

NUCLEAR REGULATORY COMMISSION

Title: Advisory Committee on Reactor Safeguards
Reactor Fuels Subcommittee

Docket Number: (not applicable)

PROCESS USING ADAMS
TEMPLATE: ACRS/ACNW-005

Location: Rockville, Maryland

Date: Monday, September 29, 2003

Work Order No.: NRC-1079

Pages 1-311

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

ACRS OFFICE COPY
RETAIN FOR THE LIFE OF THE COMMITTEE

TROY

ORIGINAL

UNITED STATES OF AMERICA
NUCLEAR REGULATORY COMMISSION

+ + + + +

ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

(ACRS)

REACTOR FUELS SUBCOMMITTEE

+ + + + +

MONDAY,

SEPTEMBER 29, 2003

+ + + + +

ROCKVILLE, MARYLAND

+ + + + +

The Subcommittee met at the Nuclear
Regulatory Commission, Two White Flint North, Room
T2B3, 11545 Rockville Pike, at 8:30 a.m., Dr. Dana
A. Powers, Chairman, presiding.

COMMITTEE MEMBERS:

DANA A. POWERS	Chairman
F . PETER FORD	Member
THOMAS S. KRESS	Member
VICTOR H RANSOM	Member

ACRS STAFF PRESENT:

RALPH CARUSO

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

(202) 234-4433

www.nealrgross.com

1 ALSO PRESENT:

2 MIKE BILLONE

3 YOVAN LUKIC

4 RALPH MEYER

5 JACK ROSENTHAL

6 JEFF SCHMIDT

7 JOHN VOGELWEDE

8

9

10

11

12

13

14

15

16

17

18

19

20

21

22

23

24

25

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

I-N-D-E-X

	<u>AGENDA ITEM</u>	<u>PAGE</u>
1		
2		
3	Introduction, Chairman Powers	4
4	Opening Remarks and Status Report, Jack	
5	Rosenthal	7
6	NRC Fuel Codes, John Vogelwede	19
7	RIA Data Scaling, Dr. Ralph Meyer	49
8	Technical Basis for Performance Based Revisions	
9	to 10 CFR 50.41, Dr. Ralph Meyer	96
10	LOCA Test Results, Mike Billone	133
11	Paks Event, Dr. Ralph Meyer	212
12	Dry Cask Storage Conditions, Mike Billone . .	225
13	Control of Crud:	
14	Yovan Lukic	266
15	Jeff Schmidt	287
16		
17		
18		
19		
20		
21		
22		
23		
24		
25		

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

P-R-O-C-E-E-D-I-N-G-S

(8:32 a.m.)

CHAIRMAN POWERS: Let's bring the meeting to order now.

This is the meeting of the Advisory Committee on Reactor Safeguards, Subcommittee on Reactor Fuels.

I'm Dan Powers, Chairman of the Subcommittee. Subcommittee members in attendance are Tom Kress, Vic Ransom, Peter Ford.

The purpose of today's meeting is to discuss ongoing activities in the Office of Research related to reactor fuel and to hear from the industry about methods to produce crud on reactor fuel and lots of other things, I hope, too.

Tomorrow we'll hear from the Electric Power Research Institute about the robust fuel program. The Subcommittee will hold discussions with representatives and the NRC staff and with industry regarding these matters. The Subcommittee will gather information, analyze relevant issues and facts, and formulate proposed positions and actions, as appropriate, for deliberation by the full Committee.

Ralph Caruso is the designated federal

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 official for this meeting.

2 The rules for participation in today's
3 meeting have been announced as part of the notice of
4 the meeting previously published in the Federal
5 Register on September 15th, 2003. Portions of
6 tomorrow meeting will be closed for discussion of
7 proprietary information.

8 A transcript of the meeting is being
9 kept and will be made available as stated in the
10 Federal Register notice.

11 It is requested that speakers first
12 identify themselves and speak with sufficient
13 clarity and volume so that they can be readily
14 heard.

15 We have received no request from any
16 member of the public for time to make an oral
17 statement.

18 What I will caution the members about is
19 one of the primary objectives of today's session is
20 to really understand where the fuel program is
21 going, not just for the next year, but the future.
22 So when it says in the agenda that we'll have
23 members' discussions, I think it says that
24 specifically on Tuesday's session, but I guarantee
25 you at the end of this session I'm going to be

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 asking the members to not only tell me what their
2 thoughts are, but to volunteer to write up proposed
3 positions on those thoughts.

4 Okay. So you might be prepared for a
5 little bit of discussion at the end of the day, and
6 that we may have to decide if we do additional leg
7 work in order to get things ready for the report on
8 reactor fuels in the research program.

9 Any members have the opening comments
10 they'd like to make about this?

11 (No response.)

12 CHAIRMAN POWERS: I will say that the
13 reactor fuels meetings that we have about once a
14 year do have a reputation for being technical
15 meetings with lots of exchange. So I encourage
16 members of the Committee, the Subcommittee, and
17 members in the audience to feel free to participate.

18 The one ground rule for participation is
19 you have to speak to a microphone, and you have to
20 tell me who you are and speak with sufficient
21 clarity and volume so that you can be heard by me,
22 and as I get old, that means you have to speak with
23 a lot of clarity and volume, but do feel free to
24 participate. The Committee is anxious to understand
25 where we're going.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 We don't have Subcommittee meetings for
2 the fuels program very often. So having an
3 understanding, making sure that we understand things
4 clearly is very important to us at this time.

5 Well, if there are no other comments to
6 be made, I'll turn to Jack Rosenthal to give opening
7 remarks and a status report.

8 MR. ROSENTHAL: Jack Rosenthal. I'm the
9 Branch Chief of the Safety Margin Systems Analysis
10 Branch, the Office of Nuclear Regulatory Research.

11 In 1998, the staff provided the
12 Commission with a program plan which identified the
13 issues that are shown in the one slide on the wall.
14 That was -- I'm sorry. And then this chart is right
15 out of the August 21st, 2003, updated of the program
16 plan which was provided to the Commission.

17 I just want to point out some salient
18 points. We're on, I think, a reasonably fast track
19 for resolving the reactivity insertion issues and
20 LOCA for high burn-up Zircaloy clad, Zirc-2, Zirc-4
21 clad fuel, with reactivity insertion position coming
22 from research to NRR at the end of this year.

23 About a year ago when we were looking
24 over the data or the few data points that we'll get
25 from Cabri and many data points from the Japanese,

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 NSRR, which are not for fuel temperature conditions,
2 we realized that we would not be able to just put
3 data points down on a piece of paper and draw a line
4 through them for the purposes of reactivity
5 insertion events, but that we would have to adjust
6 the data points to some common basis.

7 And that means that we had to develop an
8 analytic method, and Ralph Meyer will be telling you
9 about his thoughts about how he could move to points
10 around to a common basis, which is new.

11 And we had to extensively use FRAPTRAN,
12 our fuel transient code, to help us with that
13 effort.

14 LOCA, we're proceeding with testing of
15 Zirc-2 and Zirc-4, and I think that that program is
16 well underway, and there's been first of a kind ever
17 testing of high burn-up fuel, and we should be proud
18 of that.

19 In the future, most of the clad will be
20 ZIRLO or M-5, and we'll leave --

21 DR. KRESS: When you say high burn-up
22 fuel, what exactly? Seventy, 65?

23 MR. ROSENTHAL: Sixty-two megawatt days
24 per metric ton is our target. The actual fuel is a
25 few megawatts higher, 70.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 DR. MEYER: This is Ralph Meyer from the
2 Research staff.

3 Let me just clarify. When we say "high
4 burn-up fuel," what we're talking about is anything
5 above about 40 gigawatt days per ton. Now, we have
6 a current limit on the approvals that have been
7 given by NRC that sits at 62 gigawatt days per ton
8 average for the peak rod (phonetic). There are
9 efforts underway to extend that out to about 75
10 gigawatt days per ton average for the peak rod.

11 And in general, the data that are being
12 taken in these programs cover a range that's
13 sufficient to go up to the 75, although some of our
14 activities are specifically limited to 62. I'll try
15 and make that distinction a little later on.

16 DR. KRESS: Okay. When a core ends up
17 having that kind of burn-up, it will only occupy
18 maybe one third of the core at any time at that
19 level, something like that?

20 MR. ROSENTHAL: We think three or four
21 batch fuel, right?

22 DR. KRESS: Yeah.

23 MR. ROSENTHAL: Okay. Just to pick up
24 the flow, so my point was that for ZIRLO and M-5
25 clad, future clad to be tested in out years, that

1 will be a major effort, and we will surely need
2 cooperation with industry to achieve that.

3 We've done some work on dry storage,
4 which although may seem mundane, putting the stuff -
5 - pressurizing it and heating it and leaving it for
6 a while and looking at strain, in fact, that work is
7 very, very important for dry storage campaign
8 because it's showing that a fuel stored after 15
9 years and taken out has seen virtually no
10 degradation, and we briefed the ACNW on that plan.
11 They were quite pleased to see some data.

12 It's for 15 years of storage, but, it's
13 very encouraging. And what's so nice is that it
14 puts it on an experimental basis rather than on --

15 DR. KRESS: Did you skip the source term
16 and the core melt progression item?

17 MR. ROSENTHAL: I did.

18 DR. KRESS: It says it's resolved, as
19 best I can read the slide. What does that really
20 mean?

21 DR. MEYER: Yeah, it's Ralph Meyer
22 again.

23 What that means is that for burn-ups up
24 to 62 gigawatt days per ton, the staff has taken the
25 position that the source term in NUREG 1465 is

1 adequate. That's what "resolved" means in that
2 case.

3 Now, you'll see the footnote or the
4 asterisk on this table. In most or all of these
5 areas where specific issues as they were identified
6 have been resolved, there still is some ongoing work
7 in order to either improve the accuracy, move burn-
8 ups further, or something of that sort.

9 DR. KRESS: Okay. That was basically
10 what I was interested in hearing.

11 CHAIRMAN POWERS: Is this resolution
12 written down?

13 MR. ROSENTHAL: Yeah. Well, we
14 published. In 1965 we published the program plan.

15 DR. MEYER: A summary of everything that
16 I just said is in the recent Commission paper. It's
17 August 21.

18 CHAIRMAN POWERS: That is where this
19 resolution in the source term is written down?

20 DR. MEYER: It summarizes that
21 resolution in that document.

22 CHAIRMAN POWERS: Does that resolution
23 show that, indeed, the accelerated release that has
24 been seen in some experiments of volatile fission
25 products is consistent with the timing in 1465?

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 DR. MEYER: No. This document does not
2 go in that level of detail.

3 CHAIRMAN POWERS: And where do I go to
4 find the thinking that went into saying 1465 is, in
5 fact, good for 62 gigawatt days per ton?

6 DR. MEYER: I believe we have cited
7 adequate references for you to track that down. I
8 hope that's --

9 DR. KRESS: Was this resolution based on
10 the PIRT?

11 MR. SCOTT: Yes.

12 DR. KRESS: And the PIRT documents are
13 published?

14 MR. SCOTT: Yes. The answer is yes.

15 DR. MEYER: Yeah, sure. It's based on
16 the PIRT.

17 MR. ROSENTHAL: So while we're
18 proceeding well on reactivity insertion events, and
19 I think we have a program in place, LOCA, and we
20 will ultimately have to come up with performance
21 based criteria that we would recommend for use in
22 future LOCA analysis, the ATWS analysis is lagging
23 behind the two other accidents.

24 For ATWS, what we need to do is to be
25 able to predict transient fuel temperatures as a

1 function of time in what we believe would be a
2 period of rapid changes and oscillations.

3 Step 1 is to get TRACE working, which I
4 think we've achieved.

5 Step 2 is to get a 3D kinetics model
6 coupled to TRACE, which we call PARCS, as modular
7 TRACE, and that's been achieved.

8 And the next step would be to couple a
9 fuel code into that suite of codes for the module of
10 the code or couple codes, and with that capability,
11 which we should start on next year, we should be
12 able to look at the ATWS oscillations in some
13 specificity.

14 Though I just want to make another
15 couple of points. This work is very expensive, and
16 it's highly leveraged where participating with Cabri
17 we have agreements with the Japanese. We
18 participate with Halden, and we think that our
19 participation in these programs is giving us on the
20 order of perhaps \$30 million worth of worldwide
21 research.

22 Our cost is roughly three FTE and five
23 million a year, and we would expect a similar,
24 although a somewhat declining level, to continue on,
25 and that's it. That's it.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 I have a handwritten note to mention the
2 EPRI cooperation. Clearly, in the Argonne fuel
3 program, the fuel has been provided by EPRI to us
4 and providing and shipping with fuel is roughly
5 equal in cost to the program. So it's roughly a 50-
6 50 partnership with industry.

7 EPRI also participates in Cabri.

8 With that I think that we're ready for
9 the first presentation.

10 DR. FORD: I had a question about the
11 last item, the high enrichment which is deferred.

12 MR. ROSENTHAL: Right.

13 DR. FORD: There's no discussion of this
14 in your August 21st plan as to the risks associated
15 with deferring it versus the commercialization
16 plans. What sort of risk are you taking by not
17 addressing this?

18 MR. ROSENTHAL: We're going to see high
19 burn-up -- I'm sorry -- high enrichment in IRIS, the
20 proposed IRIS design, which is out some time into
21 the future. I think to prepare our plans, these are
22 mostly physics calculations to calculate neutrons
23 and specifically cross-sections and cross-section
24 sets applicable to the high enrichments, and we can
25 do that reasonably fast.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 MR. ELTAWILA: This is Farouk Eltawila
2 from Research.

3 The reason for the deferral, there is no
4 industry initiative to go above five percent
5 enrichment right now. The infrastructure is not
6 existing in the country. So there is no reason to
7 pursue research in this area.

8 DR. KRESS: There's one school of
9 thought that says the higher enrichment if you don't
10 go too far is probably a safer condition rather than
11 a more risky one because of the neutronics
12 associated with it and associated with loss of
13 coolant and the ability to -- actually in order to
14 make the Chernobyl reactor safer, they increased the
15 enrichment in it.

16 MR. ROSENTHAL: Well, they just wanted
17 to achieve --

18 DR. KRESS: Just to get rid of the
19 positive void coefficient or help make it smaller.

20 MR. ROSENTHAL: So they want to achieve
21 a negative void coefficient.

22 DR. KRESS: Yeah.

23 MR. ROSENTHAL: But I think at least in
24 my mind is the assessment that we know how to go
25 about this work; that it's dominantly physics work;

NEAL R. GROSS

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

1 and that we would do the actual work when there was
2 a need.

3 DR. KRESS: When you say "physics," it's
4 mostly --

5 MR. ROSENTHAL: Neutronics.

6 DR. KRESS: -- yeah, neutronics.

7 MR. ROSENTHAL: We have to -- you have
8 to generate cross-section sets that are applicable.

9 MR. ELTAWILA: Nobody is pursuing the --

10 MR. ROSENTHAL: No. So what I'm saying
11 is that we're able to do it, and we anticipate when
12 there's a need that we would be able to do it. So
13 in my mind the risk is small because I think we know
14 how to go about it.

15 CHAIRMAN POWERS: I guess two issues
16 come to the fore there. We need, to the extent
17 available or possible, here in the next couple of
18 days to understand better what physics capability
19 NRC needs to have in its research program.

20 We've gotten some material on that sent
21 to the Committee about what, three or four months
22 ago? It looked like a very useful and reasonable
23 program that you have for this physics work.

24 And if that's appropriate, just tell us
25 because we are aware of that sort of thing.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 The other thing I'd like to know a
2 little more about is how do the activities connected
3 with risk informing 50.46 and the Code of Federal
4 Regulations impact what you do in your loss of
5 coolant accident program here.

6 MR. ROSENTHAL: As I mentioned earlier,
7 we're going to have to come up with performance
8 based criteria, and I think if we just wait for the
9 appropriate presentation we'll hear about that.

10 CHAIRMAN POWERS: Good.

11 MR. ROSENTHAL: And later in the day we
12 can just sneak in -- well, not sneak in -- just give
13 you five minutes on the physics probably --

14 CHAIRMAN POWERS: Yeah.

15 MR. ROSENTHAL: -- to tell you what our
16 plans are. I'll do that.

17 CHAIRMAN POWERS: We just need to
18 know -- I'm particularly interested in that area in
19 knowing what the magnitude of activities that you
20 anticipate you need to maintain just to meet
21 reasonably foreseeable obligations of the agency in
22 that area.

23 And, again, you've sent us stuff on this
24 earlier, and we're aware of that material.

25 MR. ROSENTHAL: I can take a minute now

1 if you'd like.

2 CHAIRMAN POWERS: Sure.

3 MR. ROSENTHAL: Actually much of this is
4 spurred on by our mixed oxide program where we're
5 assuming that we need a quite rigorous position on
6 our ability to do independent calculations,
7 independent order calculations for mixed oxide.

8 For that purpose, we need to develop
9 cross-sections for the ability to calculate power
10 distributions, the ability to do kinetics.

11 For that purpose we're developing a code
12 call NEWT at Oak Ridge National Laboratory, which
13 will give us cross-sections. We're continuing with
14 our work on PARCS, which will let us do spatial and
15 time dependent calculations, and as I said earlier,
16 that's coupled to the thermal hydraulic code.

17 And we're benchmarking this work to St.
18 Laurent critical experiments. We have a good
19 experimentally based program, and there's also quite
20 a fair amount of UO2 data out there to also
21 benchmark against.

22 And we will have the capability to
23 independently go from evaluating nuclear data file,
24 Brookhaven, six or seven cross-sections right
25 through to doing a reactor calculation, and that's a

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 capability that we haven't had, an independent
2 capability that we haven't had in the past.

3 So that work, it's ongoing. We have
4 some capability. We're actually applying that
5 capability at Brookhaven because we find it healthy
6 when we actually move a code from where it was
7 developed to still another location for application.
8 The bumps and warts come out of it.

9 When we get the theory down right, this
10 is higher order SN calculations themselves. Then
11 the next thing will be to develop a more automated
12 scheme to apply it because, after all, what you want
13 for your integral calculations is cross-sections as
14 a function of moderator temperature, moderator
15 density, fuel temperature, burn-up, et cetera. So
16 it's a lot of crunching.

17 I think we know how to go about doing
18 it, that there isn't some theoretical hurdle, but
19 that it's a fair -- it's just plain a fair amount of
20 work.

21 CHAIRMAN POWERS: Okay.

22 MR. ROSENTHAL: Okay. With that, why
23 don't we return to the agenda? And John Vogelwede
24 is the first presenter.

25 MR. VOGELWEDE: Good morning. My name

NEAL R. GROSS

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

1 is John Vogelwede. I'm with the NRC Research staff,
2 and I'll be talking to you this morning about fuel
3 codes and how they're used at the Nuclear Regulatory
4 Commission.

5 Fuel codes have had a long history at
6 NRC, dating back to the early 1970s. They're used
7 to calculate things like fuel temperatures, fission
8 gas release, dimensional changes in the fuel and
9 cladding, and these feed into different regulatory
10 criteria.

11 The first one on there, stored energy,
12 is perhaps the best known. In 10 CFR 50, Appendix
13 K, there's a fairly prescriptive description of how
14 fuel codes should be used. It's quite old, and it's
15 probably the most prominent place for use of these
16 codes, which is to calculate fuel temperatures or
17 stored energy of the code.

18 A little bit later, in the same part of
19 the regulations, it says that in the review of the
20 LOCA calculations, one has to accommodate other
21 things in the analysis as well. These variables
22 start getting very complicated.

23 I don't know whether you can see this
24 clearly, but it gives you an idea of the number of
25 parameters that go into calculation of fuel

NEAL R. GROSS

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

1 temperature. All of these things have been done for
2 some time.

3 For thermal performance --

4 DR. FORD: Sorry. Could you go back to
5 that? Being somewhat new at this game for fuels,
6 yeah, I can understand such a diagram, the concept
7 behind such a diagram, and you say you have codes
8 that relate to all of these interactions?

9 MR. VOGELWEDE: That's correct.

10 DR. FORD: Are those codes benchmarked
11 against data?

12 MR. VOGELWEDE: Yes, and I will be
13 showing that.

14 DR. FORD: And you'll be showing that?

15 MR. VOGELWEDE: Yes.

16 CHAIRMAN POWERS: This is one of these
17 plots that Professor Apostolakis is probably
18 particularly fond of. It does not excite me the
19 least little bit because I believe I could take that
20 same plot and put it on a fairly hierarchical
21 structure with a great deal more simplicity.

22 DR. FORD: You see this in similar
23 diagrams for cracking phenomena. Some of those must
24 be high impact items --

25 MR. VOGELWEDE: Oh, yes, of course.

NEAL R. GROSS

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

1 DR. FORD: -- unless you can forget
2 about essentially.

3 MR. VOGELWEDE: To draw a parallel,
4 there's roughly a subroutine in our codes to do each
5 one of these effects that's shown in a box up here.
6 Some of them dominant fuel temperatures. Some of
7 them are second or third order clearly.

8 DR. FORD: Okay, and we'll see those
9 algorithms.

10 MR. VOGELWEDE: Yes.

11 DR. FORD: Good.

12 MR. VOGELWEDE: And I will focus on the
13 dominant ones.

14 DR. FORD: Good.

15 MR. VOGELWEDE: Both traditionally and
16 in practice the dominant consideration has been fuel
17 temperatures, not other things like mechanical
18 performance. You establish a boundary condition for
19 fuel temperatures with the coolant temperature,
20 which is used to calculate the fuel temperatures as
21 one goes in.

22 The major uncertainties in that are gap
23 conductants. It's for a radial distribution, a one
24 dimensional distribution that is a parabolic. At
25 the center of the fuel because the gradient has to

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 be zero at the center line, that is one of the
2 boundary conditions. The cladding coolant is the
3 other. You can see here that there is a -- for an
4 open gap that may not have a very good conducting
5 gas medium in it, there's a big jump there.

6 In addition to that, fuel materials or
7 ceramics are not very good conductors, and you get
8 some fairly big temperature changes going from the
9 coolant into the center line of the fuel.

10 Some of the second order effects are
11 fission gas release. For regulatory analysis one
12 wants to know how much release there is from the
13 fuel to the plenum or the fuel rod into the fuel
14 cladding gap.

15 Normally fuel is pre-pressurized with
16 helium. That becomes contaminated with the noble
17 gases that are released and degrades the
18 conductivity. Fuel densifies when it's put in.

19 Years ago the densification effect was
20 very pronounced. These days it's usually less than
21 a percent. There's also a creep of the cladding.
22 There is usually an over pressure from the system
23 coolant, and it tends to creep down to the fuel.

24 CHAIRMAN POWERS: I noticed that you
25 have on your slide associated with the creep also

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 the formation of hydrides. Do your codes calculate
2 local hydride formation or is it just all kind of a
3 uniform hydride?

4 MR. VOGELWEDE: Uniform. Local hydride
5 formation is much more difficult. We don't get into
6 that level of microscopic formation of hydrides,
7 although it's very clear that they exist, and Ralph
8 will go in, when he talks about fuel failures, to
9 how that is taken into consideration.

10 CHAIRMAN POWERS: Okay, good. Dr. Kress
11 will be particularly interested in that issue.

12 DR. KRESS: Thank you.

13 MR. VOGELWEDE: Here's some typical --

14 DR. KRESS: I was going to ask the same
15 question.

16 MR. VOGELWEDE: -- temperature
17 predictions from our fuel code. You can see that
18 temperatures start fairly high. There's a slight
19 upswing at the beginning where the fuel densifies
20 and the gap reaches its maximum size very early in
21 life.

22 Cladding then creeps down. Eventually
23 the gap is closed so you have the best conduction
24 between the fuel and the cladding.

25 Later, as fission gas releases

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 contaminate the gap, the fuel tends to rise. Now,
2 in this particular case, this was done at a constant
3 linear power rating out to about two thirds of the
4 scale, and then the power rating was dropped down.

5 It's practically impossible to run a
6 fuel out to extremely high burn-up at the same power
7 rating. After the first two cycles, one tends to
8 shift the burden of producing power to the fresher
9 assemblies.

10 DR. FORD: Now, you said earlier on that
11 -- this is obviously a calculation --

12 MR. VOGELWEDE: That's correct.

13 DR. FORD: -- that's crucial to where we
14 go from here. Are there data to confirm that those
15 calculations are correct as a function of, for
16 instance, fuel cladding characteristics, corrosion
17 rates, et cetera?

18 MR. VOGELWEDE: Yes, there are, and I'll
19 show you some data later in the presentation where
20 experimental data is taken the reactor from fuel
21 with center line thermocouples for a variety of
22 conditions, and the predictions are actually quite
23 good.

24 DR. FORD: Now, when you say "quite
25 good," in the American sense of "quite," within one

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 percent?

2 MR. VOGELWEDE: Slightly bigger than
3 that, but relative to other predictions made in the
4 world, I think that NRC codes hold their own quite
5 well.

6 DR. FORD: What's the risk when you say
7 slightly greater than one percent? Say ten percent.
8 What was the risk impact for that?

9 MR. VOGELWEDE: For ten percent, it's
10 not terribly bad because for LOCA analysis you
11 normally do this for a lead rod. So you want a lead
12 point in the code where temperatures are maximum.
13 So there is a fair amount of conservatism built into
14 the regulatory analysis so that the uncertainties
15 are adequately covered.

16 DR. FORD: Now, will you be discussing
17 this question, the margins and uncertainties later
18 on?

19 MR. VOGELWEDE: Not very much. In the
20 research standpoint, we tend to focus on best
21 estimate calculations, and I'll show you some
22 uncertainties in fuel temperature calculations, but
23 not on the overall calculations involved.

24 Here's an example of some medium burn-up
25 fuel. This is a cross-section from fuel taken from

1 the Surry reactor. I believe that the burn-up is
2 about 36,900 megawatt days per metric ton here.

3 You can see that because it is a ceramic
4 material, it tends to crack very, very quickly
5 because of the thermal stresses imposed on it,
6 surrounded by a zirconium based alloy cladding.

7 For higher burn-up, this is from H.B.
8 Robinson. You tend to accumulate more fission
9 gases. You get more stratification across the
10 radius and the center line where the fuel is hotter.
11 You get bubble link-up, more grain growth, and
12 things like that.

13 But it's still a non-homogeneous matrix
14 with cracks, so that in many cases the material
15 properties that we're talking about are a surrogate
16 for the composition including cracks and other
17 things.

18 Here's some of the parameters that we
19 need to calculate fuel performance. The dimensions
20 and so forth of the fuel. Material properties,
21 which are most often dependent on temperature, burn-
22 up and other things.

23 We have a compendium of material
24 properties called MATPRO that is used not only for
25 these fuel codes, but for other codes used in

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 regulatory analysis as well.

2 CHAIRMAN POWERS: You've listed down
3 here MATPRO, Rev. 2, and there's a flood of data
4 coming in since 1981, and in particular, you get
5 things coming out of the Halden program on these
6 extended burn-ups and whatnot. Can you explain how
7 that is recognized in the code and whatnot?

8 MR. VOGELWEDE: We've incorporated these
9 data as they become available directly into the
10 codes. We haven't done an update to MATPRO in some
11 time.

12 You are correct and, I think, I will be
13 correct for some time in the future as the new
14 cladding alloy data becomes available, the high
15 burn-up stuff that comes from Argonne that Mike
16 Billone will be talking about as well.

17 So we incorporate this directly into the
18 code. The only reason I'm mentioning MATPRO here is
19 it's some kind of a baseline.

20 CHAIRMAN POWERS: It's a standard that's
21 used by a lot of people --

22 MR. VOGELWEDE: Yes.

23 CHAIRMAN POWERS: -- outside the agency
24 and within. Is there a plan to issue a Rev. 3 on
25 MATPRO?

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 MR. VOGELWEDE: Not at this time.

2 CHAIRMAN POWERS: Is there a reason not
3 to issue an update?

4 MR. ROSENTHAL: Do we intend at some
5 point to update MATPRO? Yes, surely. And then it's
6 just a question of competing for budget resources.
7 Most compelling is the RIA and the LOCA work, and
8 you just are going to compete for resources.

