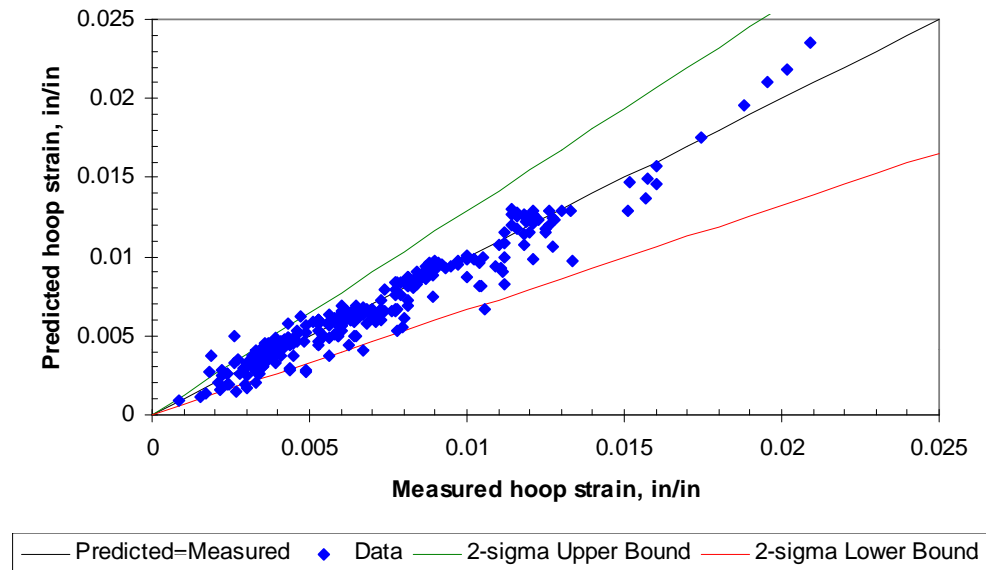
Proudly Operated by Battelle Since 1965

Model Validation: Fuel Swelling (cont.)



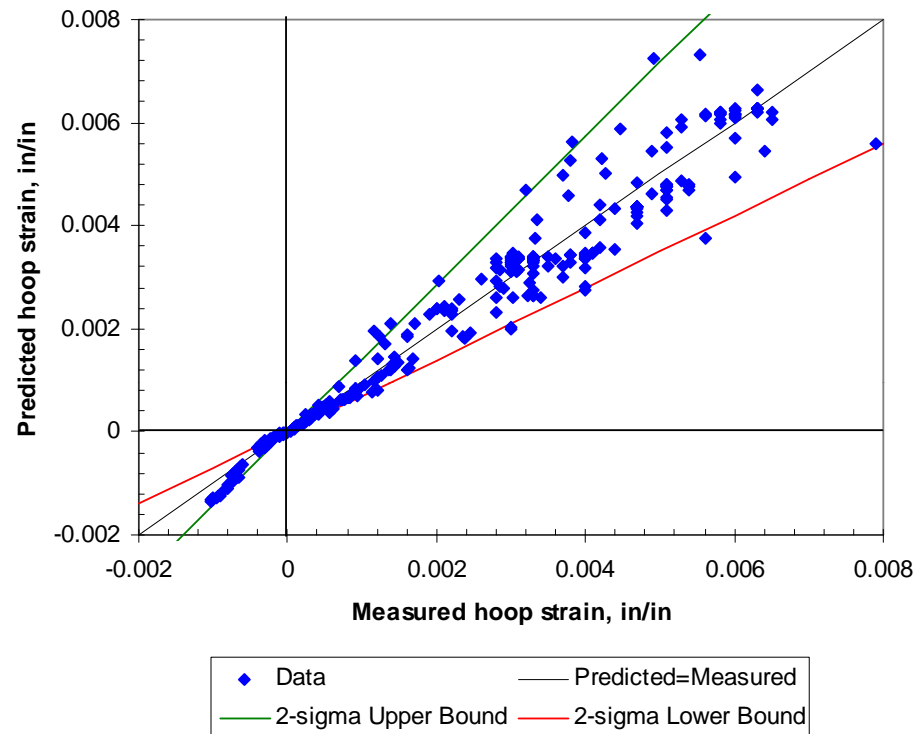
- UO_2 swelling data, model and upper and lower 2σ predictions
- $\sigma = \pm 0.08\% \Delta V/V$ per 10 GWd/MTU below 80 GWd/MTU
- $\sigma = \pm 0.16\% \Delta V/V$ per 10 GWd/MTU above 80 GWd/MTU

Model Validation: Cladding Irradiation Creep, SRA Cladding



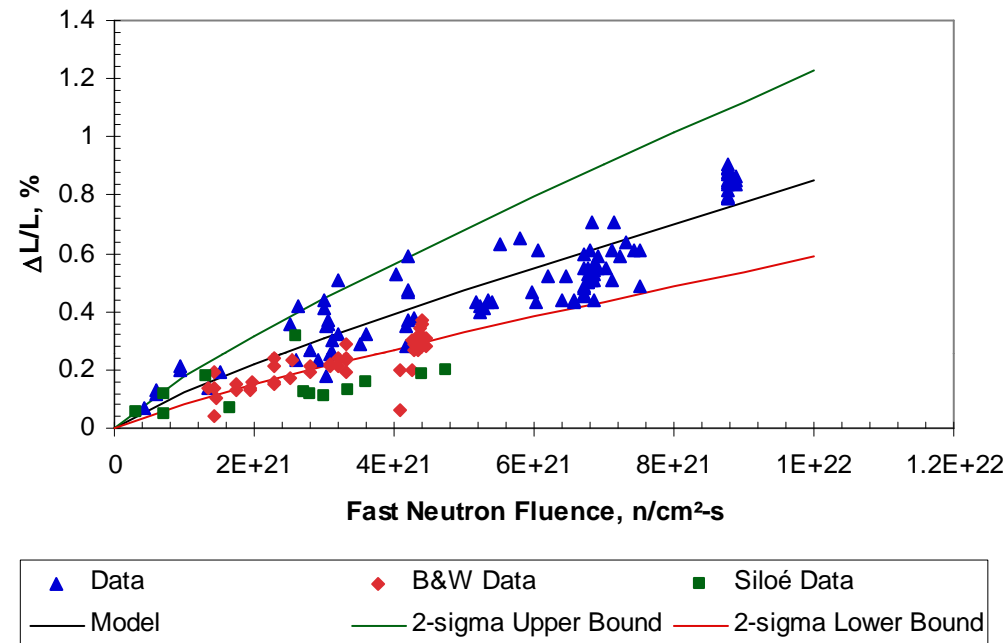
- SRA (Zircaloy-4, ZIRLO™) cladding creep data, model and upper and lower 2σ predictions
- $\sigma = \pm 14.5\%$ (relative)