9 CHAIRMAN POWERS: We clearly understand
10 that, but I have never seen on any planning document
11 that says, okay, here's MATPRO update competing. I
12 mean, maybe I've seen it and just not recognized it,
13 but so it's not competing very well.

14 DR. MEYER: This is Ralph Meyer.

15 We did a couple of years ago actually
16 plan for the upgrading MATPRO and developed a sort
17 of revolving scheme where you would have MATPRO-10,
18 MATPRO-11, MATPRO-12, which you'd keep a historical
19 record of these because codes couldn't upgrade their
20 validation every time you change the parameter.

21 And as Jack pointed out, this simply
22 gets pushed back in favor of the more pressing
23 needs, and right now we're running on rapid
24 schedules on the two subjects he mentioned, and this
25 is just getting pushed off.

1 CHAIRMAN POWERS: Yeah, it's one of
2 those things that's really easy to put off because,
3 I mean, it's not absolutely crucial at any time.
4 But you're getting a little long in the tooth here.
5 I mean, 24 years is probably long enough to wait
6 for an update.

7 DR. FORD: If I could just follow up on,
8 materials properties, of course, is not only the
9 fuel, but also the fuel cladding.

10 MR. VOGELWEDE: That's correct.

11 DR. FORD: And corrosion properties.

12 MR. VOGELWEDE: Yes.

13 DR. FORD: And how they affect
14 conductivity.

15 MR. VOGELWEDE: And to respond to both
16 your question and Dr. Powers', the updates are made
17 continuously to the code itself. The issue that he
18 raised is reflecting this back in some kind of a
19 comprehensive document like the MATPRO manual.

20 DR. FORD: Now, I read in the August
21 21st plan, and I can't put my finger on it exactly
22 right now, but there is an inference that the
23 physical model upon which the code was originally
24 based has changed. I don't know. I can't put my
25 finger on that particular incident.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 CHAIRMAN POWERS: Which code are you
2 speaking of?

3 DR. FORD: On this August the 21st.

4 CHAIRMAN POWERS: Oh, no. We've been
5 discussing MATPRO, and I'm wondering what code are
6 we discussing.

7 DR. FORD: I know, but I'm about to come
8 onto this because it relates --

9 CHAIRMAN POWERS: Tell me what code
10 you're talking about.

11 DR. FORD: The materials properties will
12 be relevant to a specific physical failure
13 phenomenon that you're proposing. Now, what happens
14 as I seem to remember in this document, the physical
15 failure phenomenon has changed. You no longer
16 believe the original one.

17 Okay. I'll defer the question, and I'll
18 look for this particular item.

19 MR. CARUSO: I think the question he's
20 asking is the materials change over time. We now
21 have ZIRLO --

22 DR. FORD: Well, exactly.

23 MR. CARUSO: -- ZIRLO-2, I'll call it,
24 and we have M5. Do those materials get reflected in
25 MATPRO?

1 MR. VOGELWEDE: Not at this time, Ralph,
2 but they do into the codes that we're using to make
3 these calculations. So --

4 MR. CARUSO: MATPRO is not a code.
5 It's?

6 MR. VOGELWEDE: MATPRO is not a code in
7 the sense that you're talking about. It is a series
8 of articles about what material property behavior
9 should be.

10 And originally we started with
11 subroutines reflecting each one of those, and they
12 were incorporated into the codes at that time.
13 Those subroutines changed in the codes, and the
14 documentation for MATPRO did not keep up to date
15 with that.

16 MR. CARUSO: So it's the documentation
17 for MATPRO that has not been updated, but the
18 code --

19 MR. VOGELWEDE: That's correct.

20 MR. CARUSO: -- the codes themselves
21 have been updated.

22 MR. SCOTT: John will get -- this is
23 Harold Scott from Research.

24 When John gets to the slide that shows
25 the reports for FRAPCON and FRAPTRAN, those

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 documents contain all of the information about the
2 material properties. So it is documented. It's
3 kept up to date as we go along, and he'll come to
4 that slide shortly.

5 MR. CARUSO: Let me just get this clear
6 in my mind. There is a MATPRO-11 document, dated
7 1981.

8 MR. VOGELWEDE: Big.

9 MR. CARUSO: Just a document, and
10 that --

11 CHAIRMAN POWERS: It's huge. It's about
12 that thick.

13 MR. CARUSO: Right. And it contains
14 physical material properties, but it hasn't been
15 updated, although the codes that use the information
16 in that document have been updated to reflect new
17 data that has been received.

18 MR. VOGELWEDE: That's correct.

19 MR. SCOTT: And that document is new NRC
20 whatever.

21 MR. CARUSO: Which is the code
22 documentations themselves.

23 MR. VOGELWEDE: That's correct.

24 DR. RANSOM: You mean they're in house?

25 MR. ROSENTHAL: I mean, there are

NEAL R. GROSS

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

1 subtleties because MATPRO is used other places, like
2 one of the thermal hydraulics codes, but this is a
3 fuel meter.

4 MR. VOGELWEDE: I'm sorry?

5 DR. RANSOM: Is this report being done
6 in house or do you have contractors? You mentioned
7 Brookhaven applying the codes. Are there other
8 people that maintain and are doing this upgrade work
9 or is this internal?

10 MR. VOGELWEDE: Yes, and I'll get to
11 that in a moment.

12 DR. RANSOM: Okay.

13 MR. VOGELWEDE: What I wanted to say is
14 that input parameters that one uses for these fuel
15 codes is, for example, power history has to come
16 from neutronics or actual in core data, and these
17 are not stand alone operations.

18 This is kind of an interesting one. We
19 found that at least three quarters of all of the
20 problems that we've had with running the fuel codes
21 tend to be errors that are made in the input. The
22 codes aren't that friendly at the moment.

23 But the typical problem is somebody
24 attempting to put in a fuel dimension of eight
25 millimeters and actually has eight meters, and

1 things don't work out correctly.

2 NRC has two major fuel codes, FRAPCON,
3 which does steady state analysis. Here's the
4 documents that are used for that. They're fairly up
5 to date, just in some cases about a year and a half
6 old, and FRAPTRAN, which does our steady or
7 transient analysis.

8 These codes at the moment are maintained
9 and supported by Pacific Northwest National
10 Laboratories. We also have a number of
11 international users who use the codes, and we've
12 documented input from them as well where they've
13 made suggestions and updates on their own.

14 We have a fairly extensive peer group
15 program supported by a Web site, annual meetings,
16 and formal reports.

17 FRAPCON 3.2 is our current steady state
18 full performance code. It calculates fuel
19 performance that can be measures in hours, days,
20 weeks, months, things like that, even years. It's
21 basically a best estimate code. In addition to
22 temperatures, it does do fission gas release,
23 mechanical analysis, and things like crud build-up.

24 FRAPTRAN is our transient code. It does
25 a lot of things in parallel. It's used for things

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 that are minutes, seconds, milliseconds in duration.
2 A good example is the reactivity initiated event.

3 We also do other things, fuel
4 performance during the loss of coolant accident.
5 FRAPTRAN has a fairly sophisticated cladding,
6 ballooning, and rupture model in it.

7 Here's an example of an RIA, which a
8 little bit complicated. The red line represents the
9 power which is a few tens of milliseconds in
10 duration. You can see the fuel surface temperature,
11 which is the green line actually peaks and is higher
12 than the center line for a short period of time.

13 So rather than this profile that I gave
14 you originally, which showed the maximum fuel
15 temperatures at the center line, this can change
16 during transient analysis.

17 Here's a number of models which are
18 common to both codes. Both of them do fuel
19 temperatures. We have sort of one and a half
20 dimensional temperature analysis.

21 The radial analysis is the most
22 detailed, but also we can do temperatures up and
23 down the length of the cladding. This is mostly a
24 function of the axial power profile.

25 DR. RANSOM: Do these codes include this

1 effective ratcheting that they used to talk about?

2 The clad locks up with fuel and --

3 MR. VOGELWEDE: It does. It does, but
4 the ratcheting model is mostly driven by thermal
5 expansion of the fuel once the fuel and the clad
6 have locked up.

7 There is experimental data for both
8 circumferential strains and for axial strains as
9 well, from in-pile data that we attempt to model,
10 and some of that is shown in our integral assessment
11 reports.

12 DR. FORD: Could you go back one slide,
13 please? I found the reference to what I was
14 referring to earlier on. If I could just quote from
15 your August 21 thing, this relates to RIAs. "Test
16 results have shown that cladding damage in high
17 burn-up zircaloy fuel occurs in a partially brittle
18 manner as a result of the mechanical expansion
19 pellets rather than by dry out and over heating of
20 the cladding as addressed by the current criteria."

21 That is to what I was referring. A
22 different physical phenomenon giving rise to the
23 failure, are the materials properties currently
24 needed reflected in that change of understanding of
25 the degradation mode?

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 That was the reason for my question.

2 DR. MEYER: Well, this is Ralph Meyer.

3 The answer is a little bit yes and a
4 little bit no. The code isn't capable of doing a
5 straight up calculation for the failure of all of
6 these, but we're using the code in a roundabout way
7 to accomplish this, and that's really the subject of
8 my presentation which follows this.

9 DR. FORD: Okay.

10 DR. MEYER: So you can bring this up
11 again when we're talking about the details.

12 DR. FORD: Okay. Thank you.

13 MR. VOGELWEDE: Here's a number of
14 sources of data that we use. This can include both
15 in and out of pile data. Here's an example for fuel
16 center line temperatures. All of the data shown on
17 this particular slide are from the Halden reactor in
18 Norway. It's all instrumented fuel assemblies. So
19 there's a center line thermocouple. All of these
20 are mixed oxide.

21 The results are as good or better than
22 what everybody else does in the world using the same
23 openly available data. Now, you can see it at
24 higher power ratings, which is --

25 CHAIRMAN POWERS: Are Halden data really

1 openly available?

2 MR. VOGELWEDE: Eventually, yes. For
3 participants in the program, usually it's released
4 to them first, but ultimately most of the
5 information becomes publicly available and can be
6 used.

7 We're reasonably pleased with this level
8 of uncertainty, although it may seem larger. At
9 higher power ratings, between ten and 12 kilowatts
10 per foot, it becomes more and more difficult to do
11 this, but this is as well as anybody else does.

12 DR. KRESS: Is this FRAPCON predictions?

13 MR. VOGELWEDE: This is FRAPCON.

14 DR. KRESS: And the colors are different
15 burn-ups?

16 MR. VOGELWEDE: The colors are different
17 assemblies.

18 DR. KRESS: Different assemblies.

19 MR. VOGELWEDE: Different experiments in
20 Halden.

21 DR. KRESS: What burn-up level do these
22 get to?

23 MR. VOGELWEDE: Harold, do you know on
24 this one? I believe they went out to about 25 or
25 30,000 megawatt days per metric ton.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 MR. SCOTT: John, this is Harold Scott
2 again.

3 Another technique that Halden uses is
4 they take rods that come out of reactors. They then
5 drill a hole down the pellet and put a thermocouple
6 in it. So there may be a few data points there that
7 are higher than 40 or higher than 25 for MOX. I
8 think they actually have a couple of assemblies that
9 were previously irradiated.

10 DR. KRESS: Well, how is it they vary
11 the center line temperature? They vary the power of
12 the reactor?

13 MR. VOGELWEDE: Yes.

14 DR. KRESS: Just where they put the
15 assembly?

16 MR. VOGELWEDE: Yes, and not all of the
17 data points are shown here. You get data points
18 that were ten minutes or weeks on end. So it's
19 fairly easy to accumulate a large amount of
20 information.

21 I'm not sure that you can see this very
22 well, but this is the radial power distribution for
23 both codes. It has a fairly sophisticated flex
24 depression model in it based on experimental data.
25 In this particular case, they use neodymium as a

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 tracer to determine the burn-up across the radius.
2 It's very, very sharply peaked at the outside radius
3 of the fuel, often two to three times the pellet
4 average.

5 So for an RIA event where you dump a lot
6 of power into the fuel, it's preferentially dumped
7 into the periphery, this outside rim of the fuel,
8 and becomes a very strong effect for accident
9 analysis, but again, this is experimental data
10 compared to that particular module in the code.

11 And this is also another case of
12 something that we put into the code and is fairly
13 well documented, but did not show up in MATPRO in
14 its original incarnation.

15 Research is not the only office that
16 uses the fuel codes. NRR uses the code for auditing
17 in some of its reviews. NMSS uses the fuel codes to
18 determine end of life rod pressures and void
19 volumes. You do this by running the code out
20 following its power history in the reactor and then
21 cooling it down to room temperature and pressure
22 conditions.

23 We also tried to encourage this in our
24 Office of Research. Recently we held a two-day
25 training session for NMSS and NRR to teach them how

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 to use these codes. I see several training
2 participants in the room today.

3 Internationally, we have 29 member
4 organizations in our user group. There's 15
5 countries represented. We have fairly extensive
6 peer review of these codes, a lot of nice feedback.

7 We have periodic meetings. Our most
8 recent one was at Argonne in July. We have a Web
9 site use URL is given on this page.

10 We have extensive international use of
11 the codes, and the reason I've listed these names
12 here is in most of these cases we have reports that
13 have been issued either cooperatively with the NRC
14 or by the member organization on use of the code,
15 suggested improvements and things like that.

16 DR. FORD: Before you go on, this is a
17 question that has come up, the use of other codes,
18 some hydraulic codes, et cetera. You have a code
19 which is being used by quite a few people, and yet
20 EPRI has another code and NMSS had another code.
21 Who's to say which code is correct? Is it strictly
22 a question of how well it predicts the observations?

23 MR. VOGELWEDE: In many cases, yes, that
24 is correct.

25 DR. FORD: And so there's an exam, is

1 there?

2 MR. VOGELWEDE: We tend to try to
3 encourage the case where NRC can use a code when
4 it's doing regulatory review of another one. So,
5 for example, EPRI's FALCON code, which is currently
6 in for review now, we have an NRC code which can be
7 used to double check.

8 DR. FORD: But it does come down to a
9 question as to which predicts the observation the
10 best.

11 MR. VOGELWEDE: I think so, yes.

12 DR. FORD: Is there a situation when a
13 FALCON code is better than the NRC code?

14 MR. ROSENTHAL: It's under review.

15 DR. FORD: Okay.

16 MR. VOGELWEDE: To get to your point of
17 whether or not NRC's codes are good or not so good,
18 we came up with this report card for our codes, on
19 the left-hand side for the steady state version, on
20 the right-hand side for the transient version, and
21 we arbitrarily assigned letter grades to things.

22 So, for example, for steady state
23 thermal performance, we have an A or we have given
24 ourselves an A for this because we believe that our
25 ability to predict experimental data is pretty good,

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 as good as anybody else.

2 In some of the other areas, let's go
3 down to the bottom. For fuel assembly and channel
4 effects, this is a single rod fuel code which
5 doesn't have the capability to do that modeling-
6 wise.

7 So it isn't a question of whether or not
8 it does good or bad. It can't do it at all.
9 Because of this, we have through a cooperative
10 agreement with Finns, have incorporated a single
11 channel code called GENFLO, which we use with
12 FRAPTRAN to simulate some of these effects. So
13 using the two codes in tandem helps us to
14 accommodate that.

15 In the same sense, we don't have the
16 ability to do neutronic type effects, and Jack
17 already talked to you about Research's efforts to
18 use other codes in combination with one another so
19 that they could do all of these calculations.

20 DR. FORD: You showed a very complex
21 interaction diagram very early on, and you also
22 indicated just previously that fuel and cladding
23 chemistry was an F or D. Is that a fatal flaw?

24 MR. VOGELWEDE: I don't believe so. It
25 is important for some of the newer things that we're

1 looking at, such as cladding failure, but for fuel
2 temperatures and fission gas release, which are the
3 traditional end products of these codes, it is not.
4 So it depends on how the code is being used.

5 DR. FORD: And yet you say in one of
6 your documents that partial brittle failure of the
7 cladding is one of the prime reasons for an IRA
8 failure, and I would have thought hydrogen
9 embrittlement would, therefore, have played a large
10 part.

11 MR. VOGELWEDE: Yes, and Ralph will get
12 into that in his presentation.

13 DR. FORD: Okay.

14 CHAIRMAN POWERS: Let me ask you a
15 couple of questions about that slide. I see in the
16 literature a lot of discussion about directed
17 diffusion of gas bubbles along vacancy gradients.
18 Do you model that in FRAPTRAN?

19 MR. VOGELWEDE: No. The fission gas
20 release is fairly straightforward. We're looking
21 for an inventory and release from the overall
22 structure. How this is handled as far as migration
23 to either grain boundaries or something like that is
24 an effort that is done, for example, in the ANC
25 subcommittee, which we participate in, but that's

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 not yet incorporated into the codes.

2 So for general releases, I don't think
3 it's a major issue, but for transient analysis,
4 we're going -- now, I think your question led to
5 things like the rim effect, how it behave during the
6 transient.

7 There's a lot of work on that. We don't
8 have that in our codes.

9 CHAIRMAN POWERS: What I was really
10 driving at is I think your codes for on the area of
11 fission gas release are crude relative to the level
12 of understanding that's evolving --

13 MR. VOGELWEDE: Yes.

14 CHAIRMAN POWERS: -- about this, and
15 what I was driving or ultimately going to drive at
16 is the technologies that you've adopted in these
17 codes are the product of an era that's perhaps 20,
18 25 years old now, and you've upgraded them to
19 account for high burn-up effects, such as the rim
20 effect and whatnot, but you've held that structure.
21 The computational structure, the phenomenological
22 structure is being held fixed, and basically what
23 you're doing is updating some features of it.

24 And what I wanted to ask is, okay, is
25 there a point at which you say, "Fine. That was

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 good and it worked well, but now we'll go to a
2 different phenomenological formulation altogether"?

3 MR. VOGELWEDE: Yes, I would agree with
4 you there. The tradition for these codes, as you
5 point out, is decades old. It has been primarily
6 focused on traditional transient and accident
7 analysis used in the safety analysis reports and not
8 in some of the newer regulatory applications that
9 we're talking about now and I agree with you on.

10 CHAIRMAN POWERS: Let me come to another
11 one. The topic is fuel clad materials properties.
12 I have received a copy of a letter from NEI to
13 Ashok, in essence, questioning the methods by
14 which --

15 MR. VOGELWEDE: Yes.

16 CHAIRMAN POWERS: -- we collect data on
17 the structural properties of alloys, et cetera. Can
18 you comment on that?

19 MR. VOGELWEDE: We have received the
20 letter. We'll be talking about how that data is
21 currently collected and the impact of the EPRI
22 letter later on in today's presentations.

23 CHAIRMAN POWERS: Okay.

24 MR. ROSENTHAL: Yeah, at the time of the
25 ECCS rulemaking the Commission settled on a non-

1 ductility, no ductility criteria, and the question
2 before us right now is: should we change our
3 fundamental thinking and go to a toughness criteria
4 in the proposed test?

5 We'll be discussing it at length in the
6 course of the day, and I think that I'd say our mind
7 is still open about how to proceed.

8 MR. VOGELWEDE: Any other questions?
9 I'm finished.

10 CHAIRMAN POWERS: Any other questions
11 for the speaker?

12 (No response.)

13 CHAIRMAN POWERS: Well, thank you. You
14 gave us a good introduction to the issues of FRAPCON
15 and FRAPTRAN.

16 Dr. Meyer, you're going to discuss RIA
17 issues.

18 Dr. Meyer, I just can't avoid commenting
19 that the last time you put up the paintbrush plot in
20 one of these Subcommittee meetings it precipitated
21 about two hours of discussion.

22 (Laughter.)

23 CHAIRMAN POWERS: And I thought you had
24 vowed never again to put that slide up, but I notice
25 that it's in the package again.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 DR. MEYER: It's there. It's there.

2 CHAIRMAN POWERS: Should I anticipate
3 another two hours of discussion?

4 (No response.)

5 DR. MEYER: Okay. Help. I've got it.
6 Okay.

7 All right. So I want to move now from
8 the very general to the very specific and talk about
9 how we're attacking the RIA problem with an
10 empirical method to determine the cladding failure
11 threshold, and to use that failure threshold to
12 demonstrate that we can avoid losing coolable
13 geometry or generating big pressure pulses, which
14 are the main objectives in surviving this accident
15 in a benign way.

16 Is there a lapel mic? I'm sorry. I'm
17 taking just a few minutes to get going.

18 CHAIRMAN POWERS: Perfectly okay. I'm
19 not agonizing over the schedule because it's a
20 Subcommittee meeting.

21 DR. MEYER: Yeah. This presentation
22 will probably take a little longer than scheduled.
23 We've trimmed back in some other areas. I think
24 we'll come out okay at the end of the day.

25 CHAIRMAN POWERS: If there's a logical

NEAL R. GROSS

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

1 break in it, Ralph, you might want to just signal me
2 about that, and we'll take a break in the middle of
3 it if it's going to run very long.

4 DR. MEYER: Okay. Now, I think I'm
5 going to stand up and try and do this.

6 And do you have a pointer?

7 CHAIRMAN POWERS: Well, you're just very
8 demanding. That's all there is to it, Ralph.
9 You're a high maintenance individual here.

10 (Laughter.)

11 DR. MEYER: Okay.

12 CHAIRMAN POWERS: And now you want
13 batteries, too.

14 DR. MEYER: Okay. So this is the
15 outline, and I'm sure you've read that by now.

16 The issue is that there has been a
17 change in failure mechanism as we move from
18 unirradiated to irradiated and particularly heavily
19 corroded material. The initial database was taken
20 on very low burn-up fuels and irradiated materials.
21 It presumed that the failure mechanism was related
22 to high temperature and oxidation.

23 And based on that, we had arrived at a
24 280 calorie per gram limit. We acknowledged two
25 decades ago that that was nonconservative by 50

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 calories per gram. Because of a mistake in
2 interpretation, it should have been 230 calories per
3 gram, but it really didn't matter because, in fact,
4 we believe the real achievable fuel enthalpies were
5 down under 100 calories per gram. So we didn't
6 bother to make any correction.

7 When we now look at data from high burn-
8 up fuel in test reactors, principally in France in
9 the Cabri reactor and Japan in the Nuclear Safety
10 Research reactor, NSRR, we see cladding failure at a
11 much lower enthalpy than that, and in many cases
12 those cladding failures are accompanied by a prompt
13 disbursement of fuel particles into the coolant, which
14 can lead to some undesirable effects.

15 So we saw a need to make a change in
16 this 280 calorie per gram number, and in particular,
17 the issue that we described in the earlier high
18 burn-up plan was to make some confirmatory
19 assessment that was good up to at least 62 gigawatt
20 days per ton, the current limit, to show that
21 everything was okay in operating reactors at that
22 time, if indeed that was the case.

23 And we believed that was the case, and
24 we still believe that was the case, and we're going
25 to do that.

1 Now, I'll get to the paintbrush slide in
2 a minute, but there are problems with the database,
3 and the problems boil down very simply, are that the
4 two machines that are generating data are not
5 producing conditions that are sufficiently like PWR
6 conditions, and so they're giving biased results,
7 and our goal with this scaling method and in this
8 presentation is to show how we're going to
9 accommodate that.

10 In the Japanese test reactor, you have a
11 natural pulse width of the machine that's about half
12 the pulse width that we expect for this range of
13 energies in the PWR, and also a test temperature
14 that is way off. The NSRR tests to date have been
15 done in room temperature capsules. They are
16 building a high temperature, high pressure capsule.
17 In 2005-2006, we'll start taking some data at high
18 temperature.

19 So you've got two things wrong. You've
20 got a pulse width that's only half what it ought to
21 be, and you've got a test temperature that for PWRs
22 is way off.

23 And the Cabri reactor, that's a very
24 controversial subject, and members of the
25 controversy are right here in this room. But they

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 have unfortunately chosen to broaden a perfectly
2 good pulse and make it a perfectly no good pulse.
3 And so they are now taking a nine and a half
4 millisecond pulse, which would just be great, and
5 artificially broadening it to 30 milliseconds based
6 on a misunderstanding that we all had a few years
7 ago, but which has subsequently been corrected.

8 So that's the problem. So we've got a
9 database that has some atypical conditions, and I
10 think I can deal with that using our code and some -
11 -

12 MS. YANG: Excuse me. Can I make a
13 comment?

14 DR. MEYER: If the Chairman wishes to
15 entertain it.

16 CHAIRMAN POWERS: Anxious to hear what
17 you have to say.

18 MS. YANG: Thanks, Dana -- Mr. Chairman.
19 Can I back to your last slide, please,
20 Ralph?

21 I want to say for the PWR condition, the
22 rod ejection accident is a hypothetical event, and
23 even give the most conservative calculation, we
24 don't get ten millisecond pulse. The PWR typical
25 pulse is greater, a lot greater, than 30

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 milliseconds.

2 And I think at the last ACRS meeting a
3 year ago we have talked about that. I think that
4 was well documented in the transcript of the
5 meeting. I think that's the PWR condition.

6 That's why with the international
7 community debate and very thorough discussion, the
8 Cabri test reactor pulse was changed to greater than
9 30 millisecond to better represent the PWR
10 condition.

11 DR. MEYER: Let me give you a couple of
12 numbers. In a PWR, a pulse with an energy of 20
13 calories per gram will have a pulse width of about
14 40 milliseconds. A pulse width energy of about 40
15 calories per gram will have a pulse width of about
16 20 milliseconds.

17 And as you go on up to 100 calories per
18 gram from 40 calories per gram, you go from 20
19 milliseconds down to ten milliseconds. I don't
20 think there's any debate about the accuracy of that
21 number, give or take a few calories per gram.

22 The debate is whether it's appropriate
23 to test up near the failure level of the cladding,
24 which is in the vicinity of 100 calories per gram
25 where the pulses would be narrow, or whether you

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 want to test down at the energy of the expected
2 pulses in a PWR, which may be 20 or 30 calories per
3 gram with broad pulses.

4 And in fact, what Cabri is doing right
5 now is a bastardized approach of using half and
6 half. They're using a high energy and a broad
7 pulse.

8 CHAIRMAN POWERS: I guess, I mean, this
9 is a common controversy that comes up, and the
10 question of where you test. I mean, oftentimes what
11 you get into is the debate of do I do a very
12 prototypic test or do I test my codes.

13 And I'll offer the opinion that the best
14 thing to do is to test your codes because nothing
15 you can do with the Cabri or the NSRR, there is no
16 conceivable thing that you can do to make those
17 completely prototypic machines. You're always going
18 to have to be taking data out of one machine and
19 analytically transforming it to make it look like a
20 reactor accident.

21 Now, where do you come in on this? I
22 mean, where do you stand on this?

23 DR. MEYER: Okay. We have not attempted
24 to put failure models into our code so that we can
25 do straight up predictions. It's very difficult,

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 and so we have chosen to stay closer to an empirical
2 database, and I'm going to show you a method which
3 allows us to make some adjustments to the data to
4 account for these variations in pulse width and test
5 temperature so that we can then rely directly on the
6 empirical database without relying on the code"so
7 much.

8 Now, we will rely on the code to make
9 the comparative calculations, and my claim is that
10 in doing comparative calculations, a lot of mistakes
11 that we make will cancel out, and that's the basis
12 for the method.

13 And I'd like to show it to you. It's a
14 little detailed. I'm not skilled at giving this
15 presentation yet because the method is fairly new,
16 and I haven't had too many opportunities to describe
17 it.

18 So if you'll bear with me, what we have
19 here is a -- we have a broad pellet in a test, a
20 narrower pellet in some cases. Well, let me back
21 that up.

22 We have a pulse in a test with a certain
23 width. We have a pulse in a PWR with a certain
24 width, and the width of the pulse is going to affect
25 the temperature, and the temperature, in turn, is

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 going to affect mechanical properties and some other
2 expansion.

3 So here are two things that happen,
4 particularly in the Japanese test. You have the
5 initial coolant temperature, which is obvious, but
6 in the case of the pulse width, you're going to see
7 that a broad pulse will lead to a higher cladding
8 temperature at the time of a certain drain
9 occurrence than will a narrow pulse.

10 I'll show you pictures of this, and it
11 is this temperature difference then that will affect
12 the mechanical properties and also the thermal
13 strain in the calculation so that there will be a
14 tendency for a broad pulse to -- for two things to
15 happen. First of all, for the cladding to be more
16 ductile at the instant that the critical stress is
17 applied, and also for the cladding to try and run
18 away from the pellet, if you will.

19 The picture to keep in mind is that
20 you're dumping thermal energy into the pellet, which
21 is expanding more than the cladding, and it pushes
22 on the cladding and it strains the cladding.

23 What we're going to be looking at is the
24 plastic strain in the cladding. Now, there are
25 several components of strain in the cladding. One

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 of them is what we call a thermal strain. It's just
2 a thermal expansion of the cladding.

3 So to the extent that the cladding can
4 thermally expand, you don't have to stretch it, and
5 so there is a component of thermal strain that is
6 effective as well. It's not too big, but it's
7 definitely there.

8 We're going to use the FRAPTRAN code to
9 do the calculations. For today's discussion I'm
10 going to guess at the mechanical properties and
11 their temperature dependence. I'm just going to
12 make some assumptions about these. I'm not going to
13 try and convince you that my assumptions are
14 correct, but just want to illustrate the method.

15 I'm going to do two numerical examples,
16 one for HBO-1, a test from Japan, and one for REP-
17 Na10, a test from Cabri.

18 Now, there's a major difference in the
19 mode of failure in these two cases. In the Japanese
20 test, HBO-1, the cladding was clearly beyond the
21 elastic region. It was in a regime where it was
22 experiencing plastic strain, and the opposite is
23 true in REP-Na10. REP-Na10 appears to have failed
24 while it was still in the elastic region, just at
25 the end of that elastic region.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 DR. FORD: That difference is
2 understood, given the difference in temperatures,
3 one at room temperature and the other at 280 degrees
4 centigrade?

5 DR. MEYER: I'm sorry. What was the
6 question?

7 DR. FORD: Just your reference to the
8 Cabri failure was due to brittle failure, elastic
9 strains, whereas at the lower temperature in the
10 Japanese reactor it is by plastic deformation,
11 necking (phonetic), do you remember? It seems
12 opposite to what you'd expect.

13 DR. MEYER: It is opposite to what you'd
14 expect. I don't understand it. I'm going to show
15 you some data that I don't fully understand yet, why
16 the Japanese seem to see more strain in the test
17 conducted at lower temperature.

18 Now, one thing is --

19 MR. SCOTT: Ralph, this is Harold Scott.

20 Don't we think that the Cabri tests have
21 lots of corrosion and a lot more hydrogen than the
22 Japanese test? So that's one possible reason why
23 the failure mode is different, is because they have
24 different amounts of embrittlement.

25 DR. MEYER: That's a good point.

NEAL R. GROSS

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

1 MR. SCOTT: I think when you said before
2 that we knew, the way we sort of know whether it was
3 plastic or elastic is partly by looking at the
4 micrographs of the fracture.

5 DR. MEYER: Well, and also by looking at
6 strain measurements, and I've got some strain
7 measurements in here. So kind of hang onto the
8 question, and we'll come back to it, but I was
9 thinking about our analytical predictions, and we
10 don't hit the Cabri predictions as well as we hit
11 the Japanese predictions.

12 So let me start off first with the
13 Japanese one. Here was the test. These are
14 measured values now. They had a total energy input
15 of 93 calories per gram. This was reconned at some
16 time like 1.2 second. They determined the time of
17 failure by looking at the instruments, and so they
18 report a failure time on an arbitrary scale. The
19 pulse had a width of 4.4 milliseconds, and the
20 coolant temperature was room temperature, about 291.

21 Those were measured test values. These
22 are our calculated results. So we now calculate at
23 the time -- at the reported time of failure, the
24 fuel enthalpy that we calculate is 60 calories per
25 gram, which by the way is exactly the same number

NEAL R. GROSS

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

1 that Jerry has reported.

2 So they calculated the same thing that
3 we calculated quite independently.

4 At the time of failure, we look at the
5 cladding permanent hoop strain in our calculation,
6 and we get .62 percent, and we're going to say that
7 this is the failure strain. In this test, .62
8 percent average plastic strain was all it could take
9 and it failed, and at that time of failure, the
10 cladding temperature was 338 degrees.

11 Okay. That's just put in for your
12 reference to define the terms that I use. I don't
13 want to spend any time on that.

14 Here is a plot of measured permanent.
15 hoop strain. This is plastic strain in the whole
16 HBO series.

17 Now, in the HBO series, they measured
18 strain on tests that didn't fail. They didn't
19 measure strain on tests that did fail, and so here
20 we were able to plot the measured strain values as a
21 function of the peak fuel enthalpy in the HBO
22 series, and you see that it intercepts the axis
23 somewhere around 30 to 40 calories per gram.

24 So if you're in the range of 60 calories
25 per gram, which is where our calculation said was

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 the failure, then you should have a permanent hoop
2 strain of about .7 percent based on these measured
3 data, and we calculated .62 percent.

4 So so far our calculation looks credible
5 and we go on.

6 CHAIRMAN POWERS: Ralph, just a question
7 on experiment here. When you have the horizontal
8 axis here, peak fuel enthalpy increase, how
9 accurately do you know that?

10 DR. MEYER: These are reported numbers,
11 but they were calculated numbers because any time
12 you're dealing with the enthalpy, you're dealing
13 with heat loss.

14 CHAIRMAN POWERS: There's not much in
15 these short pulse.

16 DR. MEYER: John or Harold, do you want
17 to give me a plus or minus on the peak fuel
18 enthalpy?

19 MR. SCOTT: We just said ten percent to
20 each other.

21 DR. MEYER: Plus or minus ten percent.

22 CHAIRMAN POWERS: And, Harold, where do
23 you think that uncertainty is coming from? Is it
24 from just the reactor characteristics?

25 MR. SCOTT: Yes.

1 CHAIRMAN POWERS: Because there's not
2 much loss in a four millisecond pulse. You're
3 getting most of it in the fuel pretty easily.

4 DR. FORD: Again, just on experimental
5 detail so I can understand it, this test, HBO-1 --

6 DR. MEYER: Yes.

7 DR. FORD: -- that was on a fuel that
8 had a certain degree of burn-up. What about the
9 cladding?

10 DR. MEYER: Yes.

11 DR. FORD: Had that been exposed to
12 lithiated water at 288 degrees Centigrade or
13 whatever the temperature was?

14 DR. MEYER: HBO, I don't know.

15 DR. FORD: Before you did the test.

16 DR. MEYER: I don't know about the water
17 chemistry, but HBO-1 had about 40 microns of
18 corrosion. I don't know the hydrogen level. It had
19 a burn-up of about 60, 65 gigawatt days per ton in
20 the length of specimen that was tested.

21 DR. FORD: I'm inferring from your
22 remark earlier on, I think it was, that this had not
23 been exposed to any degree of corrosion, corrosive
24 environment, lithiated water beforehand.

25 MR. SCOTT: You said 40 microns.

1 CHAIRMAN POWERS: Yeah, I mean, there's
2 40 microns of corrosion on it. I'm not sure what
3 you're asking.

4 DR. FORD: I'm just trying to sort out
5 in my own mind the degree of corrosion, and I take
6 your point.

7 DR. MEYER: Okay. Just a moderate level
8 of corrosion.

9 DR. FORD: Right.

10 DR. MEYER: It's certainly not a heavy
11 level of corrosion.

12 All right. So here is the four and a
13 half millisecond pulse in the test reactor, and here
14 is the ten millisecond pulse. Here is a ten
15 millisecond pulse with the same energy.

16 Okay. Now, in the calculation that we
17 ran with this pulse, we get the failure somewhere
18 over at this time, right about here, and that
19 failure occurred at .62 percent plastic strain.

20 So now the game is to go on this curve
21 and look for the time at which the plastic strain is
22 .62 percent. Well, I've got to tell you right up
23 front that it won't be exactly .62 percent because
24 it's temperature dependent. The failure strain is
25 going to -- we expect it to be temperature

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 dependent.

2 Now, here is a comparison of cladding
3 temperature as a function of fuel enthalpy for those
4 two pulses, and you can clearly see here that for
5 any enthalpy value which you can think about as the
6 amount of pellet displacement, because to a first
7 approximation, the amount of enthalpy in the fuel is
8 the amount of thermal expansion, and the pellet is
9 hard. The cladding is not so hard. It pushes on
10 the cladding.

11 So for given amount of pellet
12 displacement, you see that the cladding temperature
13 in the narrow pulse is significantly less than it is
14 in the broad pulse.

15 So now what we have to do is take that
16 temperature difference into account in the failure
17 strain that we're going to associate with that .62
18 calculated number.

19 Okay. I've said those words. I want to
20 skip this slide for now.

21 Okay. This is an assumption. Now, what
22 I've plotted here is total elongation as a function
23 of temperature. The failure strain is a total
24 elongation, but total elongation is not a fundamental
25 materials property. It's affected by geometry, by

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 the gauge length and dimensions of the specimen, and
2 so if we look at total elongation data from tests
3 that may have been on axial specimens or on ring
4 specimens with different gauge geometries, then the
5 effective gauge geometry of this non-uniform
6 deforming cladding, we're going to see a temperature
7 dependence.

8 Now, frankly, I looked at EPRI's plotted
9 data, and this is not quite as bit a slope as EPRI
10 has in their report, but it's a ballpark number, and
11 so I'm just going to use this number to illustrate
12 the method.

13 Now, in effect, what we're doing is
14 we're going to assume that the total elongated --
15 the failure strain in the specimen, which is a total
16 elongation, is going to have the same temperature
17 dependence as this. So we just ratio the two.

18 In effect, what I'm doing is drawing a
19 different line that would be right down around there
20 somewhere, which is going to be the locus of failure
21 points in this particular specimen.

22 So this is what I just said in words,
23 and so we're trying to find a new failure strain at
24 a different temperature, and we need a temperature
25 and a strain combination that are on that adjusted

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 line.

2 This is the part that I haven't figured
3 out how to explain clearly yet, but from the nods, I
4 think that you --

5 CHAIRMAN POWERS: Know exactly what you
6 mean.

7 DR. MEYER: -- understand what I'm
8 trying to do.

9 CHAIRMAN POWERS: I understand.

10 DR. MEYER: Anyway, when we go through
11 this, we find that the new failure strain is .75
12 percent at a cladding average temperature of 380K.
13 So the PWR pulse in this case is or the wider pulse
14 is at a higher cladding temperature. There's a
15 little more ductility. So you get a little higher
16 failure strain, and the corresponding fuel enthalpy
17 at that time is 69 calories per gram.

18 So in this example, a nine calorie per
19 gram increase as a result of pulse width, just pulse
20 width. I haven't altered the test temperature yet.
21 That's going to be a bigger deal than this, but I
22 wanted to look separately at these two effects for
23 the HBO case.

24 So the next thing we did then was to --
25 let me back up. I need to talk just a minute about

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 this detail.

2 And this is fascinating, and it's also
3 difficult for me to explain. But now I'm going to
4 go back one, two, three, to this figure. This is
5 the ten millisecond pulse here, ten millisecond
6 pulse.

7 And I have plotted on this same figure
8 the permanent hoop strain and the cladding
9 temperature. Now, the peak fuel enthalpy occurs
10 right about here. The enthalpy peaks out because
11 heat losses then are as big as the heat input in the
12 tail of the pulse, and when the fuel enthalpy peaks
13 out, you don't get anymore cladding hoop strength.

14 But the cladding temperature continues
15 to rise. Okay. You back up. Somewhere around here
16 is what I call a point of no return. If you don't
17 have enough strain to fail it, if you haven't
18 reached the failure strain at this point, you're not
19 going to reach it up here because the cladding
20 temperature is starting to increase more rapidly
21 than your strain value is increasing.

22 So the point is if you had done a test,
23 say, with a peak fuel enthalpy of 75 calories per
24 gram and observe the cladding failure at 60 calories
25 per gram, if you go back now and run a test with a

NEAL R. GROSS

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

1 60 calorie per gram peak fuel enthalpy, it won't
2 fail that cladding because here's where the 60 is
3 going to occur, and it's happening too slow.

4 So we had, in fact, to increase the
5 energy in the deposited pulse in order for the
6 cladding strain to keep up with the temperature
7 increase.

8 So we were not able to find an adjusted
9 failure strain in the ten millisecond pulse without
10 increasing the energy in that pulse. We increased
11 it incrementally ten percent, 20 percent, 30
12 percent. The ten percent didn't do it. Twenty
13 percent did it. Thirty percent did it and gave the
14 same answer as 20 percent.

15 And now if you have some feeling for
16 that concept, now you will understand that when we
17 try and account for this huge difference in test
18 temperature from room temperature up to nearly 300
19 Centigrade, that we need a large increase in pulse
20 energy in order to find that failure strain at the
21 right temperature in a reasonable pulse.

22 So the pulse that we used had twice the
23 energy in it as the original pulse. So this is the
24 original NSRR pulse, and this is the ten millisecond
25 wide pulse with twice the energy, and in that pulse,

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 we now find an adjusted failure strain of 1.71
2 percent. There's the temperature at 100 calories
3 per gram.

4 Now, if you go back to the measured
5 failure strain for HBO, you'll find that 1.7 -- that
6 at 100 calories per gram, 1.7 is just about on the
7 line. So this is a credible number.

8 The combined effect of pulse width and
9 test temperature with the temperature dependence
10 that we assumed is 40 calories per gram. It's huge.
11 That means on the paintbrush slide that those NSRR
12 points are going to have to be moved up about 40
13 calories per gram.

14 If we used the larger temperature
15 dependence that EPRI used, it would go up further,
16 and it's now up into the range where you have to
17 wonder whether it would fail at all by a cladding
18 mechanical interaction or whether it would go into
19 DNB and fail by a high temperature mechanism up
20 around 160 or 170 calories per gram.

21 Okay?

22 CHAIRMAN POWERS: Back to your step, do
23 you, in fact, do a step-wise conversion? The way
24 you presented it, Ralph, was first you made a
25 correction without correcting for the water

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 temperature, and then you corrected for the water
2 temperature.

3 Do you, in fact, when you actually sit
4 down and do it, do those things all at once?

5 DR. MEYER: Yeah. The second one was
6 done all at once. I didn't do the second one with a
7 four and a half millisecond pulse. So the second
8 calculation that shows the 40 calories per gram is
9 the sum of both.

10 So in this case order of magnitude was
11 you got ten calories per gram from the pulse width
12 and another 30 calories per gram from the test
13 temperature, giving you about 40 calories per gram.

14 CHAIRMAN POWERS: Okay, but that was for
15 pedagogical purposes that you did that. When you
16 really do it --

17 DR. MEYER: Yeah.

18 CHAIRMAN POWERS: The difficulty I have
19 in your way of presenting is when you did the first
20 step, you did it for a ten millisecond pulse, but
21 the lower energy. Okay?

22 DR. MEYER: Yeah.

23 CHAIRMAN POWERS: Whereas in the
24 reactor, you would actually have a broader pulse if
25 you did a low energy pulse. Okay?

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 Whereas in the second step where you did
2 both corrections, you had what's appropriate for a
3 reactor pulse.

4 DR. MEYER: In the first case, we
5 increased the power 20 percent. In the second case,
6 we increased it 100, and it included the pulse width
7 effect.

8 CHAIRMAN POWERS: Yeah, you did two
9 things. In the first example, the step that you
10 showed, you increased the pulse width, and you
11 increased the energy.

12 DR. MEYER: Yes.

13 CHAIRMAN POWERS: Okay, but the increase
14 in the pulse width is not reflective of the width
15 you would get in a PWR if you did a pulse of the
16 energy magnitude that you did.

17 DR. MEYER: Oh, yeah. Yeah, it is
18 because this curve is really flat. Once you get to
19 60, 70, 80 calories per gram, it's asymptotically
20 going to ten milliseconds.

21 CHAIRMAN POWERS: Okay.

22 DR. MEYER: So it doesn't make much
23 difference, but you're right. When we do this, we
24 will incorporate that dependence in it, but it's a
25 small thing.

1 DR. FORD: Could I ask a question again
2 on your specific methodology? Your approach for
3 correcting for the pulse width seems dependent very
4 much on the interaction between the average cladding
5 temperature and the hoop strength.

6 DR. MEYER: Yes.

7 DR. FORD: What is the uncertainty of
8 that, given, for instance, that the failure strains
9 will change dependent on the amount of corrosion?

10 If you're going to apply it to BWRs, you
11 might be talking about barrier fuel cladding. All
12 of these are going to be interactive. So there's
13 some uncertainties in these very precise 1.71
14 percent cladding, a lot of uncertainty in that.
15 What degree of uncertainty are we talking about
16 because of these other material property changes
17 which we don't know?

18 DR. MEYER: Okay. I've got to make a
19 distinction between two types of uncertainties.
20 One, the uncertainty in the material --

21 DR. FORD: Yeah.

22 DR. MEYER: -- and the properties and
23 the amount of corrosion and random defects and
24 things like that.

25 DR. FORD: Right.

NEAL R. GROSS

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

1 DR. MEYER: It is completely outside of
2 this scaling method because what we're doing is
3 looking at test HBO-1, that test run specimen, and
4 asking: what if I took that exact same specimen and
5 tested it with a PWR shaped pulse to failure?

6 DR. FORD: Yes.

7 DR. MEYER: So right away all of the
8 material variabilities are not involved because I'm
9 assuming that I'm still working on the HBO-1
10 specimen. The uncertainty in this parameter is
11 going to be determined by two things. I think by
12 far the largest is the uncertainty and the
13 temperature dependence of the mechanical properties.
14 They're poorly known at this time. EPRI's figure
15 has a nice average line, but the data scatter is
16 very large.

17 We are hoping to narrow this down
18 quickly in our program at Argonne, and so we hope to
19 make some improvements on that, but even within
20 these large uncertainties, you can now begin to get
21 an order of magnitude feeling for what it does to
22 the data.

23 I'm going to skip this slide for a
24 minute, and now this is the second example. This is
25 REP-Na10, and these are the test parameters, real

1 numbers: 170 calories per gram total energy input;
2 measured time of failure; 31 millisecond pulse; and
3 553 Kelvin initial coolant temperature. Those are
4 all measured values.

5 So we run the calculation for that
6 pulse, for those exact conditions, and this time we
7 don't get quite as good agreement as we had before.
8 If we take their reported time of failure, we get 68
9 calories per gram fuel enthalpy at the reported time
10 of failure.

11 IRSN reports 61 calories per gram at the
12 time of failure. IRSN also reports that there is no
13 plastic strain in their calculation for this
14 specimen. At the time of failure we get a little
15 bit of plastic strain.

16 So what we did just for the purpose of
17 illustrating the example is to move the failure time
18 back a very small amount so that we were still in
19 the end of the elastic region. So this is an
20 artificial example, but it's still pretty close to
21 REP-Na10.

22 So we moved it back till it was right at
23 the end of the elastic region, and at that new
24 assumed failure time, we had 59 calories per gram,
25 which is uncannily close to their 61 calories per

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 gram.

2 Now, since we're talking about failure
3 in the elastic region, strength becomes the
4 important parameter and not ductility. So we now
5 want to look at the stress on the cladding, and so
6 the hoop stress at that new assumed time of failure
7 is 450 megapascals, and the cladding average
8 temperature at that time is 743 Kelvin.

9 CHAIRMAN POWERS: When you say that IRSN
10 reported no plastic strain in the specimen, is that
11 they saw no evidence of plastic strain or they
12 calculated no --

13 DR. MEYER: No, it's calculated. In the
14 Cabri tests, the Cabri tests are in sodium.

15 CHAIRMAN POWERS: Right.

16 DR. MEYER: And they cannot measure
17 accurately the strain on a rod that has failed
18 because you get a sodium interaction with the O2 and
19 the swelling, and so they can't go in after the fact
20 and measure the strain on the failed rods.

21 I'm going to show you some data though,
22 and that's one slide that I skipped over, and it
23 will indicate that we're sort of in the crossover
24 point, and I don't know which would be correct, some
25 strain or no strain.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 CHAIRMAN POWERS: What you're also
2 saying here de facto, I believe, is that whatever
3 calculational tool the French are using, it's not
4 getting results that are wildly different than
5 what's your calculational tool is giving.

6 DR. MEYER: That's correct. That's
7 correct.

8 Okay. So now in this case, this is the
9 Cabri pulse, 31 calories per gram, and here is a ten
10 millisecond pulse with the same energy, and so we're
11 now going to look at the failure stress for the
12 pulse as we calculated it, and then we're going back
13 on this ten millisecond calculation and look for
14 that same failure stress adjusted for temperature
15 changes.

16 So it's exactly the same scenario as you
17 had for the strains, except now we're dealing with
18 stresses.

19 Don't ask me to explain this, but Mike
20 Billone is here. He can explain this if there are
21 any questions, but this is a plot of fracture
22 toughness versus temperature, and fracture toughness
23 is related to the fracture stress, and we're out in
24 a temperature region up here.

25 Actually I had already just assumed a 25

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 percent reduction in failure stress, in macroscopic
2 failure stress for a 100 degree temperature
3 reduction. This curve shows about 35 percent
4 reduction.

5 If you take a temperature here and you
6 go down 100 degrees, it's about a 35 percent change
7 on this figure. We took 25 percent in our
8 calculation.

9 So, again, it's an assumption, but it's
10 in the ballpark, and so here are the calculated
11 results. The 450 megapascal failure stress came
12 down to 350 megapascal because we're now nearly 100
13 degrees lower in temperature, and the failure stress
14 will be lower.

15 And this lower stress occurred at a time
16 where the fuel enthalpy increase was 40 calories per
17 gram instead of the 60 calories per gram that we had
18 calculated. So in this example, the REP-Na10 number
19 would be adjusted downward by 20 calories per gram.

20 And if I can go back, these are measures
21 strain values from the REP-Na series. These are all
22 of the tests that did not fail, and they're a
23 mixture of several things, and I don't think we know
24 quite how to sort them out yet, but there are two
25 MOX tests in here. The MOX results might be

NEAL R. GROSS

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

1 different than the UO2 results, and there are narrow
2 pulses. Here's a couple of nine millisecond pulses,
3 three of them, and broad pulses, 75, 35, 34.

4 These lines are not statistical fits.
5 These are just drawn to help aid the eye. Somewhere
6 in the range of 50 to 80 calories per gram is where
7 you should leave the elastic region and enter the
8 plastic region in the REP-Na test.

9 And we were at 60 and calculating a
10 small amount of plastic strain. IRSN had calculated
11 no plastic strain. So, again, the result is
12 reasonable, but there's not a very sharp point on
13 the analysis yet.

14 So here are the conclusions. Both pulse
15 width and testing temperature affect the results,
16 and the amount of that effect depends strongly on
17 the temperature dependence of the mechanical
18 properties. The mechanical properties aren't well
19 known. They're under investigation. We hope to
20 make improvements. The effect of pulse broadening
21 in Cabri, in our example, was large, about 20
22 calories per gram. The effect of pulse atypicality
23 in NSRR was modest, about ten calories per gram, but
24 the effect of low test temperature in NSRR was very
25 large, about 30 calories per gram, and these two get

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 added together. So it's a big adjustment. And I've
2 already said that.

3 Okay. Now, I have one other slide. I
4 have one other conclusion that's not on this slide.
5 If there was ever a Friday night calculation that
6 was reported on Monday morning, this is it, but it
7 occurred to me in looking at the plot that I had of
8 permanent hoop strain and cladding temperature on
9 the same graph where there was this what I call the
10 point of no return, and I've said it already, you
11 cannot fail a rod with a peak enthalpy in the pulse
12 that's the same as the enthalpy number in the
13 failure that was determined from a little larger
14 pulse. You've got to have a little extra.

15 How can I say this? About the last ten
16 calories per gram aren't going to cause a cladding
17 failure, and so here is some free margin that I
18 don't think anybody recognized before. When we
19 calculate peak fuel enthalpy and compare it to
20 something with the neutronics calculation, you know,
21 we do a neutronics calculation and we calculate a
22 peak fuel enthalpy, that peak fuel enthalpy has to
23 be something on the order of ten calories per gram
24 higher than the failure enthalpy in order to
25 actually cause the failure.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 And I know this isn't said very clearly,
2 but there is some margin in here that we didn't
3 recognize before that we can take credit for. It's
4 on that order. It may be five; it may be 15.
5 Hopefully in a few months of working on this we'll
6 be able to say what it is with confidence and use it
7 in our final assessment.

8 Now, how we're going to wrap this up is
9 we're going to do the best job we can by the end of
10 this calendar year, and we're going to put it out.
11 This is a never ending thing. We can do mechanical
12 properties measurements and calculations for years
13 and years, and we've been going on a long time on
14 this one.

15 We have a program in place to do
16 mechanical properties. I'm going to turn the
17 mechanical properties part over to Argonne and say,
18 "Give us your best temperature dependence by the end
19 of the year."

20 The analytical part, John and Harold are
21 going to work on that. We're going to do the best
22 that we can, and then we're going to write it up and
23 try and define this cladding failure boundary
24 empirically as a function of oxide thickness with
25 just these adjustments.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 We're going to use the cladding failure
2 boundary as the de facto limit in our assessment. I
3 think it's going to work. I believe we will be able
4 to show from the neutron kinetics analyses that have
5 been done to date that for reasonable control rod
6 worth we cannot generate enough fuel enthalpy in a
7 PWR rod ejection accident to reach the cladding
8 failure boundary.

9 I think that's going to be the result
10 based on preliminary evidence. If that's the case,
11 we can still with this cladding failure boundary and
12 say this is plenty adequate because if you don't
13 fail the cladding, you're not going to get any
14 energetic fuel coolant interactions. You're not
15 going to lose fuel particles and have questions come
16 up about is it coolable.

17 And we're going to do this all by the
18 end of the year and issue it as a research
19 information letter.

20 DR. FORD: When you look at the second
21 bullet on your previous graph or slide, the
22 mechanical properties are not well known. That
23 seems to me a kind of fairly fatal or high risk item
24 because when you look at all of the variables,
25 strain rate, degree of hydriding, whether you have

NEAL R. GROSS

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

1 barrier fuel cladding or not, there's a lot of
2 variables, degree of plastic constraint.

3 But are all those mechanical properties
4 going to be available by the end of the year?

5 DR. MEYER: No, but in our method, the
6 mechanical properties are already imbedded in the
7 test result, and so this is a second order. It's
8 the second order effect, the correction that's going
9 to be affected by how well or how poorly we know the
10 temperature dependence of these mechanical
11 properties.

12 And I think it's only the temperature
13 dependence that we need to get a handle on. The
14 biggest uncertainty in doing a laboratory test is in
15 adequately representing the condition of the stress
16 applied on the cladding, which is probably a plain
17 strain stress, which is very hard to replicate in a
18 test.

19 Now, we can do it. We have a plain
20 strain specimen design that can approximate that,
21 and we will try and do that. There will be
22 uncertainty in it, but I think it's a big
23 uncertainty and a second order effect can be
24 tolerated.

25 DR. FORD: In your program plan, the

NEAL R. GROSS

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

1 August 21st program plan, you also mention with
2 respect to this particular problem the Vitanza
3 multi-variable algorithms. Could you say something
4 about that?

5 DR. MEYER: I'm sorry. Try --

6 DR. FORD: Carlo Vitanza has come up
7 with a multi-variable --

8 DR. MEYER: Oh, yeah. In the plan we
9 mentioned three possible approaches to this, and we
10 said we thought we could get one of them to work.

11 DR. FORD: Right.

12 DR. MEYER: One of them is a straight up
13 calculation. We do not have a failure model in our
14 code. We can calculate strain energy density. It's
15 in the code now, but we don't have a good failure
16 model, and we are not pursuing that.

17 I think, John, have you looked further
18 at the Vitanza type approach? And I've got to ask
19 John if we're actually doing anything on that.

20 My own approach is this empirical
21 method, and I don't know whether we have made any
22 further progress on the Vitanza type approach.

23 MR. VOGELWEDE: This is John Vogelwede
24 again.

25 Vitanza's correlation is well known to

NEAL R. GROSS

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

1 us. It has a fairly significant pulse width and
2 corrosion effect in it. We have investigated
3 whether or not we could use something like this to
4 do the same transformation that Ralph is talking
5 about here.