Model Validation: Cladding Irradiation Creep, RXA Cladding



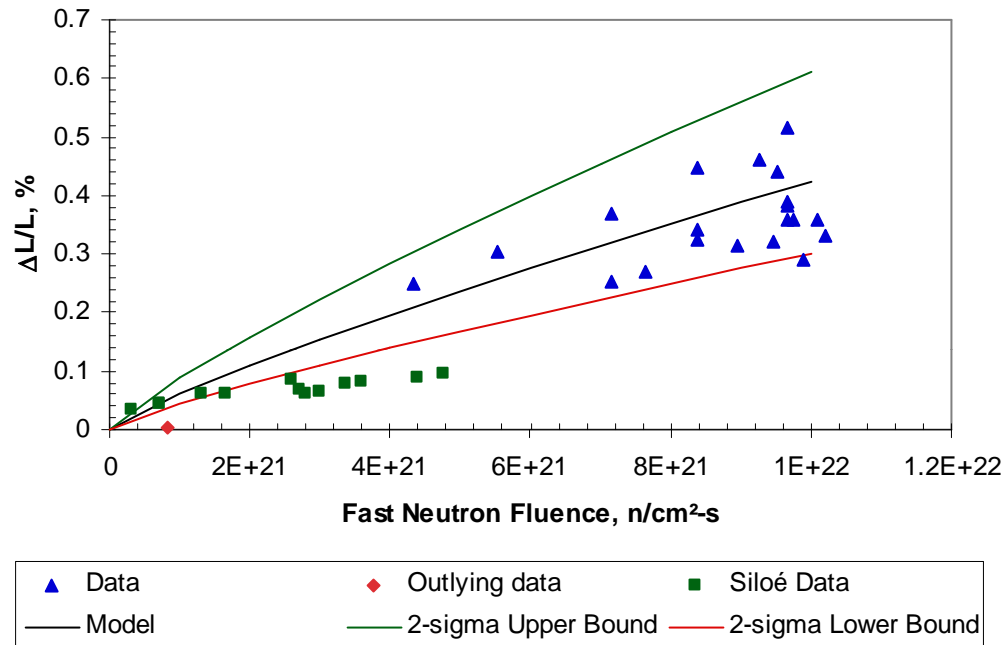
- RXA (Zircaloy-2, M5™) cladding creep data, model and upper and lower 2σ predictions
- $\sigma = \pm 21.6\%$ (relative)

Model Validation: Cladding Axial Growth, SRA Cladding



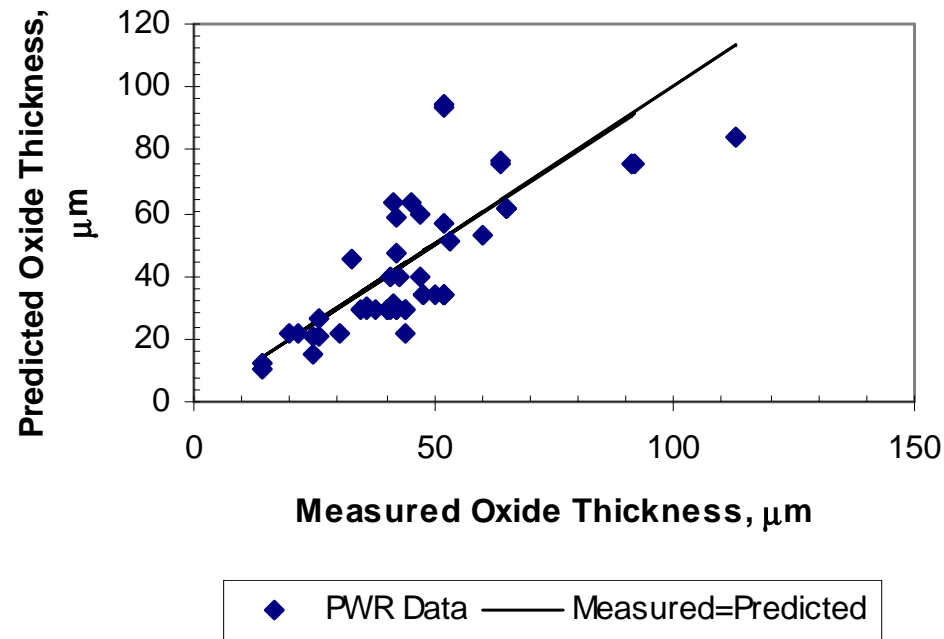
- SRA (Zircaloy-4, ZIRLO™) cladding axial growth data, model and upper and lower 2σ predictions
- $\sigma = \pm 22.3\%$ (relative)

Model Validation: Cladding Axial Growth, RXA Cladding



- RXA (Zircaloy-2, M5™) cladding axial growth data, model and upper and lower 2σ predictions
- $\sigma = \pm 20.3\%$ (relative)