6 The only thing that we've done so far is
7 to adopt something that he did in his correlation
8 where he goes from a relative to an absolute
9 enthalpy to account for the NSRR data from Japan.
10 The calculations are not too bad. He's published
11 that already.

12 DR. MEYER: So I think the answer is
13 that we're going to use one of the three approaches.

14 CHAIRMAN POWERS: It seems to me, Ralph,
15 that in this empirical approach that you've created
16 here you're now creating a vulnerability to the
17 selection of specimens that have been tested.

18 DR. MEYER: yeah.

19 CHAIRMAN POWERS: And so what do you do
20 about that? I mean, there's a natural bias to pick
21 specimens that hold together well and look nice when
22 you do the testing. What do you do about that?

23 DR. MEYER: Well, fortunately, there
24 have been some selections made that don't fit that
25 pattern, and I think those turn out to be key tests.

NEAL R. GROSS

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

1 REP-Na10 was heavily corroded. REP-Na8 was also
2 corroded, but it has a really squirrely pulse width,
3 and that one is going to be a little more difficult
4 to deal with. It had a double hump pulse at 75
5 milliseconds across.

6 CIP01, the ZIRLO rod, which probably did
7 not fail, is a good rod, and it will give us a good,
8 non-failure point. I think we can treat the
9 adjustment to the non-failure point just like this
10 one. We just say it was a non-failure.

11 I'm not quite sure how we do it, but I
12 think from looking at CIP01, I think CIP01 was right
13 at the point of no return, just past the point of no
14 return because it gave some signals, and yet it
15 still seems to have sufficient gas in the plenum,
16 and we haven't gotten reports yet on the
17 pressurization test to know whether it really failed
18 or not failed, but I would say it didn't fail at
19 this state of understanding.

20 CHAIRMAN POWERS: I guess what I'm
21 asking is: do we know enough about fuel rods coming
22 out of the reactor to know that we have a
23 representative or at least a conservative sampling
24 of the fuel rods?

25 DR. MEYER: Yeah, I actually think we

NEAL R. GROSS

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

1 do, and particularly when you recognize that the
2 newer alloys, the M5 and ZIRLO or Alloy A. What is
3 the next one coming down the line?

4 These claddings don't corrode very much,
5 and I don't think the reactivity accidents are going
6 to challenge those claddings. I think you're going
7 to have a lot of -- even the Russian E110, which we
8 describe in not very favorable terms for its LOCA
9 behavior, sails through these tests. Of course,
10 they only collect five or ten microns of oxide on
11 them, but we have never seen a PCMI failure in an
12 E110 rod yet. They're all high temperature
13 ballooning and rupture things.

14 So I really think that's the situation
15 for M5 and next generation ZIRLO at least, if not
16 this generation ZIRLO, the way it's operated in this
17 country with lower corrosion. That is, you know, as
18 soon as you get down below 60 or 50 or 60 microns of
19 corrosion, I don't think you're going to have any
20 problem at all.

21 CHAIRMAN POWERS: Rosa.

22 MS. YANG: I think I just want to make
23 two comments. One -- sorry. This is Rosa Yang,
24 EPRI -- one of them, I just want to remind
25 everybody, especially the last year, October 9th,

NEAL R. GROSS

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

1 this particular meeting there was a very detailed
2 presentation on the RIA methodology that we have
3 submitted for review that was presented by Robbie
4 Montgomery on the methodology.

5 I think Ralph Meyer here presented
6 something, and I think he correctly called it the
7 scaling method, and I think it's very interesting,
8 but I think as some of the questions already alluded
9 to, that this is a highly complex and nonlinear
10 phenomenon. It is difficult to really just look at
11 one parameter and scale it to the light water
12 reactor or the PWR condition.

13 I think the correct way to do it is to
14 really model the phenomena as best as you can, and
15 then try to benchmark that with measured parameter
16 like the cladding strain, like the temperature, like
17 different phenomena that you can model, and that's
18 what we have attempted to do in this submittal.

19 The intent is to model the NSRR data,
20 the Cabri data, and try to benchmark with measured
21 parameter, and then from there trying to make the
22 link from the test condition to the PWR condition.

23 I think, you know, given the complexity
24 of the issue, that's probably the only way you have
25 a chance of success, and that might address this

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 issue, Mr. Chairman, you're asking about have we
2 tested the relevant material, you know. Have we
3 covered enough of the variable so that that is an
4 attempt that we have tried.

5 And one other comment that I wanted to
6 make was at the last year's meeting, I think the
7 conclusion was we have a good understanding of this
8 phenomenon, and given the light water and PWR
9 condition, there's probably sufficient -- not
10 probably -- I guess there is sufficient margin that
11 this is an area that maybe we're getting to a point
12 of diminishing return; that we shouldn't spend a lot
13 of resources trying to sharpen the pencil further.

14 And I think that's consistent with a
15 comment just made that REP-Na10, which failed at,
16 you know, 70 or 80 calories per gram, and is highly
17 spalled rods, and given the advanced alloys that are
18 being used in the industry, that corrosion is much
19 lower. And I think we didn't discuss in detail,
20 but one of the key phenomena that's important for
21 the failure threshold for the RIA type of thing is
22 the cladding mechanical properties. So advanced
23 alloys should behave much better than REP-Na10 being
24 talked about here.

25 CHAIRMAN POWERS: Well, it seems to me,

NEAL R. GROSS

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

1 responding to your comments in order, if I can
2 remember them all, is that Ralph has linearized this
3 phenomenon to do his empirical process, and the
4 detailed phenomenology approach that Robbie
5 presented at our last meeting, in fact, he invented
6 the phenomenon in developing his model, and that's
7 the one that's the source of controversy there, is
8 whether you actually have a dependence that's
9 hypothesized or not.

10 And I guess we'll eventually hear CA
11 review of that phenomenology or phenomenological
12 report that NRR is coming out. Do we know when?
13 Did you see that review?

14 I think I'm getting an answer to my
15 question.

16 MS. SHOOP: This is Undine Shoop with
17 the Office of Nuclear Reactor Regulation.

18 We're currently planning to complete
19 that review by next summer based on getting the
20 information from Ralph Meyer and being able to also
21 assess that information as part of our process.

22 CHAIRMAN POWERS: Okay. So in the next
23 maybe a year from now we'll get that.

24 And then as I understand what Ralph
25 presented, what he is saying is that had we done

NEAL R. GROSS

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

1 REP-Na10 in a completely prototypic test, in this
2 hypothetical test it would not have failed it at 61
3 or 69, depending on how you look at it, but in fact
4 would have failed at 40 calories per gram.

5 DR. MEYER: That's what I'm saying, yes.
6 That's correct.

7 With regard to the mechanical properties
8 and the linear relation that I'm using, EPRI is
9 using a linear relation for this.

10 CHAIRMAN POWERS: Yes.

11 MS. YANG: It wasn't linear. No, no,
12 no, it wasn't linear.

13 DR. MEYER: Yeah, it was. It has got a
14 --

15 MS. YANG: What is linear?

16 DR. MEYER: -- A plus BT equation right
17 on the graph.

18 MS. YANG: No.

19 MR. OZER: Can I make a comment, Mr.
20 Chairman?

21 CHAIRMAN POWERS: Sure.

22 MR. OZER: This is Odelli Ozer, EPRI.

23 I think what we see as far as the
24 failure criterion is concerned is that the rods fall
25 into two categories. The rods that are heavily

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 spalled have a lower failure line than the rods that
2 are not heavily spalled.

3 The rods that are heavily spalled are
4 pushed well beyond their design corrosion levels,
5 and to use a single correlation that folds in the
6 spalled rods as well is really not fair for the rods
7 that we will be seeing in the future or the rods
8 that are operated within their limits.

9 DR. MEYER: I'm not sure how far you
10 want to go down this path, but this is --

11 CHAIRMAN POWERS: Oh, a little ways.

12 DR. MEYER: -- this is an interesting
13 point because, frankly, we don't believe that the
14 two populations are separable. Spalling, the
15 occurrence of spalling, it doesn't instantly lead to
16 bad mechanical properties. It eventually leads to
17 local hydride blisters, and as these local hydride
18 blisters grow and get thicker and thicker, they have
19 a deteriorating effect on the mechanical properties,
20 and it, in fact, has been tested as a function of
21 blister thickness at Penn State, and the transition
22 from zero thickness to basically through the wall is
23 a nice, smooth, uniform transition.

24 So we tend to think that these are all
25 part of one population and treat it in that way.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 CHAIRMAN POWERS: Well, I guess what I
2 sense the issue is is this. You've got a database
3 now of a bunch of empirical tests done in modestly
4 non-prototypic conditions, and you've come up with a
5 methodology here that you would like to correct all
6 of those data for effects that you think you
7 understand in a fairly linearized way. Okay?

8 You're not seeing such high nonlinearity
9 here that it precludes that, and you will do so.
10 And most of those experiments that you are going to
11 make that correction for are zircaloy clad rods.

12 DR. MEYER: That's correct.

13 CHAIRMAN POWERS: And now you get a
14 curve out, and you say, "Okay. If you're using
15 zircaloy, please show me in your design basis
16 analysis that you don't have any accidents that will
17 give you an energy input greater than this threshold
18 here."

19 Okay. The concern that comes about
20 says, "Gee, I'm not using zircaloy. I'm using M65,"
21 or whatever the next. Maybe M16 is what they want
22 to use. I don't know.

23 (Laughter.)

24 CHAIRMAN POWERS: And they're saying,
25 "Hey, don't constrain me with that curve and invent

NEAL R. GROSS

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

1 me some other curve."

2 And so the question I put to you is:
3 who invents that second curve?

4 DR. MEYER: Yeah. We, of course, want
5 to generate those kind of data. That would require
6 high burn-up rods clad with ZIRLO and M5, which we
7 are proposing, and we hope the industry will
8 cooperate with us and allow us to do that in the
9 future.

10 We don't plan to hold this issue open
11 until that's done because we have some other clues
12 to go on, and ironically one of the most advanced
13 set of clues that we have is from our Russian
14 program where they have measured mechanical
15 properties on unirradiated and irradiated E110,
16 compared that to zircaloy.

17 And I don't know if Mike wants to say
18 any more about that, but they don't see big effects
19 of the irradiation process or big differences from
20 the zircaloy properties.

21 So you know, I think most of the action
22 is in the corrosion. Whether zircaloy, ZIRLO, or
23 M5, the dominant factor is going to be how much
24 hydrogen have you allowed into that cladding as a
25 consequence of the corrosion process.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 And we also are studying pre-hydrided
2 materials, and in fact, are proposing for the
3 extended work on high burn-up ZIRLO and M5 that we
4 study the efficacy of using pre-hydrided specimens
5 as a surrogate for burn-up for these mechanical
6 properties tests.

7 And I think if we can go that distance,
8 then we'll have Zirconium-10, zirconium niobium, and
9 zirconium with a mix of 10 and niobium. We'll have
10 three alloys at high burn-up, and we have the
11 ability to do pre-hydrided work. We have a new
12 program starting at Penn State on the mechanisms of
13 this, and so the beginnings of a nice way of
14 wrapping this all up, confirming our guesses that
15 we're going to make this year and next year, and
16 developing a methodology which will allow us to do a
17 lot of testing on pre-hydrided, unirradiated
18 specimens and avoid the expense of going to a hot
19 cell for all of this.

20 CHAIRMAN POWERS: Other questions to the
21 speaker?

22 I'll pose a couple of issues for members
23 to think about. One issue is this question of where
24 we test, prototypic or whether we're challenging
25 codes, and the second issue to think about is the

NEAL R. GROSS

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

1 question of who draws the second curve. Is it the
2 NRC's responsibility to draw out failure curves for
3 advanced alloys that the industry brings forward or
4 is it the industry's responsibility to develop that
5 database and have the NRC review it?

6 And with that, I will recess until ten
7 after the hour.

8 (Whereupon, the foregoing matter went
9 off the record at 10:52 a.m. and went
10 back on the record at 11:13 a.m.)

11 CHAIRMAN POWERS: Let's come back into
12 session.

13 Dr. Meyer, there's no relief for you.
14 You have to do this session as well.

15 DR. MEYER: Well, I want to shift gears
16 now to the loss of coolant accident, and as Jack
17 mentioned this morning, this is one where we're
18 trying to make some definitive progress by next
19 summer. So this is still a fairly fast track item
20 at this point.

21 Now, there are really three problems
22 that we're addressing. One of them that we've been
23 talking about for several years, and that is that
24 for high burn-up fuel the ductility of the cladding
25 is affected by burn-up and corrosion, and this may

NEAL R. GROSS

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

1 have some impact then on the embrittlement criteria
2 that are in 10 CFR 50.46.

3 A second problem that we're looking at
4 is about one of the evaluation models. This is an
5 Appendix K type thing rather than a 50.46 type
6 thing. The oxidation kinetic models, which are used
7 both for calculating the oxide thickness and the
8 metal water reaction heat, may be affected by burn-
9 up and corrosion, and we need to check that out.

10 And then the third problem that we're
11 addressing now is the fact that the rule as it's
12 currently formulated only provides criteria to be
13 used by two cladding types, and we would like to see
14 some change made so that the rule can apply to all
15 cladding types and not put us in a situation where
16 we have to use a lot of exemptions from the rule.

17 So I'm going to try and describe how we
18 intend to fix all of this. So we're going to, in
19 fact, we're in the process of generating a database
20 on high burn-up fuel. We have high burn-up
21 zircaloy, Zircaloy-2 and Zircaloy-4, and we have
22 unirradiated M5 and ZIRLO in the lab, along with
23 some other cladding types.

24 And so we're working on an appropriate
25 database with those rods. Mike Billone will talk

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 about that extensively in the next presentation.
2 Mike and I decided that we would put my applications
3 presentation before his data presentation so that
4 you could see where we're trying to go with the
5 data, and then have an idea of the focus that Mike
6 should have in his program and keep the discussions
7 a little more focused on the job that we have.

8 Now, I want to make a little distinction
9 between the confirmatory check on the current
10 licensing analysis and developing a basis for a more
11 inclusive role, two separate steps.

12 One is to make a demonstration that the
13 way we're doing business now for the operating
14 reactors is okay, and then the second thing is to
15 try and fix up the rule so that it won't be
16 restricted to any particular alloy type.

17 And the form of the results of all of
18 this will be, first of all, a research information
19 letter summarizing the laboratory results, and then
20 perhaps in the same rulemaking procedure, a
21 confirmation or modification, if necessary, if the
22 grandfathered rule and a new performance based
23 option.

24 Now, what do I mean, "the grandfathered
25 rule"? Currently the -- I think I have it on the

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 next -- no, I don't have it on the next slide.

2 Well, this is the 17 percent, 2,200, and I've got it
3 on a slide a couple down to show some of the fine
4 points in the application that's currently being
5 made.

6 And if we can demonstrate that these are
7 all adequate, then we can keep them in the rule as
8 an option. So the rule as envisioned would have the
9 option of using the old 17 percent, 2,200 method or
10 the new method.

11 And what we're trying to do now is with
12 those goals in mind, to generate a database that
13 will allow us to support those kind of changes.

14 So we look back at the basis for the
15 current requirements and actually have gone back and
16 studied the documents, particularly the Commission
17 opinion of 1973 at the end of the ECCS hearing. I
18 don't know how many people -- not many people here
19 remember the ECCS hearing of '72 and '73. There's
20 one at least. Norm Lauben back here was involved in
21 that.

22 But this, I think, was the longest
23 hearing the NRC, AEC at that time, had ever had
24 that produced the rule in 50.46 and Appendix K.

25 And so we've gone back and looked at the

NEAL R. GROSS

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

1 Commission's discussion of their conclusions, and
2 for the embrittlement criteria, specifically the
3 peak cladding temperature and the limit on
4 oxidation, those were defined to maintain a coolable
5 geometry, and the way you maintain a coolable
6 geometry in the Commission's view was to keep the
7 fuel pellets inside the cladding, and the way you
8 did that was to keep the cladding from fragmenting
9 or breaking into several pieces.

10 And to accomplish that the Commission
11 said, "I want some ductility."

12 They had looked at arguments about
13 stress, loads, flexibility, and other
14 considerations, surviving quench, and very
15 succinctly said that the stress calculations, the
16 measurements of strength and flexibility of oxidized
17 rods, and the thermal shock tests are all
18 reassuring, but their use for licensing purposes
19 would involve assumption of knowledge of the
20 detailed process taking place in the core during a
21 LOCA that we do not believe is justified.

22 And for that reason they said that they
23 wanted some non-zero ductility when this LOCA was
24 all over, and that is the basis for the current
25 rule, and it is that basis that we're pursuing in

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 order to develop a database to simply use the same
2 basis and go forward.

3 That doesn't mean you have to use the
4 same basis, but it was our judgment that if we did
5 this, that we hopefully would avoid another big
6 hearing because we were sticking to the principles
7 that were established in the original hearing. And
8 that's the foundation for what we're doing in the
9 research program at this time.

10 Now, these are the embrittlement
11 criteria: don't exceed 2,200 degrees Fahrenheit
12 heat cladding temperature, and don't exceed 17
13 percent oxidation of the cladding thickness.

14 There are three fine points here that
15 may not be as well known as the original numbers.
16 One is that this determination is, in fact, done in
17 the ballooned region of the cladding. Just to
18 refresh your memory, during the LOCA the cladding
19 heats up. At somewhere around 800 degrees
20 Centigrade it not only goes through a phase change,
21 but it balloons and it ruptures, and then at about
22 900 degrees Centigrade, it starts oxidizing rapidly,
23 but below that temperature the oxidation rate is so
24 low that it's not significant.

25 So this oxide is all taking place at

NEAL R. GROSS

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

1 high temperatures after you formed a ballooned
2 region. That means that some of the oxidation can
3 occur on the inside of the balloon because it's
4 open. And so the original rule and directions in
5 Appendix K provided that you should assume two-sided
6 oxidation for one and a half inches in either
7 direction from the location of the rupture and do
8 this calculation.

9 It wasn't said in the rule, but if you
10 look at the derivation of the 17 percent number, it
11 was done using the Baker-Just oxidation correlation.
12 In other words, in determining the 17 percent number
13 from the data, the data did not include measured
14 values of oxidation. They were calculated, and they
15 were calculated with the Baker-Just correlation.

16 So if you don't use the Baker-Just
17 correlation to go backwards when you're doing your
18 analysis, then the analysis will be off by a few
19 percent.

20 Also, recently NRR has clarified the
21 interpretation of total thickness or total
22 oxidation. It says total oxidation in the rule, and
23 we clarified that to include the corrosion that
24 takes place during normal operation.

25 Now, so this including the corrosion

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 during normal operation is what we're now doing in a
2 rough approximate way to accommodate the effects of
3 burn-up, and you can think of arguments why this is
4 overly conservation or arguments why it's not
5 conservative enough.

6 Certainly during the corrosion process
7 at low temperature, oxygen is not getting into the
8 center of the material, of the metal which is going
9 to end up being this so-called prior beta phase,
10 which contains all of the strength and ductility.

11 So the oxygen isn't going to get in
12 there, but the hydrogen is going to get in. And
13 hydrogen was not included in the original
14 understanding of oxidation embrittlement, and
15 there's a fair amount of hydrogen that gets into the
16 cladding metal due to this corrosion process.

17 So it's a guess, and we all agreed it
18 was a good guess, and so that's the way we're
19 handling high burn-up effects now, and our
20 confirmatory activity is to do real tests on real
21 high burn-up specimens and see if these approximate
22 methods, in fact, did the job adequately.

23 To accomplish all of this, we have
24 several types of tests that are going on at the
25 laboratory. One are the ductility tests. We're

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 using ring compression tests to determine the
2 dependence of ductility on corrosion alloy types.
3 This is similar to the original approach.

4 We have checked out the ring compression
5 test for adequacy in determining the point at which
6 you lose ductility, and it's a good method. We've
7 checked it against ring tensile tests. We've
8 checked it against three point bend tests. Some of
9 this checking is still going on, but the early
10 indications are that the ring compression tests are
11 quite an adequate method of screening to tell where
12 the zero ductility point is.

13 DR. FORD: Ralph, I seem to remember
14 that in the past there's been a fair amount of
15 discussion about the state of stress in these
16 various tests, mechanical testing procedures. That
17 has now been resolved to everybody's satisfaction,
18 I'm assuming and that this ring compression test
19 satisfies --

20 DR. MEYER: The state of stress for --

21 DR. FORD: Yeah, plain strain, plain
22 stress, orientation of hydrides, et cetera.

23 DR. MEYER: Well, this is a -- Mike
24 Billone is going to bail me out here on all of these
25 technical questions, but this is quite a different

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 arrangement than in the reactivity accident, where
2 you have basically an expanding mandril --

3 DR. FORD: Yes.

4 DR. MEYER: -- setting up a plain strain
5 condition. What we're now talking about is a fuel
6 rod which is not being -- the cladding which is not
7 being pushed out by the fuel pellets at all because,
8 in fact, the cladding is getting hotter than the
9 pellets, and we're talking about some external load
10 that might cause a high stress on the cladding, and
11 the ductility test actually sets up tensile loads in
12 several places, and so those are the ones that we
13 measure.

14 Now, Mike, do you want to clean this up
15 in some way?

16 MR. BILLONE: No, that's fine.
17 Basically if you're going to stick with the idea of
18 ductility and not strength and failure stress, then
19 you could do a bending test, which is an axial load.
20 You can do a ring compression, which is bending in
21 the circumferential direction, and to the extent
22 that you get similar answers in terms of when they
23 go to zero ductility, the ring compression tests
24 would be fine for that purpose.

25 So there are a variety of tests

NEAL R. GROSS

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

1 included. The Japanese do axial tensile tests.
2 We're proposing bending tests followed by ring
3 compression.

4 DR. FORD: The reason why I bring it up
5 is that I seem to remember several years ago a lot
6 discussion on these various testing techniques.

7 MR. BILLONE: Exactly.

8 DR. FORD: I'd hate for us to be in a
9 year's time having someone turned around and says,
10 "But all of these tests are useless. You should
11 know that."

12 DR. MEYER: Yeah.

13 DR. FORD: A, B, C, and D. We're not in
14 that situation?

15 MR. BILLONE: Not for the LOCA criteria.

16 DR. FORD: Okay.

17 MR. BILLONE: It is very applicable to
18 the RIA analysis.

19 DR. FORD: Okay.

20 DR. MEYER: I think initially there was
21 a natural reaction when we discovered these ring
22 compression tests on the Russian cladding that were
23 done in the early '90s by a guy name Boemert
24 (phonetic) in Germany, and the first thing that you
25 ask is, "Oh, well, was his testing technique

NEAL R. GROSS

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

1 adequate?"

2 And what we found is, first of all, this
3 is the same technique that Hobson used in the early
4 '70s on which this whole thing was done. Boemert's
5 work was repeated in Prague. It was repeated in
6 Budapest. It was repeated in Moscow and
7 Dmitrovgrad, and they always got the same result.

8 And then we started testing it, and we
9 started comparing it with these other types of
10 testing, like the three point bend and the tensile
11 tests. Now, I don't want to overstate how much of
12 that with the other methods has been done because it
13 has been rather limited, but nevertheless, the ring
14 compression test is a screening test for determining
15 at what oxidation level you lose ductility. It
16 appears to be quite good.

17 DR. FORD: So what I'm hearing you
18 saying is that there is no one in the technical
19 world who is going to turn around and say in a
20 year's time all of this is useless because it's an
21 irrelevant test. That's no longer the case.

22 DR. MEYER: Well --

23 MR. BILLONE: Well, there will always be
24 somebody.

25 DR. FORD: I don't know the answer to my

1 question.

2 MR. BILLONE: Well, there will always be
3 somebody that might say that, but --

4 DR. MEYER: There are other ways of
5 doing business than ductility testing, and you're
6 going to find a chorus of people who might want to
7 do that otherwise.

8 DR. FORD: But this test is crucial to -
9 - there we go.

10 MR. ELTAWILA: This is Farouk Eltawila
11 from Research.

12 I think Ralph alluded to it, said that's
13 our test plan at this time. The issue of testing
14 has been raised again internally here at NRC and by
15 the industry, and we are planning to convene a
16 meeting with the experts in this area to see if
17 we're still doing the relevant testing or not, and
18 so that will be an issue.

19 We will be reporting to you later, but
20 just to be fair to everybody, this issue keeps
21 coming up again, and finally we're going to have
22 that meeting and try to resolve that issue.

23 DR. FORD: Thank you.

24 DR. MEYER: I think the issue though is
25 not so much about testing technique, but about what

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 approach you take to demonstrating coolable geometry
2 because in the traditional approach you do that by
3 demonstrating that you have ductility.

4 Another way of doing that which was not
5 taken originally, but could be taken, is to
6 demonstrate that you have adequate strength so that
7 you don't fail the rods under the loads that are
8 expected during a LOCA.

9 And I think when you examine the
10 industry proposal and the approach that we're
11 taking, you will see that they depart right here,
12 and for retaining ductility, I don't think there is
13 much of an argument about the adequacy of the ring
14 compression test, but there is another way of doing
15 it.

16 CHAIRMAN POWERS: Suppose that I came
17 along and I said, "Gee, what I read the Commission
18 is saying is that they want to keep the fuel rod.
19 That's what they really wanted to do."

20 DR. MEYER: Right.

21 CHAIRMAN POWERS: And so I calculate a
22 bunch of loads on the fuel rod, and through some
23 magic say, "Well, these loads are such that the fuel
24 rod stays intact even at 50 percent oxidation," say.

25 What experimental database is there

NEAL R. GROSS

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

1 available to me to show that I have the loads
2 calculated correctly?

3 DR. MEYER: Well, I think that is the
4 \$64 question. That's where this discussion will
5 come down, and that's the point that I believe the
6 Commission sidestepped initially when they said, "We
7 don't believe that we understand the details of the
8 LOCAL process enough to do that."

9 CHAIRMAN POWERS: They said that in '73,
10 and there has been a lot of water flowing over the
11 dam.

12 DR. MEYER: That's a long time ago.
13 That's right. That's right.

14 CHAIRMAN POWERS: And we're getting
15 better and better calculational methodologies
16 developed. The question is: do we know that those
17 calculational methodologies are any good?

18 I mean, they're fancier, and the LOCA
19 described in Appendix K is a stylized LOCA.

20 DR. MEYER: Yeah.

21 CHAIRMAN POWERS: So you would have to
22 know a lot more about the range of LOCAs you could
23 have, wouldn't you?

24 DR. MEYER: The only thing I can say in
25 answer to that is that in NRC's research program, we

NEAL R. GROSS

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

1 have not investigated the loads or developed
2 analytical methods to analyze the loads. Now, I
3 think the industry has done some of that. We have
4 not.

5 DR. KRESS: Are the loads mostly thermal
6 expansion? Because you've already failed the -- you
7 don't have the internal pressure anymore. That's
8 gone.

9 DR. MEYER: That's correct. That's
10 correct.

11 DR. KRESS: And you have the weight of
12 the fuel and the thermal expansion and the
13 constraints. The flowing steam is not anything. So
14 is it mostly just thermal expansion loads we're
15 talking about?

16 DR. MEYER: Well, not entirely. You can
17 imagine axial loads from constraints within the fuel
18 bundle. The Japanese have done tests where they
19 apply axial loads. Many of us think that the axial
20 loads that they apply are excessive, but in the
21 extreme what they will do is allow the rod to go
22 through its ballooning, bursting, heat-up and get up
23 to its maximum temperature, and then grab it in an
24 Instron machine and hold it.

25 DR. KRESS: Hold it? Okay.

NEAL R. GROSS

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

1 DR. MEYER: And then quench it, and now
2 it snaps. If the oxidation percentage is as low as
3 eight or nine percent, if they don't grab hold of
4 it, it survives the quench with the oxidation levels
5 as high as -- I don't know -- 28, 30 percent, even
6 more than that.

7 I don't know. The fuel is ballooned.
8 Its neighbors are ballooned. We assume that it's
9 not coplanar. They're going to be interlocked in
10 some way. All of that corrosion is taking place
11 during the transient. The grids are probably going
12 to corrode also.

13 DR. KRESS: I see.

14 DR. MEYER: From NRC's side, I think we
15 are unprepared to say anything quantitatively about
16 those loads and have thus planned to go along the
17 path where we don't have to answer those questions
18 and hope that it's the path of least resistance and
19 will get us to a revision of the rule that is in
20 many respects just a refined image of the original
21 rule.

22 But it's not the only way that the job
23 could be done.

24 CHAIRMAN POWERS: Do you have to answer
25 the question of what is enough ductility?

NEAL R. GROSS

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

1 DR. MEYER: Well, you may force me to
2 answer that question. Originally the answer was
3 just not zero, but I'm going to move on now and show
4 you where even trying to use that concept we run
5 into a problem.

6 CHAIRMAN POWERS: Okay.

7 DR. MEYER: So let me finish this slide
8 and I'll get right to the subject that I think
9 you're interested in. So we're going to do the
10 ductility test, the integral test.

11 Now, the integral tests are where we
12 take fueled segments of high burn-up rods. They're
13 about 15 inches long. The fuel is inside. We weld
14 the end plugs on them, pressurize them to an
15 appropriate level, heat them up through a stylized
16 transient. They balloon; they rupture; they
17 oxidize; and then they're cooled and quenched in
18 what we believe is a typical manner.

19 Now, we presume they're going to survive
20 the quench at the oxidation levels that we are
21 using, and so we're going to take those surviving
22 specimens, turn them sideways in a four point bend
23 apparatus and break them.

24 DR. KRESS: Does the quench somehow
25 model the injection of the ECCS?

1 DR. MEYER: Model the what?

2 DR. KRESS: The ECCS injection.

3 DR. MEYER: In the sense that if we go
4 to 1,200 Centigrade -- I'm flipping to Centigrade
5 now -- if we go to 1,200 Centigrade that we will
6 cool down to 800 Centigrade slowly and then quench,
7 which I think is about the right way to do it.

8 It turns out that cool-down period is
9 important because it will affect the way that
10 hydrogen re-precipitates and aligns itself as
11 hydrides in the cladding as it comes on down.

12 So then we're going to do these four
13 point bend tests. Now, there are a limited number
14 of the integral tests. We'll do dozens and dozens
15 of ring tests on undeformed sections of de-fueled
16 cladding. The integral tests are very difficult and
17 very expensive. So we'll do maybe a half a dozen
18 integral tests with Zircaloy-4 and a half a dozen
19 with Zircaloy-2.

20 Now, oxidation tests are separate from
21 those, and we've done quite a lot of those already
22 where we take specimens and do isothermal anneals in
23 steam to measure, to map out the oxidation kinetics.

24 DR. FORD: Could you just go through
25 that sentence? I'm having trouble deciphering what

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 it means. Oxidation tests, you're measuring oxide
2 thickness as a function of burn-up. Corrosion,
3 oxidation is corrosion.

4 DR. MEYER: Now, are we talking about
5 this one?

6 DR. FORD: Yes, yes.

7 DR. MEYER: Okay. So this is high
8 temperature oxidation at a fixed temperature during
9 a hypothetical LOCA, and we're going to do this at
10 several temperatures because you want to map out the
11 temperature dependence. So we'll do some tests at
12 1,200 Centigrade, some at 11, some at ten, maybe
13 some at 1,300, and now we can do this on specimens
14 that have different burn-ups, different corrosion
15 levels with the same burn-up, and get the effects of
16 these variables on the oxidation.

17 DR. KRESS: This is just to expand on
18 Baker-Just or Cathcart Pawel or --

19 DR. MEYER: Mike, you're going to show
20 some of these?

21 MR. ROSENTHAL: Well, I think what was
22 very nice is the side benefit from this program was
23 that the data points were lying right up on top of
24 Cathcart Pawel, very well, and that's what's used in
25 the best estimated ECCS calculations. That gives

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 you some inferment (phonetic).

2 And, in fact, that's what we would
3 advocate. That wasn't the original intent of the
4 program, but it's a very nice side benefit.

5 MR. BILLONE: Mike Billone from Argonne.

6 Just to clarify, the term "oxidation" is
7 referring to high temperature steam oxidation.
8 Corrosion refers to the low temperature phenomenon
9 in the reactor. So it's all oxidation, but the
10 terminology is different.

11 CHAIRMAN POWERS: Jack, let me follow up
12 on something. You probably didn't have anything to
13 do with what you were saying when you said, gee, all
14 of the data points are falling on Cathcart-Pawel,
15 and then I read the report coming out of the Quench
16 workshop.

17 MR. ROSENTHAL: German work.

18 CHAIRMAN POWERS: Yeah, that says
19 something about using Prupach or Klett (phonetic).
20 That's for higher temperature work?

21 Okay. But they're okay with Cathcart
22 Pawel at these temperatures?

23 DR. FORD: One of the things, you say
24 "alloy type." What about ranges of composition
25 within an alloy type? Fabrication procedures,

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 they're going to affect the kinetics. Are they
2 covered?

3 (Laughter.)

4 DR. MEYER: They're covered perhaps not
5 in a systematic manner, but we have unirradiated
6 materials. We have quite a range of unirradiated
7 materials in the lab up at Argonne. We've got
8 Zircaloy-2, Zircaloy-4, M5, ZIRLO. We also have
9 E110, several varieties of the Russian E110, and so
10 we have tested all of those, and you're going to see
11 -- I guess you're going to show some of the
12 birchbark stuff. You're going to see some wild
13 differences in which some do appear to be related to
14 fabrication, but perhaps not the things that might
15 jump to mind, like cold work and things like that;
16 more perhaps related to impurities or the source of
17 the ore or the reduction process, the chemical
18 reduction process that's used because they leave
19 different kinds of impurities in the metal.

20 And so we do see some of those, but if
21 you avoid getting into this, it's like good oxide
22 and bad oxide. You know, we've got the good oxide
23 is black, tetragonal, adherent stuff that keeps
24 hydrogen out pretty well, and as long as that forms,
25 Cathcart-Pawel seems to work.

NEAL R. GROSS

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

1 DR. FORD: Right.

2 DR. MEYER: And even with the E110, the
3 Russian cladding, when you're at very low oxidation
4 levels, the kinetics look like Cathcart-Pawel, but
5 with the E110 cladding, you get to a point pretty
6 soon where the oxide form changes, and you start
7 developing a white oxide that has a lot of cracks,
8 lets a lot of hydrogen, and its rate goes --

9 DR. FORD: And aren't those outliers the
10 ones that we should be really worried about rather
11 than the best estimate average?

12 DR. MEYER: Well, we are worried about
13 them, but we think that the original Commission
14 wanted to retain --

15 DR. FORD: From a risk point of view, is
16 that not one you're really worried with?

17 DR. MEYER: Our expectation is that we
18 can figure out what they did that caused it to be
19 that way and make sure we don't do that.

20 It looks to us like that the products
21 that are being used in this country right now have a
22 manufacturing process results in a robust, black,
23 protective oxide coating at high temperature.

24 DR. FORD: But we're hearing comments
25 about BWR fuel currently if you've got some

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 corrosion problems because of outliers, but aren't
2 those the ones we should be worried about in this
3 particular relationship? No?

4 MR. BILLONE: The BWR problems you're
5 hearing about are at operating temperatures.

6 DR. FORD: Yes. That's the corrosion --

7 MR. BILLONE: But that may be a fuel
8 cladding interaction based on special fuel pellets
9 that were developed.

10 DR. FORD: Okay. Just pushing a little
11 bit.

12 MR. BILLONE: There's nothing wrong with
13 the alloy, the Zircaloy-2 alloy that they're using.
14 There's a special problem that may have to do with
15 the fuel.

16 DR. MEYER: Okay. Now, here is the sort
17 of challenging situation that we've observed. So
18 we're trying to preserve ductility. We think that
19 we've retained ductility everywhere in the ballooned
20 region because they have set up the regulation to
21 apply the calculation double sided in the region of
22 the balloon, and when we look carefully, we find
23 some places in the balloon where even within the
24 current regulatory constraints you may not have non-
25 zero ductility, and --

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 DR. KRESS: Now, is that a local thing
2 or is it circumferentially all around or --

3 DR. MEYER: I don't have a picture for
4 this.

5 DR. KRESS: You know, i can conceive of
6 a circumferential ductility --

7 DR. MEYER: Okay.

8 MR. BILLONE: The answer is both.

9 DR. MEYER: Yeah, it's both. It's both.
10 Above the burst and below the burst, more or less
11 symmetric locations, you have peaks of high hydrogen
12 concentration. These come about from ID steam
13 oxidation, release of hydrogen which can't get swept
14 away because it's inside a stagnant area, and so it
15 goes up to where it's a little colder, and it sits
16 there, and you get these bands of very high hydrogen
17 concentration in those two locations.

18 MS. YANG: Can I just add the
19 clarification? That's been observed for low burn-up
20 fuel or for unirradiated material. What is not
21 clear is if it will appear in high burn-up fuel when
22 the fuel pellet and cladding bounding are so tight
23 that you may not have such a phenomenon. So that's
24 something that needs to be --

25 DR. MEYER: That's true.

1 MS. YANG: -- to be demonstrated first.

2 DR. MEYER: And we'll find that our real
3 soon.

4 And the other place where you have zero
5 ductility must have been known originally, although
6 the hydrogen wasn't, and that's just around the rim
7 of the burst opening because the formula in the rule
8 for calculating the oxidation limit is to take at
9 the midplane of the burst the average cladding
10 thickness, which you get from taking the cross-
11 sectional area and dividing by a circumference.

12 Well, if you look at the cross-sectional
13 area, it gets knife-edge thin as it comes right down
14 to the opening, and it's 100 percent oxidized.

15 DR. KRESS: What temperature do they use
16 for that?

17 DR. MEYER: What temperature? Well,
18 this would be true at any of the temperatures where
19 you -- suppose you're right at the --

20 DR. KRESS: Well, the clad is probably
21 at the coolant temperature at that point.

22 DR. MEYER: We're talking about the high
23 temperature. The burst occurs around 800, and then
24 this thing goes on up to nine, ten, 11, 1,200
25 degrees Centigrade and comes back down. So the

NEAL R. GROSS

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

1 burst is open that whole time, and this knife-edge
2 thin region is oxidizing, and if you're anywhere
3 close to 17 percent average, you're 100 percent in
4 the thin edge, and it's fully brittle, and you've
5 now got a nice place to start a crack that will run.

6 Mike will show you. Let's see. I may
7 even have the picture myself.

8 Mike did in his hands a couple of four
9 point bend tests, and this is one where the opening
10 of the balloon was pointed towards him, and then he
11 went like this, not touching the ballooned region,
12 and it broke. A crack went down here and found the
13 high hydrogen brittle region, and it broke cleanly
14 in that region.

15 DR. KRESS: Which is upstream and which
16 is downstream?

17 DR. MEYER: Huh?

18 DR. KRESS: Which part of this is
19 upstream and which is downstream?

20 MR. BILLONE: For this test it doesn't
21 matter, but the break is upstream.

22 DR. KRESS: It's upstream.

23 MS. YANG: And this is, of course,
24 unirradiated material.

25 MR. BILLONE: Yes.

NEAL R. GROSS

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

1 DR. FORD: Your final bullet says we're
2 expecting integral tests, sure the fuel loss will be
3 minimal.

4 DR. MEYER: Yeah.

5 DR. FORD: Now, if you go back to your
6 previous picture, why do you say that the fuel loss
7 will be minimal?

8 DR. MEYER: Okay. Here's what we're
9 counting on. It's a nice, clean break. The balloon
10 is not shattered. There is a lot of ductility in a
11 lot of the surface area of the balloon. There is no
12 ductility right there. There is no ductility here,
13 and there is no ductility here.

14 You are not going to find this entire
15 section smashed up into little pieces like a piece
16 of glass because back in here you have non-zero
17 ductility, and we're going to do tests like this.
18 These are only crude, preliminary tests. But if you
19 have -- now, we're not saying that the loads are
20 large enough to do this, but if the loads would be
21 large enough to break the cladding, you're probably
22 going to get a clean break there or a clean break
23 here, and in the constraint of the balloon, fuel
24 pellets can't come raining out of that down onto the
25 core plate.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 DR. FORD: But why can't they come to
2 the left, just come streaming out from the left?

3 MR. ROSENTHAL: Remember that I have a
4 sea of fuel rods in a fuel bundle with the bridge
5 spacers above and below, with failures that are not
6 coplanar, and I think at least my middle model is
7 that we end up with a coolable geometry when we're
8 done, and it surely won't look pristine. It will be
9 broken up, but that's okay, as long as we can insure
10 coolable geometry.

11 MS. YANG: Yeah, and again, this is an
12 unirradiated rod. So you get this rim for high
13 hydrogen, and that's where the guillotine break
14 occurred, and like we said earlier, we're not sure
15 you will get that for high burn-up rods.

16 DR. MEYER: Well, I wouldn't count on
17 not getting it because we've ruptured two high burn-
18 up rods already, and what we found was that the
19 balloon for all practical purposes looked exactly
20 the same as it did in the unirradiated tests, and
21 furthermore that the axial gas transport through the
22 rod during the LOCA was essentially unimpeded, and
23 we expected it to be throttled down, and we didn't
24 see that.

25 So, I mean, it looks quite clear that

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 you're going to get ID oxidation. Now, whether
2 there's some -- well, I just --

3 MS. YANG: We'll just wait and see.

4 DR. MEYER: Well, we're speculating now,
5 and we're going to run the tests, and we're going to
6 know pretty soon.

7 CHAIRMAN POWERS: Let me ask a question
8 that simply reflects the fact that my memory is
9 shot. I think the French came in and made a
10 presentation to us, and didn't they show us -- I
11 don't know whether they were X-ray or tomographic
12 results that showed that when you got this
13 ballooning, you had fuel pellets collapsing, not
14 pellets, but fragments collapsing down into the
15 ballooned region?

16 MR. BILLONE: That was a hypothesis.

17 MS. YANG: Yeah.

18 CHAIRMAN POWERS: I thought they showed
19 us actual results of some of the early Phebus
20 experiments. I mean, they were either tomographic
21 or X-rays. I'm not sure which.

22 MR. ROSENTHAL: I believe that's
23 tomography.

24 MS. YANG: I think I didn't see the
25 presentation. It must be very low burn-up. I don't

NEAL R. GROSS

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

1 think any so-called fuel relocation being observed
2 for high burn-up fuel. High burn-up means even
3 greater than 30 or 30,000.

4 I think when you have a large gap
5 between the fuel and the cladding, it's conceivable
6 you could have some kind of settling or the
7 relocation, but I think what we're trying to
8 demonstrate here is for higher burn-up rods. When
9 you have very tight fuel and cladding bounding, I'm
10 not sure you will have fuel relocation or even this
11 hydrogen.

12 I think we need to wait and see. That's
13 what most of these experimental programs are trying
14 to find out.

15 CHAIRMAN POWERS: Again, I don't want to
16 place a great deal of faith in my memory, but it
17 seems to me that what they spoke of was a swelling
18 of the cladding over some substantial length, and
19 maybe it was like this, and they would have a
20 somewhat larger ballooned region down here, but over
21 the entire length things would fall down into this
22 region. I mean, that's what it looks like.

23 DR. MEYER: We're well aware of the
24 hypothesis, and we are looking for evidence of that
25 in these tests. We also are trying to help design

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 the Halden test specifically to look for that
2 relocation process.

3 You know, when you start dealing with
4 random orientation of granules of stuff, then you
5 start talking about packing fractions, and you've
6 got to open up a pretty large balloon in order to
7 get the same mass of randomly oriented particles
8 that you had in the pellets.

9 And I think that that number is
10 somewhere in the range of 65 to 70 percent strain on
11 the balloon in order to get the break even point.

12 Now, we didn't see quite that much
13 strain on our balloon specimens. We had 40 to 50
14 percent, and so I don't know. That's part of the
15 mix, part of what we're trying to study, and I guess
16 there's a lot of skepticism about whether it really
17 can exist or not.

18 What we have found that wasn't expected
19 was that we lose a little fuel from the ballooned
20 area during the test. The blow-down seems to push
21 out some finds, and that we might experience some
22 cracks or severing of the fuel rod that probably
23 won't shatter the rod, and it might let out some
24 additional small pieces of fuel.

25 CHAIRMAN POWERS: The loss of a little

NEAL R. GROSS

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

1 fuel finds can't be a surprise to you. I mean,
2 that's been known since Malinowskus' (phonetic)
3 work.

4 DR. MEYER: Yeah, okay. Well, I guess
5 this is going to be the hardest part of the whole
6 thing, is that at the end of the day we don't have a
7 pure situation. We don't have ductility everywhere.
8 We can't flatly say that it won't break.

9 Okay. What can I say here?

10 CHAIRMAN POWERS: Well, here you say
11 something different than what you've been saying up
12 till now. Here you say specifically "sufficient
13 ductility," whereas up till now you've been very
14 careful to say --

15 MR. BILLONE: "Some."

16 CHAIRMAN POWERS: -- "some."

17 DR. MEYER: Yeah.

18 CHAIRMAN POWERS: Non-zero.

19 DR. MEYER: Yeah, but I actually don't
20 know the difference. Sufficient ductility in my
21 mind as I wrote this was that that band of high
22 hydrogen was not so big that it knocked a big
23 section out of the tube or that the rim of heavily
24 oxidized material produced a shattering, gaping hole
25 in the side.

NEAL R. GROSS

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

1 If the test results show that it's
2 fairly clean and tight, then I would say that's
3 sufficient ductility, and that's all I meant there.

4 Okay. So as I mentioned before, we're
5 going to try and demonstrate with high burn-up
6 zircaloy and with unirradiated ZIRLO and M5 and sort
7 of put it all together and see if it looks like that
8 the current way of doing business is sufficient, and
9 that would give us a basis for leaving that in the
10 rule as an option without change other than the
11 database that we're generating should be applied to
12 the grandfather part of the rule because we've got
13 M5 in the laboratory.

14 CHAIRMAN POWERS: More importantly, you
15 have it in the reactor.

16 DR. MEYER: And we have it in the
17 reactors. The performance based criterion would be
18 an option, and the current thinking is to simply
19 specify a ductility test, and perhaps describe the
20 details of this in a regulatory guide, and from this
21 ductility test, a licensee would then generate the
22 temperature limits and oxidation limits that would
23 correspond to the zero ductility point in the test.

24 This, in fact, could then turn loose the
25 peak cladding temperature from its 2,200 degree

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 limit right now because it's quite easy to imagine
2 getting a ductility criterion at 2,300 Fahrenheit
3 and 14 percent oxidation or something like that, and
4 so it might be necessary to rethink the peak
5 cladding temperature limit.

6 It's a curious situation, the peak
7 cladding temperature limit that's in the rule
8 because it was ostensibly put in the rule as part of
9 the embrittlement criteria. It was known that if
10 the oxidation had taken place at a temperature much
11 above 2,200 Fahrenheit or 1,200 Centigrade that the
12 diffusion of oxygen into the prior beta region would
13 be higher and you'd get more oxygen in the part of
14 the metal that was giving you your ductility.

15 But the dependence on temperature was
16 not very apparent in the original data. I guess
17 Hobson's data at 2,400 Centigrade showed some
18 enhanced hydrogen in the prior beta region, and in
19 principle everyone agreed that the effect would be
20 there, but it was not like you had plots of
21 embrittlement criteria as a function of temperature
22 and at 2,200 degrees the correlation fell apart.

23 There was, in fact, another
24 consideration, and the other consideration that was
25 discussed in the Commission opinion was one of

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 excessive metal water reaction in relation to run-
2 away temperatures, and we've looked at that, and
3 we've looked at the Cathcart-Pawel correlation,
4 which appears to work well for everything we've
5 studied if it doesn't develop the bad oxide in
6 comparison with the Baker-Just correlation, and just
7 by coincidence the metal water reaction heat, like
8 Cathcart-Pawel at 2307 is the same value that Baker-
9 Just has at 2,200.

10 Norm Lauben has done a lot of RELAP
11 calculations to look at the margin that you have to
12 where the heat balance gets unfavorable and the
13 temperatures run away, and so it looks to us from
14 the preliminary work that we've done that if you
15 allowed temperatures as high as 2,300 degrees
16 Fahrenheit that you might be preserving the same
17 margin to run-away that the Commission would have
18 thought they had initially.

19 That's just a reference point, but if
20 one finds that the embrittlement criteria are coming
21 in with temperature limits higher than 2,200, you
22 might have to think through the metal water reaction
23 arguments a little bit and perhaps put some
24 additional limit on it.

25 Now, I think that's all I had. So I'm

NEAL R. GROSS

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

1 finished.

2 CHAIRMAN POWERS: Good.

3 MR. ROSENTHAL: I just want to reiterate
4 that we're sharing with you our thoughts on the way
5 we might go. There is not uniformity amongst the
6 staff yet or any sort of decision yet on how we
7 might go.

8 We also have stakeholder input to
9 consider, and so this is where we are in our
10 thinking at this time, and we really would
11 appreciate; it would be a very timely time for ACRS
12 to provide this.

13 DR. MEYER: I want to underscore that
14 and say that the reasons for even discussing things
15 as specifically as we have is that we're trying to
16 generate a database to support something, and you
17 need to have a concept of what the something is that
18 you're trying to support. So we make up the mental
19 models of what the something is and plan the program
20 to support that.

21 CHAIRMAN POWERS: Good. Well, we'll ask
22 by the end of the day.

23 Okay. Thank you, Ralph.

24 MS. YANG: Mr. Chairman, can we give a
25 short presentation just to describe what the

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 industry position in terms of the type of data that
2 should be generated?

3 I don't really want to have a debate
4 here, but I just thought it might be helpful at this
5 point to at least briefly describe what an
6 alternative suggestion here is.

7 CHAIRMAN POWERS: You've got 12 hours
8 tomorrow.

9 MS. YANG: Okay.

10 CHAIRMAN POWERS: I want to move on with
11 Mike talking about the LOCA test results.

12 MR. BILLONE: Are you guys okay with
13 lunch? It's going to take me an hour.

14 CHAIRMAN POWERS: You've got an hour.

15 MR. BILLONE: All right. I'm going to
16 take you back a few years. I'm going to use the
17 viewgraph projector.

18 CHAIRMAN POWERS: Oh, good man.

19 MR. BILLONE: And I also have some chalk
20 for demonstration.

21 Okay. Ralph, do you still have that
22 pointer?

23 DR. MEYER: yes.

24 CHAIRMAN POWERS: Thanks. One that
25 works. I usually point it at someone's eyes.

NEAL R. GROSS

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

1 All right. I have one presentation, and
2 I have a bunch of back-up slides in case I've
3 anticipated your questions correctly. We'll see.

4 I also like to move around. I hope that
5 doesn't cause a problem.

6 In the handout you have, it's rather
7 long, and I think the way to approach it -- first
8 all, we have to get rid of --

9 CHAIRMAN POWERS: Yeah, we have to get
10 rid of --

11 PARTICIPANT: Ralph, how do we get rid
12 of this thing?

13 MR. BILLONE: You could always shut it.

14 PARTICIPANT: Well, the question is how
15 to turn it off.

16 MR. BILLONE: You just rotate it.

17 CHAIRMAN POWERS: No, it's up here on
18 the projector.

19 MR. BILLONE: Oh, I'm sorry. I'm sorry.

20 CHAIRMAN POWERS: Just go ask Aaron to
21 come help us. Charge ahead, Mike. We'll read them
22 off the handouts if nothing else.

23 MR. BILLONE: Okay.

24 CHAIRMAN POWERS: The first one tells us
25 your name.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 MR. BILLONE: Yeah.

2 CHAIRMAN POWERS: And even the date,
3 which is always useful for me because I never know
4 what day it is.

5 MR. BILLONE: Okay, all right. So we're
6 going to talk about LOCA test results generated at
7 the Argonne program -- oh, this is a nightmare --
8 and I'd like to acknowledge my colleagues, Yung Yan
9 and Tanya Burtseva. They like to work. They don't
10 like to talk. I like to talk. So I'm here. Okay.

11 CHAIRMAN POWERS: You might twist the
12 knob there and get us a little bit in focus or I'll
13 think it's me.

14 MR. BILLONE: Oh, good. Thank you.
15 Thanks a lot.

16 All right. In this morning's
17 presentation I'm going to talk about our LOCA
18 relevant research. I'm going to pick up the dry
19 cask storage in a later presentation. I'm going to
20 his our advanced alloy post-quench ductility testing
21 of unirradiated material, steam oxidation of high
22 burn-up Zirc-2 and Zirc-4 cladding, LOCA integral
23 tests with fuel, boiling water reactor, and PWR
24 cladding. That's to be followed by post-quench
25 ductility of high burn-up LOCA integral test

NEAL R. GROSS

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

1 specimens, and we've also had proposed several ramp-
2 to-burst tests with varying the heating rate and the
3 internal pressure in the program.

4 Let's hold off on these two until later
5 this afternoon. Let me just give you an idea of the
6 materials we have at Argonne. I'll go through this
7 list quickly.

8 We have a variety of Zirc-2 designs,
9 eight by eight, nine by nine; ten by ten is to be
10 provided; a variety of Zirc-4, normal Zirc-4
11 archived to our Robinson cladding, and low tin 17 by
12 17 provided by Westinghouse. Framatome is also
13 going to provide us with some.

14 We have ZIRLO provided by Westinghouse,
15 M5 provided by Framatome, and a variety of the E110
16 claddings. The focus of our program is really the
17 alloys used in the United States. The E110 is here
18 to try to understand why it behaves the way it does
19 and make sure that none of these alloys are on the
20 edge of some kind of cliff.

21 I'll show you the table of the
22 irradiated fuel rod segments we have at Argonne.
23 Some of these are for dry cask storage, and we'll
24 come back to it, and on this table, would you please
25 correct a wonderful typo? You've got an 1888 for a

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 discharge date for the Surry reactor. So would you
2 please make it 1981 for me?

3 But we have for PWR cladding, we have
4 the Robinson, which has primarily for the LOCA
5 program 64 to 67 gigawatt days per metric ton
6 averaged over the whole fuel column. It gives you
7 an enrichment, Zirc-4, and gives you a discharge
8 date.

9 Limerick is the BWR cladding, which I'll
10 show you some results for. The pins that we're
11 testing are 56 to 57 gigawatt days per metric ton,
12 and this is lined cladding. About ten percent of
13 the wall thickness is zirconium, low alloy zirconium
14 on the ID of the cladding, and this is about .7
15 millimeters in thickness.

16 So for LOCA we're just going to be
17 talking about these. I'll come back and pick up
18 these other two when we talk about dry cask storage.

19 All right. The nice thing about some of
20 the variables of the LOCA test, if we go to the
21 Limerick test, you have very little oxide, something
22 over ten microns, but some tenacious crud, and
23 because you have very low oxide and it doesn't vary
24 axially very much because your coolant temperature
25 is pegged at about 288 degrees C., you only have

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 about 70 ppm of hydrogen that you picked up from in
2 reactor corrosion.

3 If you contrast that with the Robinson,
4 which is more typical of a pressurized water reactor
5 with an increase in cooling rate as you move along,
6 you've got up to 110 microns of oxide, and as far as
7 what we measured, up to 800 wave parts per million
8 of hydrogen.

9 So Robinson is very interesting because
10 if you want to study the effects of hydrogen, you
11 could go to gridspan four with high hydrogen
12 content. You can go to gridspan two with low
13 hydrogen content, all with the same irradiation
14 conditions.

15 So, again, these two would be for our
16 LOCA relevant program. Okay. Let me just summarize
17 where we are in each of these.

18 For the advanced alloy post-quench
19 ductility study, we received cladding over a period
20 of time. We did extensive validation, looking at
21 temperature responses, metallography, hydrogen pick-
22 up, oxygen pick-up, and our test matrix calls for
23 tests at 1,000, 1,100, 1,200, 1,260 degrees C.

24 We've completed the results for all
25 alloys oxidized at 1,000 degrees C. and 1,100

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 degrees C., up to a calculated ECR of 20 percent.

2 We've also measured the ECR by measuring
3 the oxygen pick-up. So when I give you results, I
4 give you results versus measured ECRs.