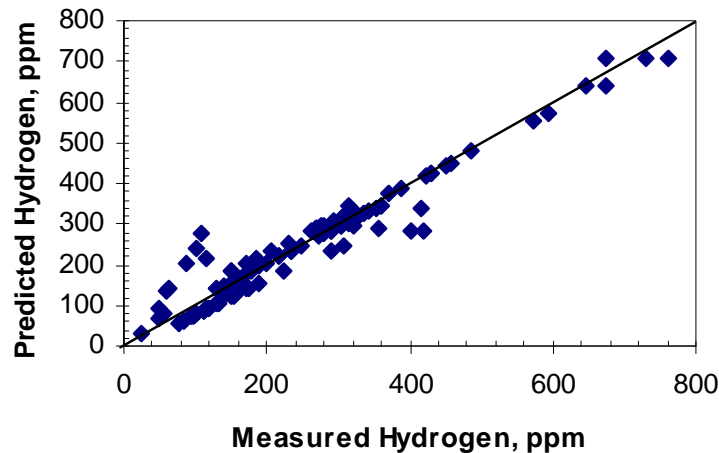
Model Validation: Cladding Corrosion



Example for Zircaloy-4

- Zircaloy-2 (BWR) $\sigma=\pm 7.6\mu\text{m}$ (absolute)
- Zircaloy-4 (PWR) $\sigma=\pm 15.3\mu\text{m}$ (absolute)
- ZIRLO™ (PWR) $\sigma=\pm 15\mu\text{m}$ (absolute)
- M5™ (PWR) $\sigma=\pm 5\mu\text{m}$ (absolute)

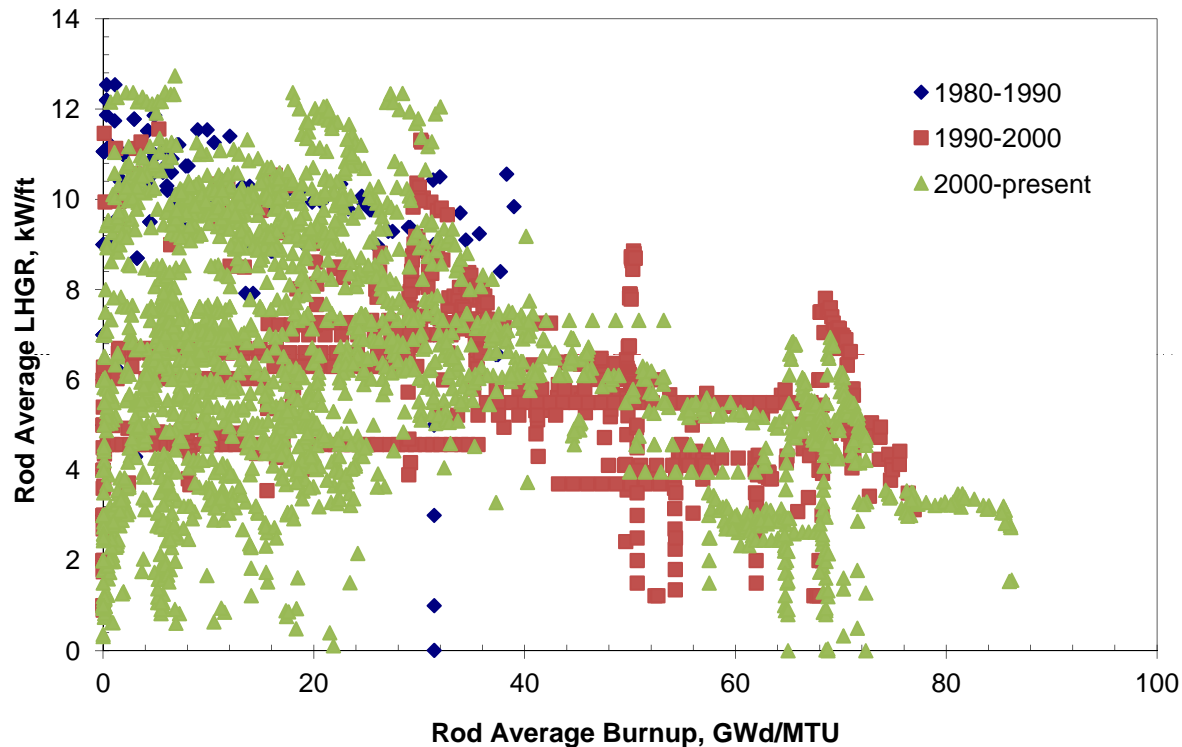
Model Validation: Cladding Hydrogen Pickup