5 We completed our E110 study as far as we
6 can go, with emphasis on oxidation at 1,000 degrees
7 C. The alloy is particularly challenged at 1,000
8 degrees C.

9 By "completed," I mean we've oxidized
10 the samples and done all of the ring compression
11 tests. We intend that each one of these
12 temperatures in the single ECR to do a four point
13 bending test of a balloon and burst sample of the
14 advanced alloys. We would call our LOCA integral
15 test followed by LOCA ring compression test.

16 That's our current plan, and that's
17 subject to input from the interested parties as to
18 what other tests might be done.

19 All right. For those oxidation tests of
20 unirradiated alloys, this is the kind of temperature
21 history. We have a fairly rapid ramp-up to about
22 100 degrees C. from our gold temperature, slowing
23 down so that we don't overshoot. We hold for a
24 certain amount of time, depending on how much oxide
25 you want, oxidation you want.

NEAL R. GROSS

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

1 Slow cool to about 800 degrees C., and
2 what's not shown here is the rapid quench. We have
3 the water hit the sample, and the sample temperature
4 is about 800 degrees C.

5 So that's what we expose small samples,
6 25 millimeter samples to, and then we proceed to do
7 ring compression tests on those and look at oxygen
8 and hydrogen pick-up on those samples. So that's
9 for our advanced alloy program.

10 Let me give you a quick summary of where
11 we are on the LOCA program. Of course, we do
12 oxidation kinetic studies. The Limerick has been
13 completed. The Robinson is about to start.

14 Let me go down here because this is more
15 the emphasis of my talk. Our LOCA integral tests
16 currently are pegged at the 2,200 F., the 1,204
17 degrees C. peak temperature, and for a time range of
18 one to five minutes.

19 Five minutes turns out to give us a
20 Cathcart-Pawel calculated ECR of about 20 percent
21 peak in the burst region. We're measuring somewhere
22 around 18 to 19 percent. So this would be an over
23 test relative to the criteria, but an interesting
24 test relative to phenomena.

25 We're coasting along last year. We had

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 completed a Limerick ramp-to-burst test. That's an
2 actual irradiated fuel segment, and then ramp-to-
3 burst followed by oxidation for five minutes at
4 1,204 degrees C. That was about a year ago.

5 Then we lost about a year because our
6 hot cells were essentially shut down for major
7 maintenance, and so we were back to where we were
8 last year, and I'll show you where that is.

9 When we looked at these two samples in
10 detail based on nondestructive results -- that means
11 looking at profilometry of diameter changes and
12 photography, we saw more similarities than
13 differences between the unirradiated Zirc-2, which
14 had zirconium pellets in it tested out of cell, and
15 the irradiated with fuel tested in cell.

16 We're in the process -- and Rosa brought
17 up this point -- of determining axial profiles of
18 hydrogen pickup and oxygen pickup, and the only
19 thing it might save you -- I'm sorry. That's too
20 dramatic. I'm supposed to present data. I'm not
21 supposed to be melodramatic.

22 The issue of whether you pick up
23 hydrogen inside the high burn-up rod is not so much
24 the fuel cladding tight bonding because the cladding
25 is going to expand away from the fuel. It's the

NEAL R. GROSS

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

1 oxide layer that you pick up in the reactor on the
2 ID of the cladding, and the question is we have
3 evidence we know it's not protective against steam
4 oxidation. It will oxidize just the same as air
5 cladding, but does it prevent pickup of hydrogen?
6 That's what we're in the process of determining.

7 We're hoping to run the Limerick test
8 with quench this month, and then initiate the
9 Robinson test, the PWR test with the high oxygen and
10 hydrogen levels in the fall of 2003.

11 Let me show you where we are with this
12 Limerick test. And off line, if someone wants to
13 know what we've been doing with our hot cells, I'll
14 tell you. I don't want to start that story because
15 it sounds like a sob story of complaining.

16 This is our stylized -- I never knew
17 that term "stylized LOCA" -- this is our stylized
18 LOCA. What we have run is at room temperature
19 pressurizing the top of the sample, having pressure
20 transducers at the top and the bottom, and measuring
21 permeability or time response to the bottom
22 transducer, which was much higher than we thought,
23 meaning that the pressure equilibrated much quicker
24 than we thought for high burn-up fuel.

25 Then we depressurized, went up to 300

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 degrees C., really 300 even if it doesn't look like
2 it; repressurized, did the same test, and got high
3 permeability; introduced steam, ran up to burst, and
4 actually in this first test we didn't have steam.
5 We had argon. We ran up to burst and then stopped.
6 That was the first test.

7 The second test went through this
8 sequence of five minutes. A program cooled down
9 three degrees per second, and then we quenched in
10 the cell a year ago. So we did slow cooling, but
11 that test was -- those two tests were completed a
12 year ago.

13 And what we're shooting for now is this
14 same sequence, only with the quench hitting the
15 sample at 800 degrees C.

16 Okay. There was a tremendous amount of
17 movement in our hot cells and moving radioactive
18 material away from half the hot cells so that the
19 shield window could be repaired, trying to move it
20 back. Equipment got damaged, and we need to test
21 out all of our sample preparation techniques, which
22 we were doing very quickly, as well as the LOCA
23 apparatus.

24 This is the particular Limerick rod
25 we're working on right now. It's called J4. This

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 is a gamma scan. It gives you a rough idea of the
2 burn-up profile, and we've just cut these three new
3 samples from this rod. These are two good samples
4 that we'll use in our testing. This sample which is
5 in the down slope of the power profile or the burn-
6 up profile we're using to practice removing fuel
7 from about half to one inch from each end in the
8 welding end caps, and that's going on today.

9 Hopefully that's successful. We'll move
10 on to these two this week and we'll have two samples
11 ready to go.

12 Let's skip that one. I'm going to skip
13 some slides as we go along.

14 A quickie. Let's go back now and do
15 some details on the advanced alloy program and the
16 high burn-up program. So we'll get into details
17 now.

18 Basically our approach, we know very
19 well that alloys like M5 and to some extent E110
20 have this unusual behavior at 1,000 degrees C. where
21 they oxidize at much less than Zirc-4 and the rest
22 of the alloys. What we're going to do is use a
23 calculated Cathcart-Pawel time to set our test
24 matrix, which means we're going to go up to 20
25 percent calculated ECR, and we'll also, as I said,

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 measure the ECRs.

2 That means that these corresponding
3 temperatures or double sided oxidation, these are
4 the maximum times that we're going to oxidize these
5 samples. This is close to an hour down to minutes,
6 depending on what the peak temperature is.

7 What's interesting, as you go up in
8 temperature, you're increasing the oxide solubility
9 in your ductile layer, and eventually if you keep
10 going up, that ductile layer will become embrittled
11 by oxygen.

12 So we determined the measured ECR based
13 on weight gain. In the process of doing this, we
14 want to look at the oxidation kinetics because we're
15 generating the samples by oxidizing. It's useful
16 data, as well as the post quench ductility data, and
17 the approach is to compare the results for ZIRLO and
18 M5 to Zirc-4 and Zirc-2 data when we get the
19 appropriate Zirc-2.

20 There seemed to be some sensitivity on
21 the part of the vendors who gave us the cladding
22 that these two alloys not be compared directly on
23 the same graph. So I will show you graphs of ZIRLO
24 compared to Zirc-4 followed by M5 compared to Zirc-
25 4, as opposed to one nice, simple graph, and I'm

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 going to respect that sensitivity.

2 We've explored factors that may
3 contribute to E110 behavior. We certainly confirmed
4 that it's very poor post quench ductility
5 performance at low test times, particularly at 1,000
6 degrees C.

7 We've explored the effects of surface
8 roughness and surface chemistry on oxide instability
9 and got some interesting results in being able to
10 delay the instability by smoothing the surface.

11 And we've done some characterization of
12 both chemistry, metallography, SEM, and some TEM.
13 The moral of this story is there's more than one
14 reason why E110 will behave the way I show you it
15 behaves, and some of the things that we could do, we
16 don't manufacture E110. All we could do is work
17 from the outside and play with the surface. It may
18 delay the instability, but it doesn't eliminate the
19 instability.

20 Okay. Very quickly in terms of
21 apparatus, I don't want to get into too much with
22 apparatus. Basically, this is a 25 millimeter long
23 sample. This looks like overkill. This is a quartz
24 tube, and steam enters from the bottom. It's held
25 in place with Inconel holders, and isolated from

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 those holders by something that we'll see in the
2 next section.

3 We have the thermocouples coming down
4 through here, through the top, and steam exiting at
5 the bottom. Let me show you how we get double sided
6 oxidation out of this with the next slide. This is
7 just an enlargement of that test section.

8 Basically we have the steam -- well, I
9 can tell the thermocouples are head to the top. So
10 I know this is the bottom. We have steam flow
11 within the quartz tube coming this way. We have
12 three or four holes substantially, a bottom for
13 steam to get in. This is hollow. Steam could
14 continue on, but it's too long of a path, and it
15 gets cool. So steam would condense. So we put
16 holes for steam exit there.

17 Our sample is here protected from the
18 Inconel with aluminum spacers and zirconia washers,
19 and that's our basic set-up. We only run one sample
20 at a time for each of the alloys under each of the
21 conditions.

22 Okay. Let's talk about good oxide and
23 bad oxide, and let's put some fancy words to it, and
24 let's show some pretty pictures. Protective oxide
25 layers. This is under high temperature steam.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 Generally in appearance they're lustrous black.
2 They're a particular phase of the material called
3 tetragonal, and they are ZrO_2 minus X. They're
4 hypostoichometric. They're slightly under the two
5 to one ratio.

6 You need this at temperatures at 1,100
7 degrees C. and below because this form of oxide is
8 not thermodynamically stable in 1,000 degrees C. or
9 1,100 degrees C. However, it is stable under
10 compressive stress and that forms under compressive
11 stress, and it's stable for the hypostoichometry.

12 So you rely on those two things to give
13 you the good oxide. If you have that, how can you
14 lose ductility? Protective means protective against
15 hydrogen pickup, and it means that oxidation is
16 diffusion control.

17 Well, if you keep going in time, you
18 will bend the effective ductile layer as you
19 increase time at temperature or weight gain and ECR.
20 If you increase temperature, go to 1,260 and beyond,
21 you will increase the oxygen content in that ductile
22 layer, and it will become brittle.

23 Also, there's a chance that obviously
24 with high burn-up you could have the effects of
25 hydrogen causing embrittlement from in reactor

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 corrosion, and I'll show you what happens during
2 LOCA ballooning and burst of unirradiated cladding
3 in terms of hydrogen pickup.

4 So these are mechanisms in which
5 eventually you're going to go to zero ductility.

6 There is also not so good oxide, and
7 this is classical break-away oxidation which we've
8 observed for Zirc-4 and M5. We would observe it for
9 ZIRLO if we tested ZIRLO, but it's something that
10 happens at very, very high, long times, like three
11 hours at 1,000 degrees C. We're not studying this
12 because we don't think it's LOCA relevant. We could
13 study it, but it would be of more academic interest.

14 What we have looked at is what happens
15 to E110 because this classical break-away oxidation,
16 after your oxide grows big enough, it's something
17 that happens from the outside layer and moves in.
18 E110 seems to develop an instability right at the
19 metal oxide interface, and we see local enhancement
20 of the oxidation rate, local enhancement of hydrogen
21 uptake at 1,100 degrees C., and then -- let me do
22 this with pictures rather than words. That's too
23 many words.

24 Okay. Top picture. Good, lustrous --
25 well, it's hard to get lustrous black to show up.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 That is lustrous black, and believe it or not,
2 that's Zirc-4 after about 870 seconds, which
3 measures out to about 18 percent ECR in steam at
4 1,100 degrees C. It only picked up eight weight
5 parts per million of hydrogen. It was fabricated
6 with five and it only picked up eight during this
7 process. That's very low.

8 E110 looks the same after you ramp it
9 for 75 seconds up to 1,000 degrees C. and you only
10 hold it for five second. It kind of looks like this
11 until you look under high magnification. You see
12 these very small white spots. These white spots
13 will grow. So the point is they form during the
14 temperature ramp, and they will go very unstably as
15 shown in the next picture, almost the next picture,
16 not quite.

17 Let's look at the good stuff first. One
18 of the things we did was we looked at metallography
19 for a couple of reasons. We want to make sure
20 things are going okay. In other words, we're
21 growing an OD oxide and an ID oxide of about the
22 same.

23 We know this is brittle. We know that
24 the high oxygen alpha phase, the white stuff you're
25 looking at, is even more brittle. So from a post-

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 quench ductility point of view, you throw this away,
2 you throw all of the white stuff away, and what will
3 give you ductility is this gray stuff. In this
4 picture it turns out gray. That's what's called the
5 prior beta layer.

6 As long as this is not loaded with
7 hydrogen and as long as you didn't ramp the
8 temperature up too high so it's loaded with more
9 oxygen, that's where your ductility comes from.

10 So if I took this sample and exposed it
11 to a ring compression test -- hopefully that's my
12 next slide -- traditionally in the ring compression
13 test you get four snaps, four breaks. It breaks
14 into four points, and this is the load that you're
15 applying to the ring. This is the displacement, and
16 this is the methodology we use. This is the
17 effective elastic part which we're not interested
18 in. It's this part here: do you have any
19 ductility?

20 And from that previous picture you
21 should. You had enough gray stuff in that picture
22 and it was low in hydrogen, and this comes out to if
23 you divided this by about -- if you multiply this by
24 ten, you get percent coincidentally. So this is
25 about three percent plastic deformation that you get

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 before you start this cracking.

2 It's probably a little bit more in that
3 this may not be a through-wall crack. To get four
4 cracks, this might be one through-wall crack. This
5 might be a second through-wall crack, a third, and
6 then a fourth.

7 But the point is that previous picture
8 does have ductility, and I want to make the point
9 that we don't simply rely on this picture to tell
10 whether or not we have ductility or not. We use
11 this offset method to determine plastic deformation
12 that's classical with ductile materials. We look at
13 the metallography to make sure we have ductile
14 materials, and we measure the hydrogen content to
15 make sure we have an embrittlement with hydrogen.

16 That's the good stuff. All right.
17 Let's go to the stuff that's still kind of a mystery
18 to us, but this is E110 at 1,100 degrees C. In this
19 sample you can see those white spots have grown.
20 They've cracked. They've interlinked a little bit,
21 and you've picked up some hydrogen at each of these
22 cracks, but only about 200 weight parts per million.

23 It turns out that this sample with the
24 oxygen and the hydrogen is brittle. If you cut this
25 underneath the white spots, you will see the

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 enhanced nodular oxidation. This is all oxide.

2 Under the black spots, you'll see the
3 thinner oxide. So this is not what is treated by a
4 Cathcart-Pawel model or any of the other models.
5 This is an instability.

6 So we're calling white bad and black
7 good, reversing the process. That's 1,100 degrees
8 C. The alloy is not too bad at 1,100. It's better
9 at 1,200. It's a disaster at 1,000 and probably
10 worse at 950.

11 So let's take E110 for a very small
12 time, 300 seconds, and then a longer time, 1400
13 second at 1,000 degrees C., double sided oxidation,
14 and if you look at the surface of this, it's ugly.
15 I mean, all of this gray or white stuff is the kind
16 of oxide that cracks and allows hydrogen pickup, and
17 it has picked up about 120 ppm of hydrogen at this
18 very low calculated ECR.

19 And if you look underneath this gray
20 area and take a cross-section, you can see that it's
21 actually cracked and delaminated, and that allows
22 steam to come in direct contact with the metal, but
23 let's go on in time.

24 This is 1,400 seconds at 1,000 degrees
25 C., and you have a mess, but you can actually

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 describe it. All of these areas interlink and this
2 whole thing becomes essentially white oxide. It
3 cracks, it spalls, it delaminates. It picks up
4 4,000 weight parts per million hydrogen. You don't
5 even have to test this. This is brittle.

6 So what we did is we explored the
7 transition between this picture, and it turns out
8 this is ductile. It's very high ductility, but a
9 couple of hundred seconds later it has got zero
10 ductility because it's going to continue to pick up
11 hydrogen. So when it gets to about 400 ppm of
12 hydrogen, a little more oxygen, then it does go
13 brittle.

14 So somewhere around 500, 600 seconds is
15 when E110 goes bad at 1,000 degrees C., but really
16 keep in mind that the seeds of all this were right
17 at the beginning when you were starting up the high
18 temperature. Those tiny white spots accrued.

19 I'm not going to show you much on E110.
20 So let me just say that we were able to delay this
21 significantly by simply polishing the surface of
22 E110 because a rough surface can disturb the
23 compressive stresses. As a matter of fact, the ends
24 of the sample can disturb it from E110. Welding a
25 thermocouple on it can disturb it.

NEAL R. GROSS

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

1 There's something else causing this
2 instability, but you can as a catalyst, think of it
3 as a catalyst. Roughened surfaces, certain surface
4 chemistries, discontinuities will all make this
5 happen much, much sooner.

6 MR. CARUSO: The picture on the right,
7 is the black area fuel? Is that fuel pellets or is
8 that just an underlying --

9 MR. BILLONE: No, no, no. This is
10 epoxy.

11 MR. CARUSO: No, no, no. On the right.

12 MR. BILLONE: This?

13 MR. CARUSO: Yes.

14 MR. BILLONE: This is E110 cladding. I
15 mean it starts out like this with no fuel in it.

16 MR. CARUSO: I'm trying to understand
17 the scale. Is that the same scale as the one on the
18 left?

19 MR. BILLONE: Approximately. These are
20 approximately the same scale.

21 MR. CARUSO: So it looks like it has
22 shavings that have come off?

23 MR. BILLONE: Yeah. It spalls. I mean,
24 if you look at this at low time and you keep going
25 on in time, this eventually will -- well, this is a

NEAL R. GROSS

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

1 little bit of spalling, but it will eventually --
2 I'm sorry -- delaminate. This is delamination. It
3 separated from the base metal. It will eventually
4 spall off, and then you will grow new oxide. It
5 will also be bad. It will spall off.

6 So all of this is oxide that you're
7 looking at.

8 MR. CARUSO: But the black area in the
9 middle --

10 MR. BILLONE: The black is sort of a
11 dull black oxide between this and the base metal
12 that has grown.

13 MR. CARUSO: How much of the base metal
14 did you lose to those shavings? What percentage?

15 MR. BILLONE: This our Russian
16 colleagues measure for us. We lost so much of it
17 the measurement was meaningless, but somewhere
18 around ten percent of the zirconium was oxidized to
19 cause this picture, somewhere around ten percent.

20 But really five, six, seven, eight --
21 between seven and eight percent is where you went
22 completely brittle, long before you got to this
23 picture.

24 There's no fuel here. This is all ugly
25 cladding basically.

NEAL R. GROSS

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

1 DR. FORD: Mike.

2 MR. BILLONE: Yes.

3 DR. FORD: It concerns me that, you
4 know, you're doing a lot of correlation between the
5 damage, the burst, and the fracture of the zircaloy
6 cladding, and the appearance of the oxide, and yet I
7 haven't heard once anyone talk about the
8 relationship, the well known relationship between
9 nodule oxidation which you're showing there and
10 general oxidation and the fabrication procedures for
11 the cladding and the compositions.

12 And you're only looking at four or five
13 specimens. Is there anywhere in your methodology
14 that you look at the past history of the last ten
15 years for the development of optimum cladding,
16 compositions, and how you can fill in the
17 experimental program that takes into account the
18 variability that you will have in these alloys as
19 far as composition is concerned?

20 MR. BILLONE: Well, we did a lot of
21 probing because in some of our tests the inner
22 surface oxidized a little different than the outer
23 surface. We had to ask the question: is there a
24 different treatment?

25 I mean, there's etching and there's

1 polishing, and there's all kinds of variables, and
2 essentially we were able to track over the last ten
3 to 20 years the evolution, and the evolution is such
4 that where they used to etch as a final step, remove
5 as much as 25 microns from the OD, they don't do
6 that any more. Their final steps are polishing.

7 And when we play around, we did etching
8 and an oxidation, and we got some strange results.
9 We did polishing and oxidation, and we got some very
10 good results.

11 They seem to be going in the -- they
12 seem to have arrived in the right direction long
13 before we discovered the importance of these
14 variables, we at Argonne.

15 DR. MEYER: This is Ralph Meyer.

16 Could I comment on this, too? Because I
17 think I know the itch you're trying to scratch.

18 DR. FORD: Yeah.

19 DR. MEYER: In the BWR nodule or
20 corrosion, it was related substantially to the
21 distribution of the particles and to the beta
22 quenching and the temperature controls subsequently.

23 There's a parallel program going on
24 through Kurchatov Institute in Moscow, which is
25 working very closely with us, and they are also

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 doing some of the same things that we're doing at
2 Argonne, but they have different cladding specimens
3 available to them.

4 And what they've found was that there
5 are other features that seem to be controlling this
6 not necessarily related to the beta quench. I'm not
7 saying that we've ruled out the beta quench, but one
8 thing that they found. They had a batch of tubing
9 that was made with a western ingot of zirconium, and
10 they claim they put that through the same tube
11 fabrication process as standard E110, and they got a
12 product that did not show this white oxidation like
13 you see here. It's called G110.

14 So now this raises the possibility that
15 the impurity content which you would expect to be
16 different between the electro-refined Russian
17 zirconium metal and the chemically refined Western
18 zirconium ingot might be different.

19 So at the present time we're aware of
20 several things that seem to affect this. Second
21 phase particle size is one of them. Source material
22 is another one. Surface condition is another one.

23 Mike is not able to investigate all of
24 these at Argonne because he doesn't have the variety
25 of materials that are available in Russia.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 DR. FORD: Right.

2 DR. MEYER: But we're able to get more
3 of those varieties into the test program in Russia
4 and have come down to that point.

5 We will get an update on the Russian
6 work at the Nuclear Safety Research Conference near
7 the end of next month.

8 MR. BILLONE: Okay. Sorry.

9 DR. FORD: And another thing. Again,
10 skipping through your graphs, I see no mention of
11 the Zircaloy-2 from Limerick, which was presumably
12 barrier fuel.

13 MR. BILLONE: No, no.

14 DR. FORD: There's no barrier fuel in
15 this?

16 MR. BILLONE: I have the Limerick Zirc-
17 2.

18 DR. FORD: Oh, you do?

19 MR. BILLONE: As a matter of fact, the
20 next picture is Limerick Zirc-2, not the high burn-
21 up. So let me get to the next picture.

22 DR. FORD: Okay.

23 MR. BILLONE: Let me try to be clear
24 when I'm talking about Limerick Zirc-2 in these
25 pictures.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 DR. FORD: Right.

2 MR. BILLONE: So okay. I want to show
3 you the results of what we've done, which is the
4 ring compression tests. They're to be followed by
5 four point bend tests, and based on our experience
6 with Limerick Zirc-2 unirradiated, their potential
7 failure locations under four point bend tests and
8 modes in uniform bending are the burst region, which
9 is thin, flawed cladding, high ECR, and oxygen
10 embrittlement, and the neck regions which are thick,
11 and an unclogged cladding. Most of those things are
12 good. Low ECR, but very, very high hydrogen.

13 And there's a transition here which may
14 render the whole burst region basically lacking in
15 ductility, and we'll see what we mean by that.

16 Let me go to that picture now. We'll
17 come back to it because it really wasn't part of
18 this high burn-up program -- I mean, sorry, it
19 wasn't part of the advanced alloy program. And
20 Ralph and Rosa, who have seen this picture, we've
21 added more points. Odelli, we keep adding more
22 points.

23 Basically what I'm going to give you is
24 distributions of hydrogen, and this is really an
25 oxygen distribution converted to ECR, starting at

NEAL R. GROSS

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

1 the burst center and moving below and, well, above.
2 Okay. This is a distance above the burst center.

3 So this is going towards the top of the
4 specimen. This is going towards the bottom of the
5 specimen. And really we get about a 158 to 170
6 millimeter balloon in our samples, but what you see
7 is in the burst region. Of course, you have the
8 highest oxygen pickup relative to the thickness.
9 It's the thinnest material, and this is averaged
10 over the circumference.

11 And then as you move away, this is still
12 in the balloon region. You haven't gotten to the
13 neck region. Your hydrogen for the unirradiated
14 material which has room to pick up hydrogen, it has
15 zirconium pellets inside. These hydrogen contents
16 are so high that this is guaranteed to be brittle.
17 It might be stronger in this region, but it's
18 definitely lacking in ductility.

19 And even as you go -- let me work on
20 this side -- as you go to decreasing hydrogen,
21 you're going to increasing oxygen, and so in terms
22 of ductility within the balloon region, let's just
23 say that this whole area has the potential for
24 acting in a structural sense like a brittle material
25 if you're going to subject to bending, and we'll

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 come back and --

2 DR. FORD: This is Zircaloy-2 from
3 Limerick?

4 MR. BILLONE: This is Zircaloy-2 from
5 Limerick, unirradiated, unirradiated.

6 DR. FORD: Right.

7 MR. BILLONE: And so what we're doing
8 right now with the tests we ran last year --

9 DR. FORD: I guess I haven't given my
10 concern.

11 MR. BILLONE: Okay.

12 DR. FORD: If it's from Limerick,
13 presumably it's a barrier fuel cladding, i.e., it's
14 got zirconium on the ID.

15 MR. BILLONE: Right.

16 DR. FORD: Zirconium is going to oxidize
17 like crazy, is it not?

18 MR. BILLONE: No. There's no difference
19 in the high temperature oxidation of zirconium,
20 Zircaloy-2, Zircaloy-4, da-da-da-da-da-da-da-da.
21 The temperatures of 1,100, 1,200 degrees C.

22 DR. FORD: Okay.

23 MR. BILLONE: And what I'm suggesting to
24 you is this is not particularly Zirc-2. This is
25 well known phenomenon that demonstrated Zirc-4 in

NEAL R. GROSS

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

1 1981. Only the magnitudes weren't as great, and all
2 the cladding alloys to some extent will have this
3 qualitative picture when tested in the unirradiated
4 condition.

5 That's my prediction, but that's what
6 we're in the process of doing, is testing all of the
7 alloys under the balloon and burst condition.

8 But I want to show you this now and then
9 I want to come back to it because my demonstration
10 tests and my pictures all pertain to something that
11 looks like this in terms of oxygen and hydrogen.
12 That's why I wanted to hit it early. I'll hit it
13 again soon.

14 Okay. In my back-up slides I have a lot
15 of graphs. I'm not going to do the graphs. I'm
16 going to try to do it this way.

17 When we look at the data results for
18 1,100 degrees C. oxidation temperatures, and that
19 was up to 1,100 seconds coincidentally, Zirc-4 and 5
20 and ZIRLO data are all in agreement with the
21 Cathcart-Pawel prediction. I think I do have a
22 graph of that. I just didn't identify the points,
23 meaning within plus or minus ten percent.

24 So 1,100 degrees C., the oxidation
25 kinetics are very similar for these three alloys.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 We could not get meaningful data from the as
2 received E110 because of the oxide instability. The
3 oxide flaked off.

4 However, if we polished and machined it
5 or at least polished it, we could delay the
6 instability and basically the E110 data polished
7 prior to instability behaves the same as these three
8 alloys up here.

9 Things start to change when you go to
10 1,000 degrees C. Zirc-4 and ZIRLO are in very good
11 agreement, as published previously by Westinghouse.
12 They're very similar weight gain kinetics. As
13 published by a variety of groups, M5 is
14 significantly lower at this particular temperature.
15 It picks up less oxygen during the same period of
16 time. Whereas at 1,050 and 950 it's about the same,
17 at 1,000 it's different.

18 Again, we could not get meaningful data
19 for E110 unless we polished it, and basically M5 and
20 E110 both behaved the same in terms of weight gain
21 kinetics. The Zirc-1 niobium alloys at 1,000
22 degrees C. pick up less oxygen than the Zirc-10
23 alloys.

24 We're in the process of preparing tests
25 at 1,200 and 1,260 degrees C., and during our

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 studies basically if you don't pick up hydrogen, we
2 saw no effects of quench at 800 degrees C. on the
3 weight gain. We also saw no effects on the post-
4 quench ductility, but we'll hold that until the next
5 slide.

6 All right. This is my compromise with
7 the vendors. That's all the alloys that I just
8 mentioned at 1,100 degrees C., and we're comparing
9 the Cathcart-Pawel correlation to the measured
10 weight gain. The alloy that falls off a little bit
11 is the E110.

12 And in terms of the alloys we're
13 interested in, they're all in excellent agreement at
14 1,100 degrees C., and most likely we'll get the same
15 results as 1,200 degrees C.

16 It's 1,000 degrees C. where we start
17 seeing alloy differences.

18 CHAIRMAN POWERS: Do I read it correctly
19 that you have a consistent bias to underpredict the
20 amount of weight gain in ZIRLO?

21 MR. BILLONE: I'm sorry?

22 CHAIRMAN POWERS: Do you consistently
23 underpredict the weight gain in ZIRLO with Cathcart-
24 Pawel?

25 MR. BILLONE: No.

NEAL R. GROSS

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

1 CHAIRMAN POWERS: It seems like that's
2 what you have with the plot.

3 MR. BILLONE: I'd have to dig for the
4 ZIRLO plot. Let me show you. I have a table with
5 results at about 20 percent ECR, predicted versus
6 measured for two temperatures. Definitely not 1,000
7 degrees C. A thousand degrees C., Cathcart-Pawel
8 predicts more than is measured for ZIRLO.

9 Actually our Zirc-4 should match
10 Cathcart-Pawel because it was done with Zirc-4, and
11 our Zirc-4 tends to be a little bit high, the
12 measured values.

13 Okay. We have detailed results at five
14 percent ECR, ten percent ECR, 15, 17, 20. I'm just
15 going to show you 20. Basically you're not
16 comparing the alloys. You don't notice there's a
17 comparison, but at 1,100 degrees C. oxidation
18 temperature and 20 percent calculated ECR, well, the
19 Zirc-4 came out okay, and I just contradicted
20 myself. The ZIRLO is a little bit higher, but not
21 significantly higher. That's five percent, and the
22 M5 is a little bit lower.

23 So at 1,100 degrees C. this is all about
24 20 percent measured ECR. These are the offset
25 displacements converted to strains by dividing by

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 the diameters. They all indicate that you have some
2 plasticity still left in these samples after 20
3 percent ECR.

4 We went ahead and measured the hydrogen
5 pickups, and they are low, consistent with the fact
6 that you have ductility. We'll look at the
7 metallography to do the third confirming factor. At
8 1,100 degrees C. if all you're doing is picking up
9 oxygen and no hydrogen, you're not going to
10 embrittle within the ECR range that you're
11 interested in.

12 Add these to your table because I had
13 this in progress. This is, again, Friday night.
14 With M5 you can see the clear decrease in weight
15 gain compared to the other alloys for the same test
16 time, but you don't see any increase in ductility,
17 which is kind of interesting because the oxygen
18 pickup is much less. There's hardly any hydrogen
19 pickup for these two, and the ZIRLO for some reason
20 picks up about 110 weight parts per million of
21 hydrogen.

22 Having just gotten this Friday night, I
23 do not have an explanation for why that alloy
24 behaves differently. As I say, we'll have
25 metallography on all of these for you to back them

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 up, but basically at these temperatures, these three
2 alloys test out as being ductile in tests where you
3 don't have ballooning and burst. These are just
4 undeformed rings that you're oxidizing on both
5 sides. This is basically consistent with what's
6 published in the literature. They're good up to at
7 least this ECR without hydrogen.

8 Okay. Let me try to do the summary of
9 the E110 results very quickly as far as we could
10 take it. Clearly, the alloy is more challenged at
11 1,000 degrees C. than 1,100 degrees C. and then at
12 1,200 degrees C. The farther away you get from that
13 phase equilibrium temperature for the good oxide,
14 the more chance for instability in the development
15 of the white monoclinic oxide.

16 But there is a difference. At 1,100
17 degrees C. basically these white nodes stay pretty
18 much separate, and they lead to a combination of
19 oxygen and hydrogen embrittlement. That sample that
20 I showed you had 200 ppm of hydrogen and it was
21 brittle. At 1,000 degrees C., you have delamination
22 and spallation of the oxide at least at very high
23 hydrogen embrittlement, at fairly low weight gains
24 or ECRs.

25 We ran a couple of tests at 950 for the

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 same times as 1,000, and the samples at least look
2 worse than they did at 1,000. So, I mean,
3 definitely there's a problem in that ramp-up and in
4 the hold time.

5 We found that the surface roughness, the
6 grooves in the material, welding TCs in the
7 material, the ends, they're all initiation sites for
8 oxide transitions and instability, and for one thing
9 they definitely would disturb the compressive stress
10 field that you need.

11 There's something else disturbing the
12 chemistry that you need to keep it as ZrO two minus
13 X. There's something dragging a little extra oxygen
14 in there, pushing you towards that white oxide
15 phase.

16 Okay. Surface polishing significantly
17 improves the E110 behavior. Etching, especially
18 with HF, degrades. As said here, "etching as
19 received E110 significantly degrades the initial
20 oxide due to the fluorine pickup."

21 This work is in progress, and all we can
22 find is in looking at a tiny, tiny spot with TEM,
23 it's an indication of nonuniform distribution of
24 niobium particles in comparing E110 to M5.

25 So that's where we are with the E110.

NEAL R. GROSS

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

1 That work is being continued by our Russian
2 colleagues.

3 CHAIRMAN POWERS: Mike, if you're going
4 to move to the LOCA integral tests now --

5 MR. BILLONE: Yeah. Do you want to
6 break?

7 CHAIRMAN POWERS: Yeah, let's break for
8 --

9 MR. BILLONE: Thank you.

10 CHAIRMAN POWERS: -- lunch until, say,
11 1:45.

12 MR. BILLONE: That would be wonderful.

13 CHAIRMAN POWERS: Okay. We're recessed
14 until 1:45.

15 (Whereupon, at 1:01 p.m., the meeting
16 was recessed for lunch, to reconvene at 1:45 p.m.,
17 the same day.)

18

19

20

21

22

23

24

25

A-F-T-E-R-N-O-O-N S-E-S-S-I-O-N

(1:47 p.m.)

CHAIRMAN POWERS: Let's come back into session to continue hearing about the testing going on at the Argonne program from Mike Billone.

MR. BILLONE: Okay. While people are gathering, let me just summarize what I presented already on advanced alloy from one slide and then we'll move on to the LOCA high burn-up stuff.

As I talked about with our current oxidation quench study, and as we see cladding and basically for Zircaloy-4, ZIRLO, and M5, you're looking at oxygen induced embrittlement. These are short rings that we're oxidizing. They don't pick up any hydrogen with the exception of that last ZIRLO point, which is about 100 weight parts per million, and that's not enough to embrittle it.

All three alloys retain ductility at the two temperatures we've completed, up to 20 percent ECR calculated, and that's based on three things: the load flexion curve, the hydrogen pickup, and the metallography that we're making this statement.

For E110 it's hydrogen and oxygen induced embrittlement. What's in progress are the LOCA integral tests for ballooning and burst for

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 each of the alloys at each temperature, and that
2 would be one test, one ECR each temperature, each
3 alloy, followed by four point bend tests.

4 And we've talked about issues associated
5 with hydrogen concentration. I think you'll see
6 those in all of the unirradiated alloys.

7 So let's move on to our work with high
8 burn-up Limerick fuel, and all of this from now on
9 will be pertaining to Limerick Zirc-2.

10 I showed you our temperature history,
11 and I'll show it to you again. Basically we
12 stabilize at 300 degrees C. We pressurize. Pick
13 your units by 8.3 megapascals.

14 This will only rise to about 8.6 during
15 the test. It's almost a constant pressure test.

16 So as we ramp from five degrees C. per
17 second, there's not a huge change in pressure
18 through ballooning and burst at 1,204 degrees C.
19 For our unirradiated materials we've held from one
20 to ten minutes. Ten minutes is too aggressive.
21 That's about 30 percent Cathcart-Pawel ECR, about
22 1.3 times that Baker-Just.

23 Cooled to 800 degrees C. at three
24 degrees C. and quenched. We've done detailed
25 profilometry, metallography, hydrogen and oxygen

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 determination. Our samples, and in progress are
2 four point bend tests and ring compression tests.

3 So far results of post-quench ductility
4 tests, these are demonstration tests that I did with
5 my hands in front of various audiences just to learn
6 something about it, and you all have a concept of
7 brittle versus ductile, and I haven't done this in
8 20 years, but they don't make chalk the way they
9 used to.

10 Chalk we know is basically brittle. It
11 fails with no plastic flow, and it fails straight
12 across based on maximum principal stress. This
13 metal, on the other hand, is highly ductile. It
14 will bend excessively. You probably can't even get
15 it to break unless you fatigue it.

16 So we have a sense of ductile versus
17 brittle. This happens to be a fluorescent tube,
18 which is not quite glass, and we had to do it this
19 way, but this is a four point bend test, and you
20 could get shattering with the glass or you could get
21 a clean break.

22 If you score it, if you put a little
23 scratch on it, then you'll get a clean break across,
24 and it's basically low fracture toughness material.

25 So what we're interested in is as a

NEAL R. GROSS

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

1 structure, the four point bend test, does this
2 material behave like the chalk in the glass or does
3 it behave like this or somewhere in between, and
4 we're going to find out it's a little more
5 complicated than that because as pointed up earlier,
6 we don't have a uniform degree of embrittlement.

7 Okay. I'm sorry you have a black and
8 white copy of this, but let me try to -- okay.

9 If we compare our companion out of cell
10 test, and this would be ramp-to-burst and then
11 cooled in argon. So there's no oxidation of these
12 tests. If we look at the change in diameter
13 starting from the top going to the bottom of the
14 specimen, basically we find for the unirradiated
15 with zirconia pellets inside slightly higher average
16 burst strain and a wider balloon, and you're
17 following the blue and the green, and a much more
18 concentrated balloon region, slightly less
19 ballooning strain if you average these two numbers
20 together. This is 30, so approximately 40 percent
21 average strain for ballooning for that.

22 CHAIRMAN POWERS: Mike, if I did any one
23 of the tests 500 times and plotted them up there,
24 would there be any significant difference?

25 MR. BILLONE: What we find is there's a

1 little shift on where --

2 CHAIRMAN POWERS: Yeah, what I'm asking
3 is is that little shift significant?

4 MR. BILLONE: Not in terms of the
5 parameters we're looking at, which is what is the
6 extent of the ballooning region, what is the
7 maximum, and what does the cross-section look like.

8 Yeah, we would get slightly different
9 results each time we insert a test strain and run
10 the test.

11 DR. FORD: When you do this four point
12 bend test as a measurement of the ductility, how
13 does that relate to the actual strain or the
14 straining mode that you will have in a post --

15 MR. BILLONE: Well, you do out of cell.
16 You do the test in an Instron.

17 DR. FORD: I recognize that.

18 MR. BILLONE: Yeah.

19 DR. FORD: But what sort of -- are you
20 going to have bending stresses on this structure,
21 too?

22 MR. BILLONE: Yes. Let me get to that
23 when I get to the -- I mean, I have a nice
24 demonstration sample, but it failed during transport
25 because it was too brittle in the high hydrogen

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 region, but --

2 (Laughter.)

3 MR. BILLONE: -- you won't get the
4 theatrics of a live demonstration.

5 Let me go through what's similar between
6 high burn-up fuel and unirradiated fuel, and some of
7 the details of what the cross-sections look like for
8 the two.

9 Basically for Limerick we found more
10 similarities than differences, except in the burst
11 shape hopefully, and then I'll get to the
12 demonstration samples.

13 So you saw the diameter profiles, and
14 this would be the fuel high burn-up sample. These
15 two burst at about the same temperature during the
16 ramp. This would be unirradiated Zirc-2 out of
17 cell; irradiated high burn-up Zirc-2 in cell with
18 fuel limit.

19 They burst at about the same temperature
20 and about the same pressure. I just showed you the
21 burst strains, which are a little bit different.
22 The main difference is the shape of this opening.
23 This is more of a dog bone shape, and this is more
24 of an oval shape.

25 If I go to bend this sample with this

NEAL R. GROSS

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

1 region under tension, the stress concentrations will
2 be a little bit different than that. That is the
3 one difference we found between the high burn-up and
4 the unirradiated. We expected to find more than
5 that.

6 That's based on nondestructive testing.
7 I'll mention something about destructive, but it's
8 not too hard to guess what's going to happen. If
9 you take the unirradiated Zirc-2, just burst it and
10 then cool down with no oxidation and look at the
11 thickness variation as you go around, this is 180
12 degrees from burst. Obviously this region, as Ralph
13 was saying, steam enters here. You're going to get
14 essentially 100 percent oxidation here. It's going
15 to drop off to maybe 13 percent here, and there's a
16 nice algorithm explaining how you determine what
17 this average thickness is and do you ECR
18 calculation.

19 But what you're going to have is after
20 oxidation I'll show you the picture. You're going
21 to have a gradient this way in which you're going to
22 have almost completely 100 percent brittle material
23 here, transitioning to a locally ductile material
24 there, and the question is: how does that behave in
25 a structural test? And what does "some ductility"

NEAL R. GROSS

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

1 mean?

2 Actually I'm not supposed to answer that
3 question. I'm just supposed to respond.

4 If you go to the neck cross-section,
5 obviously this is without oxidation, without
6 hydrating, you obviously haven't -- your circular
7 structure only is six percent reduction in wall
8 thickness, and that's a fairly strong and ductile
9 sample at this point in time. This is just at
10 burst.

11 Later when we look at some of the
12 pictures, we'll find out that we do get some bending
13 during the ejection of gas from the rod, and clearly
14 at zero percent ECR, you have ductility with these
15 two pictures that I've shown.

16 All right. Okay. I showed you the
17 profilometry with no oxidation, and now let's look
18 at five minutes of oxidation, and this gets back to
19 Dana's point. We're getting the ballooning and
20 burst for the unoxidized sample. It's nice for
21 looking because they don't overlap. This is the
22 unoxidized sample. It has moved up a little bit
23 towards the top in terms of where the ballooning and
24 burst occurred.

25 You have to realize in response to

NEAL R. GROSS

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

1 Dana's question, too, ballooning and burst is an
2 instability phenomenon, and if you happen to have a
3 uniform temperature, which we don't have, over about
4 100 millimeters, exactly where that ballooning and
5 burst is going to initiate, once it is initiated, it
6 takes off on you. It's an instability phenomenon
7 that could occur anywhere within this region.

8 So our in cell test has about the same
9 for strain; again, a little more narrow in terms of
10 burst length, and we'll look at -- we'll do some
11 cuts here and some cuts here and look at what the
12 cross-sections look like because the question with
13 the high burn-up fuel is do you have full double
14 sided oxidation with the fuel in there. Do you have
15 the hydrogen pick-up with the fuel in there.

16 Okay. By the time we took a photograph
17 of this picture, we had lost most of the fuel from
18 this section. If you look at a cross-section of the
19 fuel before we start, the cracks are such that if
20 you have an opening, .3 millimeters, it's large
21 enough for fuel particles to come out of here.

22 And so we lost about less than a pellet
23 initially, and then with further handling we lost
24 more.

25 This strain's shape, which looked a

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 little better in the previous picture, we got a
2 little more bending. I'm sorry. I don't have a --
3 out of plane bending this way. So this side went in
4 and this came out a little bit, and you ended up
5 with this kind of burst opening, but you're looking
6 at the picture after five minutes of oxidation and
7 steam, and it's clearly ductile at the time of
8 burst, and the question is: is it ductile at this
9 point?

10 DR. FORD: I thought someone said
11 earlier on that you would not be using pellets.

12 MR. BILLONE: No, I'm sorry. This
13 sample with fuel in it, the whole thing is like 300
14 millimeters, 12 inches. That will be subjected to a
15 four point bend test with fuel in it.

16 DR. FORD: Yeah.

17 MR. BILLONE: Let's assume it breaks
18 here or it breaks here. In the regions that are
19 essentially circular, we would cut eight millimeter
20 rings, defuel them, and then subject them to ring
21 compression tests because they should be essentially
22 brittle if the hydrogen is high.

23 So the idea is you subject them to ring
24 compression tests. If you happen to get zero
25 ductility, no ductility, then you measure the

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 hydrogen and you correlate the two. So the ring
2 compression test would be with the fuel.

3 Okay. This is the picture I wanted to
4 show that we've been alluding to. Even in the
5 cutting of this in cell, you've lost the tips which
6 were 100 percent oxidized. I've put this in terms
7 of ECR. It's really oxygen pickup relative to the
8 thickness, and this 36 percent goes to essentially
9 100 percent.

10 But although this region here -- and the
11 only thing keeping you ductile -- I don't know if
12 you can see it -- is this region from here to here.
13 That's the prior beta layer. It's essentially
14 missing from here. It's 100 percent brittle.

15 This region, based on our ring
16 compression tests and our other program, this really
17 should be ductile, locally ductile, and how this
18 sample is going to behave depends on how you bend
19 it. If you bend it with this under tension, you're
20 going to rapidly initiate a crack, which is going to
21 go across that cross-section, and you may miss
22 whatever ductility you have.

23 If you do the reverse, something
24 interesting would happen depending on whether
25 pellets are left inside or not. Those are some of

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 the results I wanted to show you.

2 All right. That was unirradiated. For
3 the irradiated, which is harder to get the
4 metallography in cell, basically what you're looking
5 at is a similar type cross-section. This is our in
6 cell high burn-up test. Ignore this wide opening.
7 It's just going to put pieces together, but
8 essentially the oxide layer is dark. So you're not
9 looking at that, but you're seeing essentially the
10 same structure, very thin tips going around to
11 thicker regions.

12 And we've looked at the detailed
13 micrographs of the oxide layer. It is double sided
14 oxidation all the way around here, the same as you
15 would get in an unirradiated test. We don't expect
16 this region to pick up any hydrogen. So we're not
17 measuring hydrogen in that region.

18 So what is the influence of the fuel on
19 the oxidation? It's zero. You've expanded about
20 40, 50 percent away from the fuel. Even if you had
21 fuel particles in there, it doesn't protect you
22 against the steam.

23 All right. Let's go back to the
24 unirradiated graphs real quickly because I've gotten
25 failures in both of these regions in bending. If

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 you move 22 millimeters, close to an inch, above the
2 burst center, you're still in the balloon region.
3 The ECR is 16 percent, but the hydrogen is 2,500
4 weight parts per million.

5 This really should be brittle, and
6 you're still in the balloon region. You haven't hit
7 the neck region yet.

8 It looks okay. I mean, you've got a
9 nice, thick prior beta layer, but it's loaded with
10 hydrogen. As a matter of fact, one of our bending
11 test failures did occur there.

12 And as you get closer to the neck, when
13 you get to the neck region, you essentially have one
14 sided oxidation, very little oxidation on this side.
15 I mean, ignore this. This is from the epoxy.

16 So your ECR drops way down low, but your
17 hydrogen peaks to 3,500, and this is close to two
18 inches above the burst center. So you have a
19 gradation of thin, weak, oxidized cladding in the
20 burst region, which may look brittle in the tests,
21 and then as you move, you continue to have what may
22 be brittle for unirradiated material.

23 What we're in the process of doing at
24 this location for the irradiated tests, we're
25 measuring the hydrogen here and in the previous

NEAL R. GROSS

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

1 picture to find out if this secondary hydriding,
2 which is all picked up from the inner surface, and
3 the question is that oxide layer that you form, that
4 fuel clouding bond that you form during or up to
5 high burn-up irradiation, is it protective against
6 hydrogen? It's certainly not protective against
7 oxygen and steam oxidation.

8 Okay. We've seen this picture. So
9 let's take this picture now and let's take several
10 samples with this kind of picture. Let's expose it
11 to four point bending which essentially at all of
12 these locations you're exposing it to the same
13 bending moment, and where it fails. We're
14 interested in two things. Where does it fail?
15 Here, here, here or in between? And how does it
16 fail? What kind of failure mode do we have?

17 Let me do this with pictures because I
18 don't want to take up too much of your time. All
19 right. I was going to physically show this to you.

20 But this is the sample prior to the
21 test. This is after five minutes of oxidation at
22 1,200 degrees C. You can see a slight bend to the
23 sample that occurred during burst, and clearly the
24 sample was ductile at that point in time. It has
25 got permanent plastic deformation.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 The idea of the four point bend test --
2 and this was the first one I performed in June, at
3 our June meeting -- this is the burst region. I'm
4 going to put that under tension, and this ductile
5 region is under compression.

6 For this test I left the pellets in, and
7 the pellets were supposed to be left in for the test
8 I was going to do, but these are 2,500 millimeter
9 long, 100 percent dense zirconium pellets. They're
10 very, very, very stiff, and when you try to bend,
11 they add to the stiffness of it.

12 Fortunately it didn't affect -- the
13 thing failed before I got too far into the bending,
14 and in this particular test it failed right at the
15 center of the burst, and it failed with a snap.

16 And, again, I'm doing this by hand.
17 It's not an Instron. I don't have a bending moment
18 versus deflection curve, but it failed more like the
19 chalk than like this. That's just a qualitative
20 description.

21 And it also fails basically straight
22 across. We're in the process of measuring. Even
23 though this was a reject sample we weren't
24 interested in, because the failure is interesting
25 we're measuring the oxygen content right here to see

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 what the peak ECR is for this particular sample.

2 All right. At this point I thought I
3 knew everything, and so a month later when we had
4 our international meeting I figured I would just
5 take this sample, a different sample, turn it 180
6 degrees C., and put the good side under tension and
7 the bad side under compression and try to control it
8 to get bending before a break.

9 That was being a little too cocky. So
10 that's what I was trying to demonstrate.
11 Essentially I've turned the sample upside down, and
12 so this good side is under tension -- did I do this
13 right? -- and this bad side is under compression.

14 I mean, it was an interesting test
15 because I did it very slowly, and I did it with a
16 lot of witnesses, and what I was foiled by is the
17 sample Ralph showed you, and I'll pass it around.
18 That's the one I just broke today.

19 As you can see what happened on the
20 compressive side, again, I'm trying to bend the
21 other side of this, and what happened is this burst
22 area fragmented. Cracks started growing in all
23 different directions, and the axial crack grew here
24 and grew down here.

25 When the axial crack hit the high

NEAL R. GROSS

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

1 hydrogen region, it snapped across the high hydrogen
2 region. So depending on how you do the test, I
3 mean, that determines the location of failure, and
4 it's obviously much more complicated when you put
5 this burst section under compression and get these
6 cracks growing all over the place.

7 MR. CARUSO: And these are without the
8 zirconium pellets inside?

9 MR. BILLONE: This test was without the
10 zirconium pellets, and so I was intrigued by the
11 results, but my pride was hurt. So I came back here
12 on August 18th and left the pellets in and repeated
13 the test because I was convinced I could get the
14 good side to show ductility.

15 So if you leave the pellets in and just
16 do the same test, the pellets stabilize this region.
17 It's not a great picture, and I apologize. You do
18 get cracking in the burst region, and the cracks go
19 in all directions.

20 But on the ductile side which is under
21 tension, I don't know if you can see it. This is a
22 pellet that's wedged in there, and essentially
23 you're bending with very high ductility the 180
24 degrees from burst part, which is at about 13
25 percent ECR, around that pellet, and it took a lot

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 of force to get this bending.

2 So, again, what does "some ductility"
3 mean? This is consistent with the metallography in
4 the sense that that back side has ductility, but in
5 every test that I'm familiar with when you talk
6 about fracture toughness or you talk about the
7 ability of a material to withstand loads, you never
8 perform a test this way. You always put the flawed
9 region under tension and you look at how that crack
10 grows.

11 And if it grows rapidly with very little
12 plastic deformation in a structure sense, you call
13 it brittle. Then there's mixed mode, which we're
14 really in, and then there's ductile behavior where
15 you get bend before break.

16 DR. FORD: I'm assuming that these are
17 wasted samples. These are just --

18 MR. BILLONE: These were all reject
19 samples.

20 DR. FORD: Yeah, got you.

21 MR. BILLONE: There's little
22 oscillations in the temperature history. We didn't
23 like them for the --

24 DR. FORD: But the controlled
25 experiments will be presumably done at different

NEAL R. GROSS

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

1 strain rates, different temperatures.

2 MR. BILLONE: Yeah, most definitely out
3 of reactor.

4 DR. FORD: Yeah, with the fuel in.

5 MR. BILLONE: With the fuel in it, but I
6 would choose to do the burst opening always under
7 tension. That would be my choice.

8 DR. FORD: But is that necessarily --

9 MR. BILLONE: Well, if this thing bends,
10 I mean, I'm not supposed to be relating this to an
11 actual reactor event, but if --

12 DR. FORD: Well, why not?

13 MR. BILLONE: -- if you had a seismic
14 event and you got an aftershock after the quench,
15 you would induce some bending.

16 DR. FORD: Sure.

17 MR. BILLONE: So, I mean, it's not
18 just going to bend one way. It's going to bend both
19 ways. So I'm just trying to be consistent with all
20 testing that I'm familiar with.

21 If you're going to take a flawed sample
22 and test it for fracture toughness, which is not
23 what we're doing, we won't get a fracture toughness
24 out of this, and honestly, this was a nice impact
25 sample with pellets in it. I was going to do some

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 kind of tricks with it, and it failed between the
2 hotel and here. I don't know how it failed, but it
3 failed in the high hydrogen region, and I have no
4 idea of the loads inside the tube.

5 But basically, the idea is with the
6 burst opening --

7 DR. FORD: All I'm questioning is you
8 had some peculiar results using your samples which
9 didn't go according to what your intuition told you.
10 So, therefore, should you not be doing your
11 controlled tests, not necessarily --

12 MR. BILLONE: That's the next slide.
13 It's the next slide, but my intuition was bordering
14 on hubris because I thought I knew the answers and
15 that is not how you do research.

16 Okay. All right. We already know the
17 observations. Skip that, skip that. I am winding
18 down now.

19 Okay. I think it's two slides and we're
20 done.

21 Comparing our out of cell results with
22 our high burn-up results, we saw a lot of
23 similarities. Pressurization rate, meaning
24 permeability, when you pressurize from the top and
25 you measure gas at the bottom, and depressurization

NEAL R. GROSS

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

1 rates at bursts at least down to the three
2 megapascals of pressure are all similar.

3 Maximum circumferential strain and burst
4 region are more similar than different. Length and
5 maximum opening of the burst were similar. Extent
6 of double sided oxidation in burst region and
7 maximum ECR appear to be similar.

8 Differences are the shape of the burst
9 region which will affect the stress concentrations
10 and response to bending tests, and of course, the
11 axial extent of the burst region was much less for
12 the high burn-up fuel than for the unirradiated.

13 And the second and extent of secondary
14 hydriding we know is very, very high for these
15 unirradiated. We're in the process of determining
16 it for the irradiated.

17 Expectations as we move to the Robinson
18 HBR cladding, again, all of this is work done with
19 low hydrogen content, high burn-up Zirc-2.

20 As we move to the Zirc-4, the hydrogen
21 content, we hope to take samples from the 400 weight
22 parts per million regions and the 800 weight part
23 per million regions. These contents will have an
24 effect, a significant effect on ballooning and
25 burst, as the JAERI results will show, because the

NEAL R. GROSS

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

1 hydrogen does lower this transition from one phase
2 to the other phase.

3 And we've been purposely bursting in the
4 alpha phase to get the largest balloon we could
5 produce, and essentially in order to do that, we're
6 going to have to increase our pressure to get the
7 same kind o results for hydrided Zirc-4. So that's
8 one effect we know that we saw in the results of the
9 JAERI test, is hydrogen will affect the phase
10 transition temperature, which will, in turn, affect
11 the ballooning size. Okay.

12 CHAIRMAN POWERS: Is the length of your
13 balloon region and the size of the opening a
14 function of the material or the furnace you're
15 testing it no?

16 MR. BILLONE: We just completed -- we
17 wanted to rebenchmark our in-cell apparatus. So we
18 put a fresh two sample in cell in the same place
19 that the high burn-up was, and we got the same
20 result.