Example for Zircaloy-4

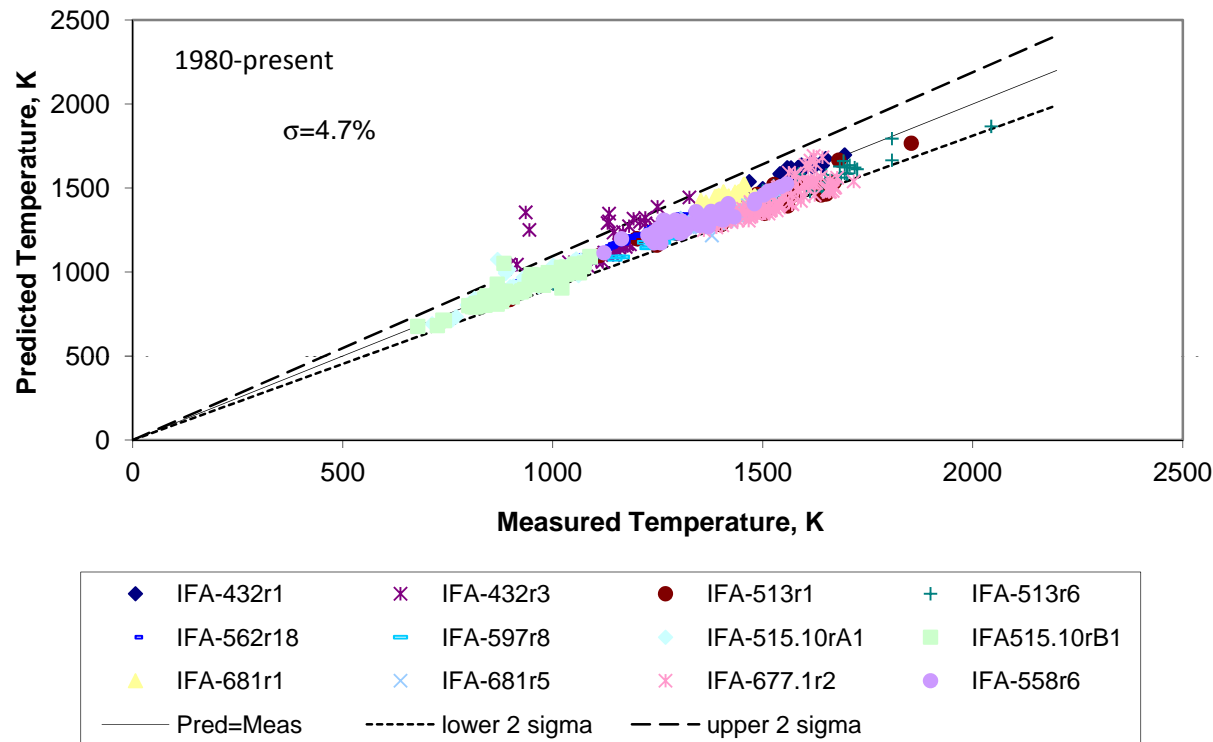
- Zircaloy-2 prior to 1998 (BWR) $\sigma = \pm 10$ ppm (<45 GWd/MTU)
- Zircaloy-2 since 1998 (BWR) $\sigma = \pm 11$ ppm (<49 GWd/MTU)
- Zircaloy-2 since 1998 (BWR) $\sigma = \pm 61$ ppm (>49 GWd/MTU)
- Zircaloy-4 (PWR) $\sigma = \pm 40$ ppm
- ZIRLO™ (PWR) $\sigma = \pm 45$ ppm
- M5™ (PWR) $\sigma = \pm 20$ ppm

Integral Assessment: Temperature Range of data



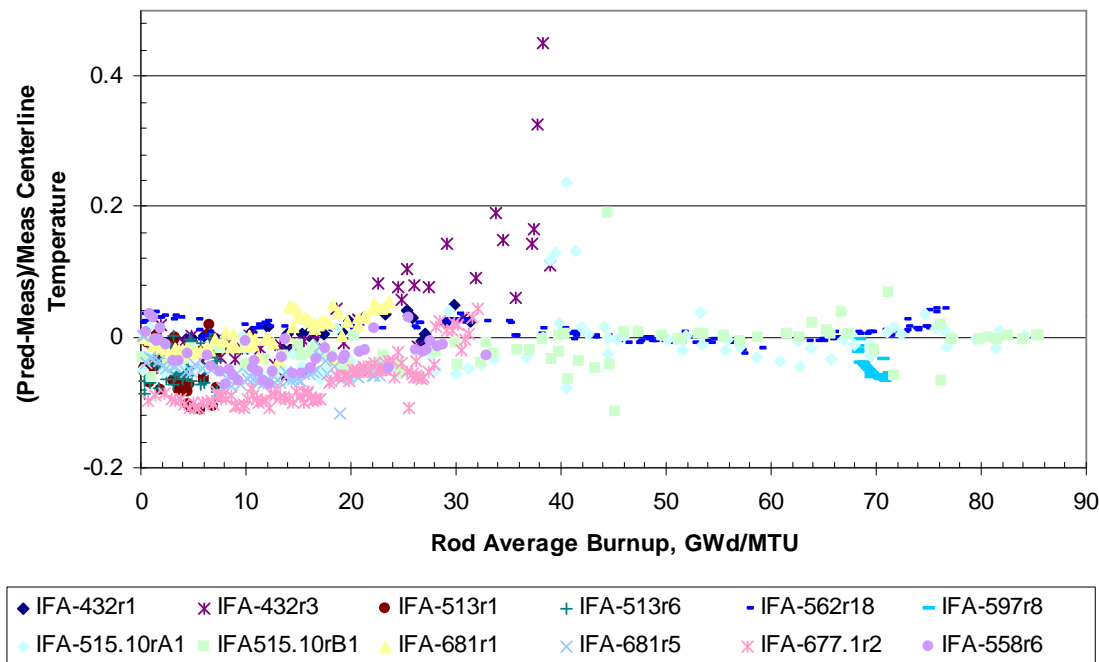
- Rod-average LHGR vs. rod-average burnup for temperature assessment cases

Integral Assessment: Temperature Predicted vs. Measured



- Measured and predicted centerline temperature for the UO_2 assessment cases throughout life
- $\sigma=\pm 4.7\%$ (relative)

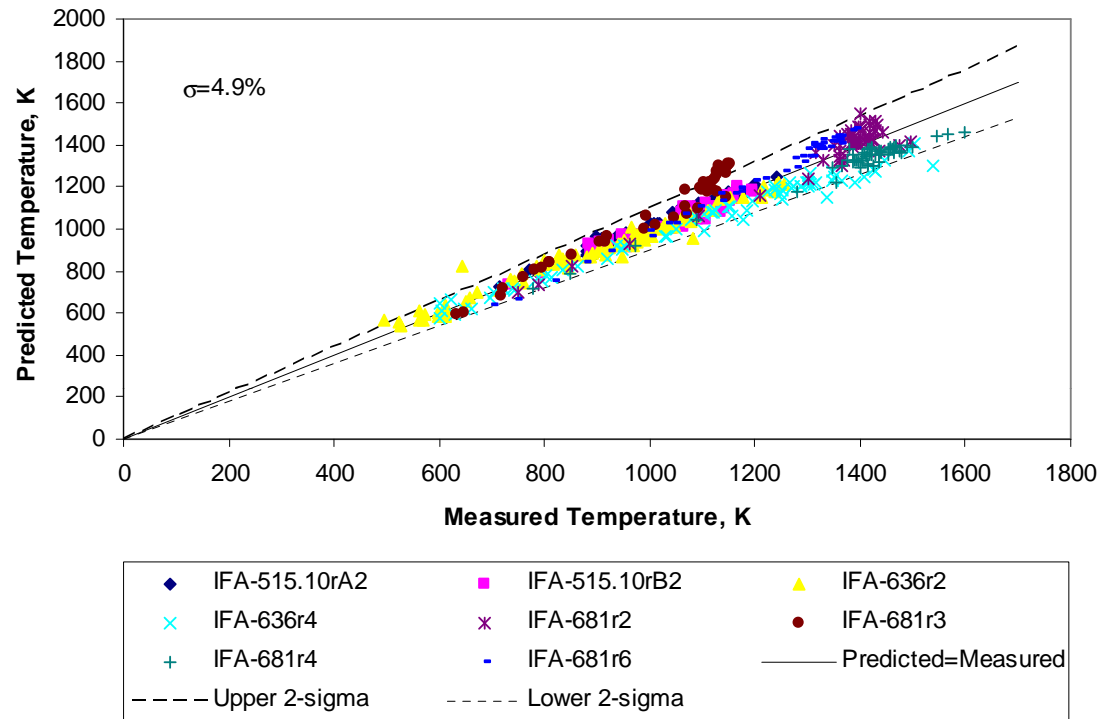
Integral Assessment: Temperature (Predicted – Measured)/Measured vs. Burnup



- Measured and predicted centerline temperature for the UO_2 assessment cases throughout life
- $\sigma = \pm 4.7\%$ (relative)

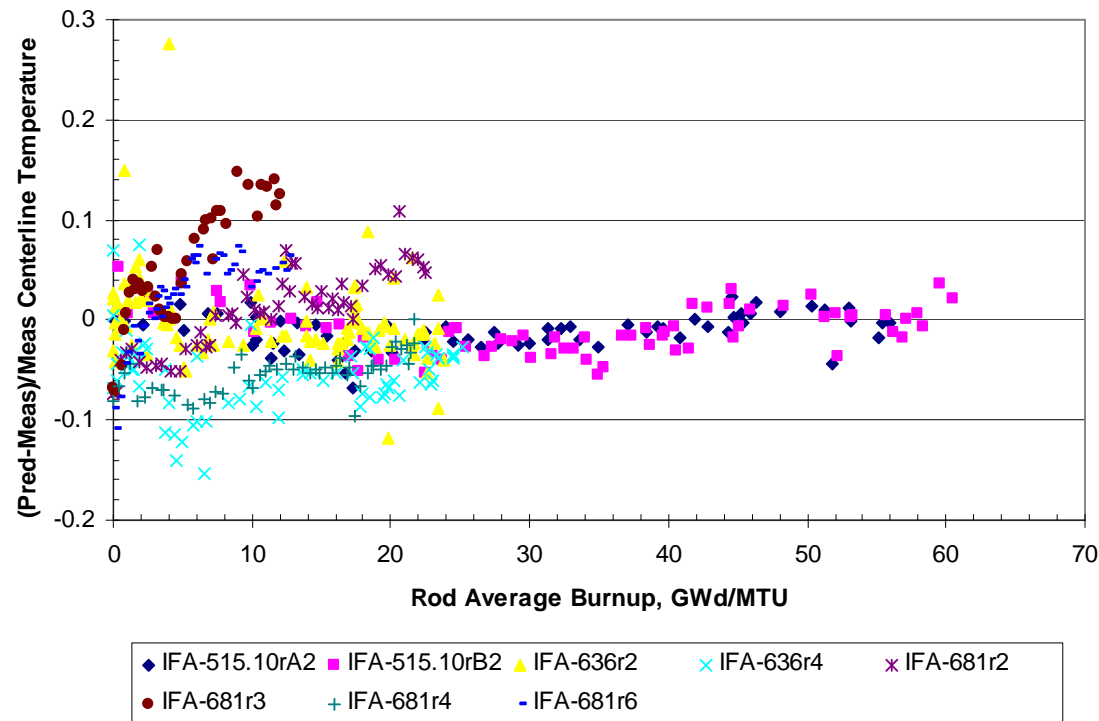


Integral Assessment: Temperature Predicted vs. Measured



- Measured and predicted centerline temperature for the $\text{UO}_2\text{-Gd}_2\text{O}_3$ assessment cases throughout life (all since 2000)
- $\sigma=\pm 4.9\%$ (relative)

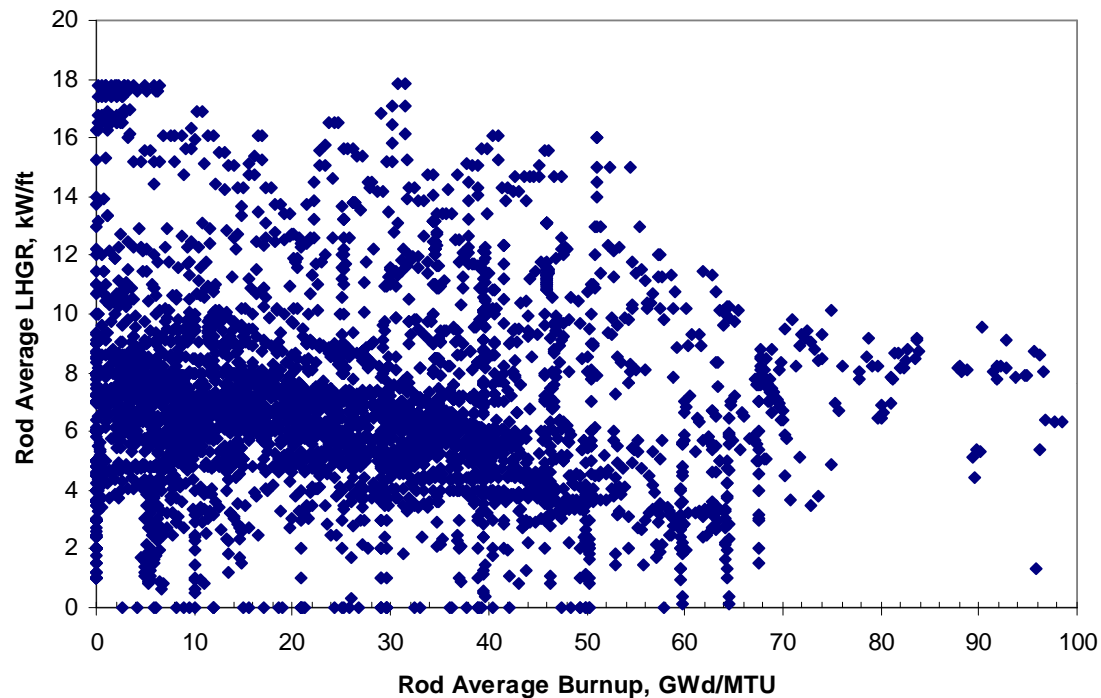
Integral Assessment: Temperature (Predicted – Measured)/Measured vs. Burnup



- Measured and predicted centerline temperature for the $\text{UO}_2\text{-Gd}_2\text{O}_3$ assessment cases throughout life
- $\sigma = \pm 4.9\%$ (relative)

Integral Assessment: Fission Gas Release

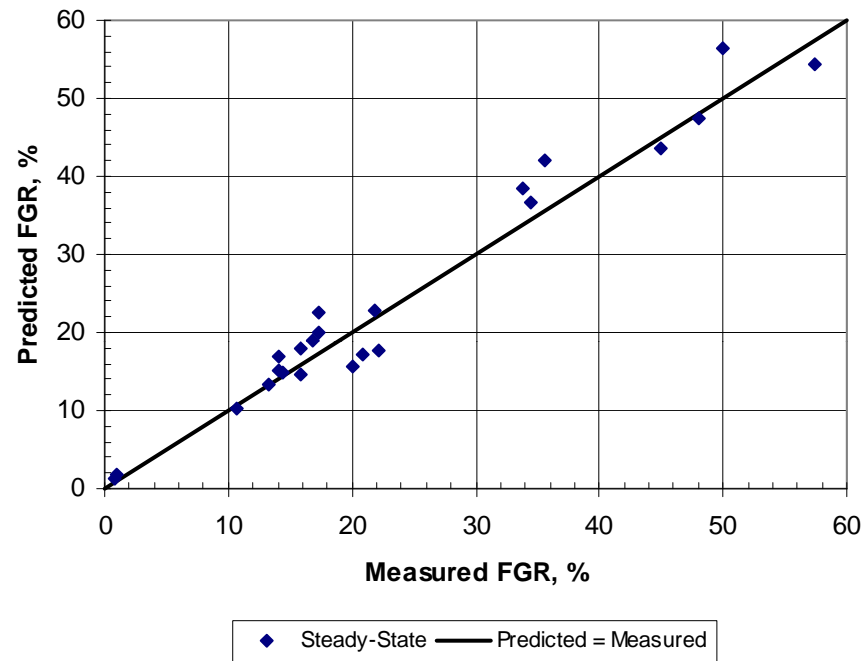
Range of data



- Rod-average LHGR vs. rod-average burnup for fission gas release assessment cases

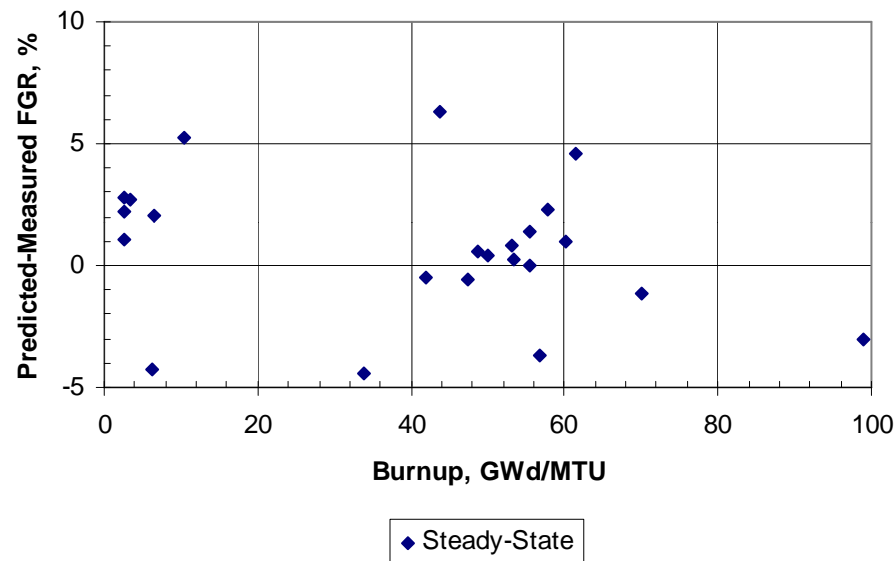


Integral Assessment: Fission Gas Release Predicted vs. Measured



- Comparison of FRAPCON-3.4 predictions to measured FGR data for the UO_2 steady-state assessment cases
- $\sigma = \pm 2.6\%$ (absolute)

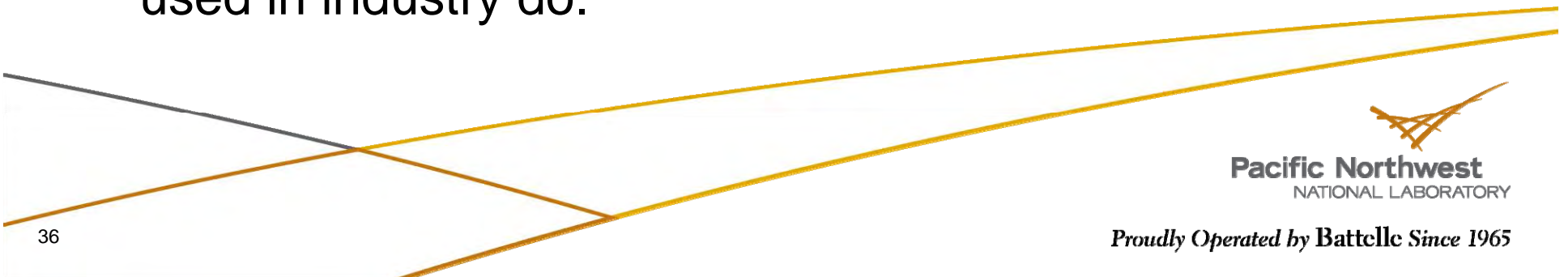
Integral Assessment: Fission Gas Release Predicted – Measured vs. Burnup



- Predicted minus measured FGR versus rod-average burnup for the UO_2 steady-state assessment cases
- $\sigma = \pm 2.6\%$ (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

FRAPCON Simulator: Manufacturing Parameters

Cladding outer diameter	Distribution: Constant	Value: 0.422	in		
Cladding inner diameter	Distribution: Constant	Value: 0.3734	in		
Cladding surface roughness	Distribution: Constant	Value: 3.9E-6	in		
Pellet diameter	Distribution: Constant	Value: 0.3659	in		
Pellet Density	Distribution: Constant	Value: 96.56	%T.D.		
Pellet re-sinter density	Distribution: Constant	Value: 1.0	kg/m ³		
Pellet roughness	Distribution: Constant	Value: 1.97E-5	in		
Pellet dish diameter	Distribution: Constant	Value: 0.2171	in		
Pellet dish depth	Distribution: Uniform	Value: 0.0105	in		
Rod fill pressure	Distribution: LogUniform (base e)	Value: 275.0	psi		
Rod plenum length	Distribution: Triangle	Value: 11.563	in		

Exit Help Back Next

Uncertainty Analysis with FRAPCON-3.4 Input

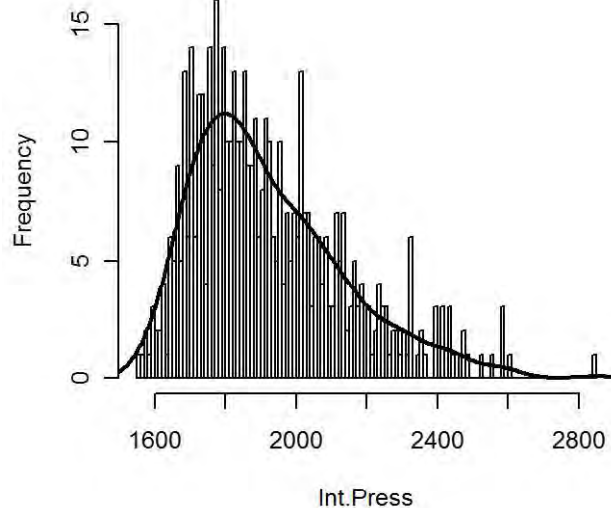
FRAPCON Simulator: Simulation Parameters

Parameter	Distribution	Value
Fuel thermal conductivity	Constant	0.0
Fuel thermal expansion	Constant	0.0
Fuel gas release	Constant	0.0
Fuel swelling	Constant	0.0
Cladding creep	Constant	0.0
Cladding axial growth	Constant	0.0
Cladding corrosion	Constant	0.0
Cladding hydrogen pickup	Constant	0.0
Uncertainty (multiplicative) of power levels	Constant	0.0

Exit Help Back Run

Uncertainty Analysis with FRAPCON-3.4 Output

- Output distributions
- Inputs and outputs for each realization



Results.dat - Notepad

Real	Int.Press	Cnt.Temp	Strain	FGR	DCO	DCI	ROUGH	POD	DEN	RSNT
1	1.78952E+03	2.62999E+03	4.52323E-01	1.50300E+01	4.22000E-01	3.73400E-01	3.90000E-01	3.90000E-01	3.90000E-01	3.90000E-01
2	1.65482E+03	2.68428E+03	5.95411E-01	1.16100E+01	4.22000E-01	3.73400E-01	3.90000E-01	3.90000E-01	3.90000E-01	3.90000E-01
3	2.16289E+03	2.82969E+03	5.51791E-01	1.98700E+01	4.22000E-01	3.73400E-01	3.90000E-01	3.90000E-01	3.90000E-01	3.90000E-01
4	2.10606E+03	2.82276E+03	5.46886E-01	1.84400E+01	4.22000E-01	3.73400E-01	3.90000E-01	3.90000E-01	3.90000E-01	3.90000E-01
5	2.53833E+03	2.81593E+03	1.05104E+00	2.25600E+01	4.22000E-01	3.73400E-01	3.90000E-01	3.90000E-01	3.90000E-01	3.90000E-01
6	1.39913E+03	2.51920E+03	6.45997E-01	7.86000E+00	4.22000E-01	3.73400E-01	3.90000E-01	3.90000E-01	3.90000E-01	3.90000E-01
7	1.19533E+03	2.33894E+03	3.80605E-01	6.41000E+00	4.22000E-01	3.73400E-01	3.90000E-01	3.90000E-01	3.90000E-01	3.90000E-01
8	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	4.22000E-01	3.73400E-01	3.90000E-01	3.90000E-01	3.90000E-01	3.90000E-01
9	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	4.22000E-01	3.73400E-01	3.90000E-01	3.90000E-01	3.90000E-01	3.90000E-01
10	2.18889E+03	2.90831E+03	3.83521E-01	2.01000E+01	4.22000E-01	3.73400E-01	3.90000E-01	3.90000E-01	3.90000E-01	3.90000E-01
11	1.17435E+03	2.45758E+03	4.17531E-01	5.24000E+00	4.22000E-01	3.73400E-01	3.90000E-01	3.90000E-01	3.90000E-01	3.90000E-01
12	2.63451E+03	3.08784E+03	3.79090E-01	2.78400E+01	4.22000E-01	3.73400E-01	3.90000E-01	3.90000E-01	3.90000E-01	3.90000E-01
13	2.06329E+03	2.94862E+03	4.66872E-01	2.00100E+01	4.22000E-01	3.73400E-01	3.90000E-01	3.90000E-01	3.90000E-01	3.90000E-01
14	1.84756E+03	2.68775E+03	5.21069E-01	1.57100E+01	4.22000E-01	3.73400E-01	3.90000E-01	3.90000E-01	3.90000E-01	3.90000E-01
15	1.52357E+03	2.51963E+03	4.97465E-01	1.20100E+01	4.22000E-01	3.73400E-01	3.90000E-01	3.90000E-01	3.90000E-01	3.90000E-01
16	1.20363E+03	2.42023E+03	2.59632E-01	5.31000E+00	4.22000E-01	3.73400E-01	3.90000E-01	3.90000E-01	3.90000E-01	3.90000E-01
17	1.77857E+03	2.70365E+03	4.25561E-01	1.40500E+01	4.22000E-01	3.73400E-01	3.90000E-01	3.90000E-01	3.90000E-01	3.90000E-01
18	2.45844E+03	2.85759E+03	5.45986E-01	2.45800E+01	4.22000E-01	3.73400E-01	3.90000E-01	3.90000E-01	3.90000E-01	3.90000E-01
19	2.35549E+03	2.81102E+03	7.05168E-01	2.22200E+01	4.22000E-01	3.73400E-01	3.90000E-01	3.90000E-01	3.90000E-01	3.90000E-01

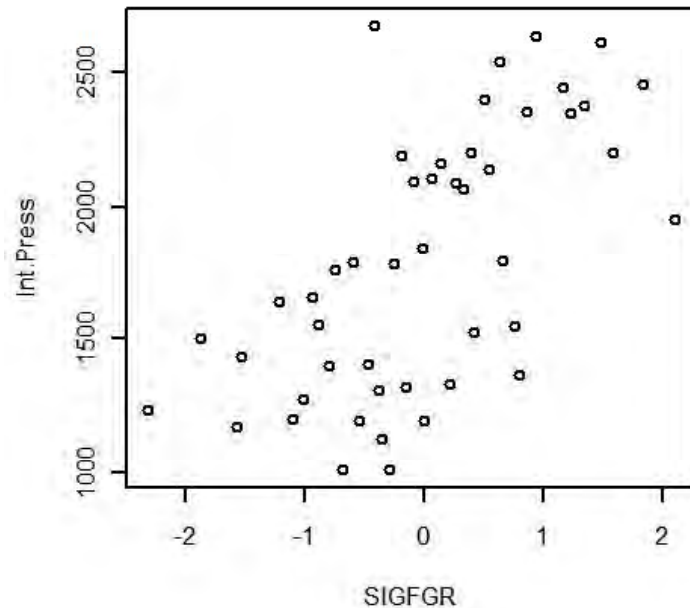
- Calculated Upper Tolerance Limits

UTL.txt - Notepad

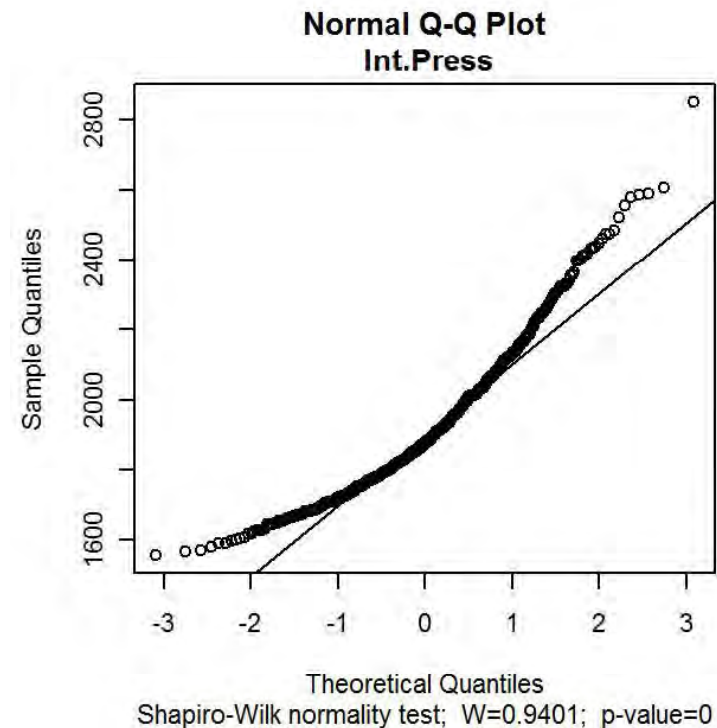
alpha	gamma	n	Int.Press	Cnt.Temp	Strain	FGR
0.1	0.9	47	2576.107	3037.06	0.745293	25.97670
0.1	0.95	47	2621.872	3058.25	0.760819	26.63641
0.1	0.99	47	2717.15	3102.366	0.7931427	28.00987
0.1	0.999	47	2842.729	3160.512	0.8357464	29.82013
0.05	0.9	47	2778.895	3130.956	0.8140901	28.89994
0.05	0.95	47	2832.344	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.