21 So for the first order I would say no,
22 meaning that unirradiated material without fuel in
23 it tends to give us a longer burst region and a
24 different shape to the burst opening than the fuel
25 high burn-up when tested in the same apparatus.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 CHAIRMAN POWERS: I guess I'm confused
2 then. Put your slide back up.

3 MR. BILLONE: Okay. I never showed you
4 an apparatus. We have an apparatus out of cell and
5 then right in cell we have a duplicate apparatus and
6 we have common instrumentation in between.

7 CHAIRMAN POWERS: But here you're saying
8 the similarities.

9 MR. BILLONE: Right.

10 CHAIRMAN POWERS: The length and the
11 maximum opening of the burst, and what I'm asking
12 you: is that a function of the materials or is that
13 a function in the way you're testing it?

14 In other words, if I put a different
15 furnace in there --

16 MR. BILLONE: Oh, I'm sorry.

17 CHAIRMAN POWERS: -- will I get a
18 different length and a different maximum opening?

19 MR. BILLONE: The answer is yes and no.
20 Yes, you would get different answers, but you'd
21 still get the same -- I think you'd still get the
22 same relative similarity between irradiated and
23 unirradiated.

24 In other words, we're getting about a
25 half inch burst length.

NEAL R. GROSS

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

1 MR. ROSENTHAL: Why don't you put up the
2 slide that has the burn-up, the high burn-up fuel
3 burst above and the unirradiated below, you know?

4 MR. BILLONE: Oh.

5 MR. ROSENTHAL: One is taken through the
6 window.

7 MR. BILLONE: Yeah.

8 MR. ROSENTHAL: You know, the yellow,
9 and then if you could find that, then people could
10 stare at that and decide whether the characteristics
11 of those two bursts are similar or different.

12 CHAIRMAN POWERS: Well, that might be an
13 interesting exercise, but it doesn't yield results
14 that are very useful to me. The result that I'm
15 interested in is you get this kind of a burst in
16 your test.

17 MR. ROSENTHAL: Right.

18 CHAIRMAN POWERS: What I'd really like
19 to know is what kind of a burst do I get in the
20 reactor.

21 MR. BILLONE: Ah, okay. I tell you one
22 thing that will be different is, since our
23 relatively uniform heating zone is about 125
24 millimeters, about five inches, we're not going to
25 get a balloon longer than that, and that's test

NEAL R. GROSS

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

1 specific.

2 The strain that we get is pretty much --
3 will be different for different internal pressures
4 that you start with, and we're shooting for
5 something like 60 percent. We get something between
6 40 and 60, which varies from test.

7 That's really up to modelers or whatever
8 you want to say to translate this data, these data -
9 - sorry -- into reactor relevant conditions. We're
10 looking for phenomena that are different between
11 high burn-up fuel and regular fuel when tested under
12 the same conditions, and that translation will be
13 made separately by EPRI and by NRC to how relevant
14 this is to reactors.

15 So we never intended, to run tests that
16 would directly be applied to a full length rod and a
17 bundle. We're more humble than that.

18 MR. SCOTT: This is Harold Scott. Let
19 me just mention just thinking about all of the tests
20 that they did at Oak Ridge and in Germany and in
21 other places with unirradiated and irradiated rods,
22 the balloons were always relatively short except for
23 the ones they did in England, and those had a
24 particular reason why they did that, and these were
25 bundled tests. They had long, heated zones.

NEAL R. GROSS

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

1 So from a material property, as Mike
2 said before, you're going to find one little place
3 that goes first, and so it's almost impossible to
4 get a long length balloon.

5 Now, maybe they'll have slightly
6 different shapes. I think that fish mouth thing may
7 look different in the same apparatus or from
8 different apparatus, but in general, the total
9 length of the balloon is always going to be short.

10 MS. YANG: Can I just add one more
11 thing?

12 MR. BILLONE: Yeah, Rosa.

13 MS. YANG: I think in terms of uniform
14 temperature this is probably more uniform here than
15 in the reactor, so tend to promote the balloon size.

16 And another difference between this and
17 the reactor is these tests are heated from the
18 outside on the cladding. So, in fact, the cladding
19 temperature is hotter than the fuel, while in the
20 LOCA in the reactor the temperature of the cladding
21 comes from the fuel. So if anything, this
22 particular test is more conservative in terms of
23 promoting the balloon because of the way the
24 experiment is heated.

25 MR. BILLONE: Okay. I'm going to --

NEAL R. GROSS

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

1 CHAIRMAN POWERS: I'm puzzled with that
2 one a little bit. Why does this lead to a more --

3 MR. BILLONE: I'm not responding.

4 CHAIRMAN POWERS: -- a longer balloon
5 than in the reactor? Because assuredly I have seen
6 in reactor tests with balloons that were that long.
7 So I'm going to have to think about that a little
8 bit.

9 MR. BILLONE: All right. Let me just
10 tell you where we're going, and then I'll sit down.
11 I promise, I promise, I promise.

12 What I would like to do, what we can do
13 easily out of cell in an Instron, which has just
14 arrived this week, a new tabletop model just for
15 this purpose, is as I mentioned before, we know at
16 zero ECR we can see the specimen bend. We know it
17 has got plastic deformation from a structural point
18 of view.

19 All of the tests we've been conducting
20 up till now have been at a 20 percent calculated
21 ECR. It's very inexpensive to just march down.
22 These are hold times, and so just from the ramp
23 alone, you're at three percent ECR, and as you go up
24 in time one minute, two minute, three minute, four
25 minute, five minute, you will probably recapture

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 more and more ductility in that balloon inverse
2 region because we know before we even oxidize and
3 we're at zero ECR we're ductile. We think we know,
4 but we're going to put it in an Instron to find out,
5 that this essentially would look like a brittle
6 material under bending.

7 And there will be an ECR, and again,
8 these are calculated with Cathcart-Pawel models. So
9 this is like the Baker-Just 17 percent, somewhere
10 around two minute test.

11 CHAIRMAN POWERS: Now, what would I
12 learn from this?

13 MR. BILLONE: What would you learn from
14 this? You'd get a better feeling of what some
15 ductility meant and what ECR it corresponded to. In
16 other words, it would be completely ductile prior to
17 the oxidation and may appear brittle here and may
18 appear quite ductile here.

19 All I have is two extremes. I have what
20 the shape of the LOCA test specimen is after burst,
21 which has got some permanent bending in it, plastic
22 bending, and I have hand demonstrations at this
23 level which suggest that from a structural point of
24 view it behaves in a brittle manner.

25 All right. These would all be done in

NEAL R. GROSS

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

1 an Instron, and you would get a bending moment
2 versus deflection curves, and you'd look and see
3 whether you got --

4 CHAIRMAN POWERS: Well, I guess I can
5 certainly see why it might be useful to do one at 20
6 and one at 16. It's the nine and the three that I
7 don't understand at all.

8 MR. BILLONE: Well, we'd start here and
9 work back. See, what the problem is -- okay. I'll
10 tell you. Now I know what the nine and the three
11 is. That hydrogen pickup occurs very early in the
12 process. It's not correlated with absolute ECR. So
13 as I make the balloon region stronger and more
14 ductile, do I just simply shift the failure load
15 to --

16 CHAIRMAN POWERS: Oh, okay. Now I
17 understand.

18 MR. BILLONE: I forgot. I forgot why I
19 did it. So you mentioned it. All right, but that's
20 something you can do easily out of cell.

21 Let's end it with that. We're working
22 very hard to do the in cell quench test as soon as
23 possible. With the Limerick, we may do one more
24 Limerick, a total of two quench tests, and then move
25 on to the Robinson.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 CHAIRMAN POWERS: How do your efforts in
2 the quenching relate to the quench program in
3 Germany?

4 MR. BILLONE: How do they relate?
5 Someone remind me. Are these low burn-up fuels, old
6 program?

7 CHAIRMAN POWERS: I think it's no burn-
8 up fuel.

9 MR. BILLONE: It's got to be old.

10 MR. SCOTT: A severe accident, right?
11 They take them up to 2,800 C. and watch how much
12 hydrogen comes out, then quench them.

13 CHAIRMAN POWERS: Well, I think that in
14 their international standard problem they were
15 actually doing a quench for a DBA; that they do do
16 tests. I know Quench 7 and Quench 9 are definitely
17 severe accidents, but I think the international
18 standard problem is intended to be a LOCA DBA.

19 MR. SCOTT: They did burn some at lower.
20 That's true.

21 CHAIRMAN POWERS: Yeah. I believe that
22 to be the case, but I'm asking you guys. I'm not
23 supposed to answer that question.

24 MR. BILLONE: Harold has to answer that
25 one for me. I'm not familiar with those tests.

NEAL R. GROSS

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

1 CHAIRMAN POWERS: I mean, they're
2 clearly out of pile tests, but the interesting
3 feature of them, of course, is that they're bundles
4 and not --

5 MR. BILLONE: right.

6 CHAIRMAN POWERS: -- and not single
7 rods.

8 And so that leads me to the next
9 question. What do you need to know about fuel
10 bundle behavior that you're not going to learn from
11 single rod tests?

12 MR. BILLONE: Just about everything. As
13 Ralph mentioned, with a fuel bundle, you're going to
14 have bursts at different locations unless they're
15 going to be coplanar, and I guess some of the issues
16 are -- and I'm making this up as I go along -- if
17 you have any vibrations and you have these balloon
18 regions, the whacking against the neighboring rod,
19 or if the bending during a LOCA event is not
20 perfectly in phase for every rod, you're going to
21 have not only bending loads, but you're going to
22 have some impact loads.

23 And I think -- well, plus, you don't
24 have an infinite room to balloon burst, and you're
25 going to hit the next rod. So you're --

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 CHAIRMAN POWERS: And does that do
2 anything to you?

3 MR. BILLONE: Well, I don't think it's
4 going to affect your core coolability, but I'm --

5 CHAIRMAN POWERS: Gee, I would think so.
6 You're not going to cool the two parts to the touch.

7 MR. BILLONE: Well, no, but you'll have
8 a lot of -- that's somebody else's area. That's my
9 take, the core coolability versus --

10 CHAIRMAN POWERS: Could we --

11 MR. BILLONE: -- not an issue per
12 bundle.

13 DR. MEYER: This is Ralph Meyer.

14 MR. BILLONE: Jack, can you help me out?
15 Ralph?

16 DR. MEYER: Let me say that this really
17 was a modest program. We did not set out to
18 readdress questions that might not have been
19 answered satisfactorily about single rod versus
20 multi-rod or bundled tests. We set out only to look
21 at burn-up effects, which I think we can do
22 adequately with single rod tests.

23 Now, that may not answer multi-rod
24 tests, questions about multi-rod behavior that you
25 might have, but we really never attempted to do

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 that.

2 We did not at the outset have any multi-
3 rod questions that we thought were burning, and so
4 it's just not in the scope of things. Although this
5 program is expensive in terms of current budgets,
6 this is a very, very modest program compared to the
7 amounts of money that were put in during the days of
8 multi-rod burst tests, and I just don't think we can
9 answer those, any of those questions.

10 CHAIRMAN POWERS: Well, it's a question
11 that the Subcommittee has got to answer.

12 DR. MEYER: I'm sorry?

13 CHAIRMAN POWERS: It's a question the
14 Subcommittee has to address.

15 DR. MEYER: Yeah.

16 CHAIRMAN POWERS: I mean, the question
17 actually is pretty succinct. Are we getting
18 anything out of these tests with just a single rod,
19 or do we have to go to multi-rod tests, and the
20 single rod tests are just interesting academic
21 exercises?

22 I mean that's the question that the
23 Subcommittee has to address.

24 DR. MEYER: Well, I think you have to
25 ask the question in two parts. One is do you have

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 to go to multi-rod tests in order to see the effects
2 of burn-up, and then the other part is do you have
3 to go to multi-rod tests in order to answer
4 questions that you never thought were adequately
5 answered before.

6 MR. ROSENTHAL: The program addresses
7 the former but not the latter.

8 MR. BILLONE: I think in terms of our
9 focus, which is to address ductility, post-quench
10 ductility of high burn-up, I think what we're doing
11 is okay. There is a broader question that you're
12 asking. It's not just academic to learn whether
13 high burn-up fuel picks up 4,000 ppm of hydrogen or
14 zero hydrogen on the other surface, and it's not
15 academic to learn that it has permeability that
16 allows gas to flow to that balloon region and
17 sustain it and keep it going. These are unknown,
18 totally unknown questions that are addressed by
19 modeling prior.

20 So there's a lot about fuel and cladding
21 behavior that we're able to learn that will teach us
22 something about a single rod. Putting that together
23 into a bundle is another world for me.

24 Does anyone have my sample that I passed
25 around or did it get -- okay. Thanks.

NEAL R. GROSS

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

1 All right. Shall we go on?

2 CHAIRMAN POWERS: Wait, wait.

3 MR. ROSENTHAL: Dana, let me just say,
4 you know, in terms of my own thought process, I
5 think that in overall LOCA activities we're going to
6 be emphasizing small break LOCAs over large break
7 LOCA, and we have to look at small break LOCA
8 phenomenology as some sort of design basis, and
9 that's not to say that once we define some break
10 size we'll still look at bigger LOCAs, but we'll
11 look at those through the lenses of severe accident.

12 So that when we do that exercise we'll
13 stack up what we think we don't know without being -
14 - because I think in the past we've been what I call
15 large break LOCA-centric. So then when we restack
16 for the future risk informed LOCA rules within that
17 small break LOCA context with the severe accident
18 stuff with the bigger breaks, I don't know where the
19 multi-rod tests will come out against all of the
20 other phenomenology that we'll be interested in.

21 But that would be the context that I
22 would love to put it in.

23 CHAIRMAN POWERS: I understand what
24 you're saying.

25 MR. OZER: Mr. Chairman, this is Odelli

NEAL R. GROSS

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

1 Ozer.

2 May I read a passage from NUREG 1230
3 relating to the coolability issue where there are
4 multiple rods or the coolability in reactor? May I?

5 CHAIRMAN POWERS: If you think I'll
6 learn something from it. I have no idea what NUREG
7 1230 is.

8 MR. OZER: This says that research
9 conducted since the ECCS hearings has in general
10 yielded two important results. The first is that
11 total blockage is nearly impossible to attain -- and
12 this is based on a reference from BNL -- even if the
13 2,200 and 17 percent ECR criteria are closely
14 approached or exceeded.

15 A second result is that even cases with
16 large blockages remain coolable. In fact, a number
17 of experimental cases in which the blockage actually
18 enhances local cooling, this has been documented.

19 MR. LAUBEN: Excuse me. Dana, NUREG
20 1230 is a compendium of ECCS research that was
21 published in about 1980 --

22 MR. OZER: 1988, yeah.

23 MR. LAUBEN: And I think that you're --

24 MR. CARUSO: Get a mic.

25 CHAIRMAN POWERS: You have to come to a

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 microphone.

2 MR. LAUBEN: You're talking about ECCS
3 coolability in there. It's not necessarily talking
4 about the phenomenology of clad ballooning and
5 rupture, and most of the ballooning and rupture
6 experiments that were done with cooling were done
7 with fairly prescribed geometries for the ruptured
8 and swollen region.

9 Not to say that they were wrong. Some
10 of them were even flat plates in the early days, but
11 others were more typical of ballooned regions.
12 However, I don't know how those tests would have to
13 do with the typicality of ballooned regions based on
14 the -- you know, for those kind of tests.

15 MR. OZER: I thought the question was of
16 interference between adjacent rods, when you have
17 ballooning not just in one rod, but in multiple
18 rods.

19 CHAIRMAN POWERS: The question was
20 explicitly what is it that we need to know about
21 real reactor behavior that we're not going to get
22 from single rod tests.

23 The answer was nearly everything, which
24 was a distressing answer, but perhaps an honest and
25 true one, and I'm a bit at a loss because I know

NEAL R. GROSS

COURT REPORTERS AND TRANSCRIBERS

1323 RHODE ISLAND AVE., N.W.

WASHINGTON, D.C. 20005-3701

(202) 234-4433

www.nealrgross.com

1 the Committee has to address this.

2 The question had been posed a little
3 differently to us. The question had been posed:
4 are we going to learn so little from the single rod
5 tests that there's no point in carrying them out?

6 I think that what we've learned today is
7 enough to dispel that particular version of the
8 question, but the modified version, is there more
9 needs to be done, is still a little open to me.

10 DR. MEYER: This is Ralph Meyer.

11 Let me --

12 CHAIRMAN POWERS: Let me --

13 DR. MEYER: -- address your question
14 before --

15 CHAIRMAN POWERS: Let me first of all --

16 DR. MEYER: Okay.

17 CHAIRMAN POWERS: -- tell you that Dr.
18 Kress is going to take over chairing the session
19 because in about 15 minutes I'm going to run up and
20 talk to the boss man.

21 DR. MEYER: Okay. When the multi-rod
22 tests were done earlier. Harold can help me out if
23 I oversimplify this too much, but it seemed to me
24 that there were really only two substantial
25 conclusions from the multi-rod tests, and that was

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 that the burst sizes and appearances were about the
2 same as you saw in the single rod test, and that the
3 burst locations were not coplanar.

4 So there was not a lot of detail that
5 came out of the multi-rod test in terms of what you
6 need for a safety analysis. Now, if that's an
7 oversimplification, then somebody will correct me,
8 but as we moved into high burn-up effects, there was
9 nothing that came to our mind about bundle effects
10 that would be raised by high burn-up effects. It
11 all looked like we could address the burn-up
12 questions by looking at single rods.

13 CHAIRMAN POWERS: Well, about two years
14 ago -- when did the French talk to us? About two
15 years ago we had a presentation from --

16 DR. MEYER: Alan Myatt (phonetic).

17 CHAIRMAN POWERS: Myar (phonetic), who
18 came in and showed us some interesting pictures and
19 whatnot, and he argued fairly passionately that
20 there was a bundle effect here.

21 Since the time I have seen some
22 calculations on really basically dealing with heat
23 transfer of single rods versus bundles which says,
24 well, on heat transfer effects I just don't learn
25 anything from single rod tests. So I really have to

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 go to bundles, and even multi-bundle to understand
2 the heat transfer.

3 The question we're struggling with now
4 is a modified question. Is there more we need to do
5 to understand what goes on in the reactor accident?

6 DR. MEYER: Does Rosa want to comment on
7 this? I don't have anything to say right now.

8 MS. YANG: I think the bundle one -- I
9 forgot the name of the test -- I think you have
10 summarized it quite well.

11 The only other thing I remember was
12 these ballooned regions were all in the midspan.
13 None of them are really close to the grids. So sort
14 of confirming what you said earlier, the axial
15 constrain effect is not big.

16 I think what Alan Myar (phonetic), at
17 least the presentation I heard when he was promoting
18 the Phebus program, was more on the fuel relocation.
19 I haven't heard him make any really argument, even
20 argument -- forget about convincing --

21 CHAIRMAN POWERS: Yes.

22 MS. YANG: -- to say there's any really
23 bundle effect, except his test is a five-by-five
24 array.

25 So I thought because of that he since

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 has changed his emphasis to more focus on source
2 term in addition to LOCA.

3 DR. MEYER: Yeah, I had the same
4 understanding, that Myatt's main concern was the
5 axial relocation, which is going to be looked at as
6 carefully as we can in the out of reactor tests at
7 Argonne, and also specifically in the Halden test.

8 The Halden tests are designed almost
9 exclusively for that purpose.

10 CHAIRMAN POWERS: Okay. You may go
11 ahead, Mr. Chairman. Charge ahead, Ralph.

12 DR. KRESS: I'm already here. Go ahead.

13 DR. MEYER: Okay. So I thought I would
14 tell you a little about what I know about the fuel
15 damage at the Paks Nuclear Power Plant in Hungary.
16 I'm not going to attempt to give you a detailed
17 description of the chronology of events and things
18 like that.

19 What I want to do is just to go quickly
20 over what happened and then to inform you of an
21 interest that NRC has in cooperation with CSNI in
22 some possible cooperative effort to examine the
23 damaged fuel that are in this cleaning tank.

24 So the background is that after
25 chemically cleaning some steam generator tubes in

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 the Paks Unit 2, that they had a crud build-up on a
2 lot of fuel elements, and they had hired Siemens
3 from Germany, which is now part of the Framatome
4 organization, to come in and clean the fuel in a
5 special cleaning machine that they had.

6 So they had a big tank. They could put
7 30 fuel assemblies in this tank at one time. Now,
8 these are VVER fuel assemblies. They're small,
9 hexagonal array assemblies with a flow shroud around
10 them, and they had used this successfully on five
11 batches of fuel and were cleaning the sixth batch of
12 fuel when, because of the unavailability of a crane
13 one evening, they left the fuel in the tank
14 overnight to be moved out of the tank the next
15 morning.

16 Now, in this cleaning tank there were
17 three circulation pumps. There was a large pump
18 which they used during the cleaning operation, which
19 had been completed. So they had put the oxalic acid
20 in and removed the crud and taken samples, and they
21 were satisfied that it was done, and they had
22 flushed it, and they had turned off the main coolant
23 pump and left running a smaller pump.

24 There was also a back-up smaller pump in
25 case of some failure, but there was no failure in

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 the pump. The small cooling pump which they thought
2 would be adequate to keep it cool overnight was left
3 running.

4 It was not adequate. There was a
5 problem with the circulation, and so there was
6 overheating. They believe there was as steam bubble
7 that formed in the top of this tank, and there was
8 some release of fission products. Noble gas
9 activity was detected several places in the plant.

10 This is a picture of the cleaning tank.
11 I'm really not going to do much with this picture,
12 but it's fairly large. Here you see one of the 30
13 assemblies. There's this upper grid structure, and
14 a lower grid structure. There are, in fact, some
15 bypass flow holes in the shroud which may have
16 figured into the inadequacy of the cooling. There
17 was also the possibility of some misalignment of the
18 nozzles in the lower plate.

19 The details of this are unimportant from
20 our point of interest here now, and so I just show
21 you this. This tank is submerged in an area between
22 the reactor and the storage pool, and it has
23 interfered with further operation of the plant. So
24 the plant is shut down at this time.

25 So all 30 fuel assemblies are badly

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 damaged. We've seen some pictures. If you visit
2 over there they'll show you some pictures, but they
3 won't give you anything to take away. So I don't
4 have any pictures that I can show you. I'll try and
5 describe some of the damage a little bit.

6 From the activity releases we were able
7 to just make an estimate. Well, we were told that
8 roughly 20 percent of the gap activity was released.
9 This is based on detector measurements, and from
10 that estimate it seems to us that some of the fuel
11 got kind of warm, but it didn't really get hot. If
12 you had gotten above 2,000 Centigrade, you'd
13 probably start seeing more than gap activity, and
14 they didn't see anything more than gap activity.

15 So this was our inference about the
16 possible temperature limits, which, in fact, are
17 consistent with calculations that have been done in
18 Hungary and in Germany on this.

19 Now, I've seen pictures of some of this.
20 The shrouds, many of them are broken just below that
21 upper grid area. It's a strange looking geometry
22 that's left. Many of the fuel assemblies are
23 intact. Many of them have the top broken and are
24 just laying askew.

25 There are pieces of the channel box, of

NEAL R. GROSS

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

(202) 234-4433

www.nealgross.com

1 the shroud wall that maybe are ten or 12 inches long
2 and several inches wide that are just missing.

3 You can look inside of these open places
4 in the shroud and see fuel rods. So there are a lot
5 of fuel rods that are left intact in the bundle
6 array.

7 And now I wish I didn't have to tell you
8 this, but we see long sausage balloons in some
9 places.

10 CHAIRMAN POWERS: Why do you not want to
11 tell me that?

12 DR. MEYER: Because we just told you
13 that all of these balloons were short.

14 CHAIRMAN POWERS: But I didn't believe
15 you when you said that anyway. So I mean, we know
16 we can get long sausage balloons. We've done it
17 before. Coming in and telling me that you --

18 DR. MEYER: Well, Ed Hindle did it in a
19 big muffle furnace where he had creamy smooth,
20 uniform temperatures, and we never saw that kind of
21 behavior with internally heated test runs.

22 The thing here is that you've now been
23 shut down for a period of weeks. The heat
24 generation rate is extremely low, and within this
25 shroud there are obviously some areas of very

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 uniform heating which is not the result of any
2 significant heat flow from the fuel where local
3 variations in gap can --

4 CHAIRMAN POWERS: If you're trying to
5 persuade me that we'll never see long sausage
6 balloons in reactor accidents, give up now while
7 you're ahead.

8 DR. MEYER: Well, there's one other --
9 (Laughter.)

10 DR. MEYER: Well, I haven't told you the
11 other thing, which is that the sausage balloons,
12 insofar as I can remember seeing them, were
13 relatively small in diameter and so far none of the
14 long balloons were seen to be ruptured. They did
15 see a number of balloons that were ruptured, and
16 they were all short.

17 So we don't understand all of this, but
18 the fact that there are ballooned rods which have
19 not been "rubbleized" still inside of these flow
20 shrouds I think makes this much more interesting for
21 pathological examination than if it had just been a
22 rubble pile.

23 CHAIRMAN POWERS: I mean that's all a
24 very fair statement, but where I run into trouble is
25 saying X or Y can never happen. Simply because

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 you've never seen it in an experiment you've done
2 with one foot sections, that's where I have real
3 trouble.

4 MS. YANG: Ralph, did they estimate how
5 long they were left at high temperature time-wise?
6 Was it overnight?

7 DR. MEYER: Well, yeah, it was overnight
8 that it was left like that.

9 PARTICIPANT: Didn't they stop the main
10 pump in the afternoon and then they noticed
11 something in the evening, something like that?

12 DR. MEYER: Yes. It was fairly late in
13 the evening.

14 PARTICIPANT: It was like nine o'clock,
15 and they noticed something at like 11.

16 DR. MEYER: And then about an hour later
17 they started noticing some pressure increase and
18 then some activity.

19 I don't -- I didn't prepare to give you
20 a chronology of this, but I can tell you that Ann
21 MacLachlan wrote a real nice summary of this in the
22 May 8th Nucleonics Week. So if you want a good
23 summary of the overall event, that's one of the best
24 places to look for it.

25 Now, what we did was to discuss the

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 possibility of some cooperative effort to examine
2 the fuel, and there was a meeting to discuss this in
3 Budapest just a couple of weeks ago, and the
4 participants there were from NRC. There were two of
5 us from NRC, one guy from IRSN in France, two guys
6 from GRS in Germany. So this was not Siemens. This
7 was another part of the German population, the GRS
8 Institute.

9 Of course, in Hungary you had the Atomic
10 Energy Authority, the personnel from the power plant
11 and also the research institute, KFKI.

12 The Russian team was interesting. Just
13 two days before the meeting, the Russians had been
14 awarded the recovery contract, and the contract went
15 to TVEL. They call it TVEL. It's T-V-E-L, and so
16 TVEL was there, and they had a team for this
17 recovery effort, and the team included the Bochvar
18 Institute, which is sort of -- TVEL is the
19 manufacturer. Bochvar is sort of the design
20 institute. Kurchatov, which is an independent
21 institute, and then I can't remember whether the
22 other fellow was from Dmitrovgrad or not, but
23 Dmitrovgrad, the reactor. Russian Institute of
24 Atomic Reactors was the fourth partner in this
25 consortium of Russian institutes and companies, and

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 that's where the hot cells are.

2 DR. KRESS: Ralph.

3 DR. MEYER: Yeah.

4 DR. KRESS: Do you have any idea of what
5 burn-up this fuel had been taken to?

6 DR. MEYER: I just don't recall. I'm
7 sure we can find out, but I don't recall. I don't
8 recall.

9 MS. YANG: Probably not very high.
10 They're cleaning it and then putting it back in.

11 DR. KRESS: Yeah, that's what I would
12 have thought.

13 DR. MEYER: Right. So it wasn't fresh,
14 and it wasn't ready to be discharged. In between.

15 So anyway, we discussed this possibility
16 of cooperative effort, and there was sort of
17 agreement in principle to continue considering this
18 possibility. There were no major decisions made at
19 the meeting.

20 There were, of course, two organizations
21 there that had concerns about this. One was the
22 Paks Power Plant people because they don't want
23 anything done that might slow down the recovery of
24 the plant, and then TVEL, the Russian organization,
25 didn't want anything that might increase their costs

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 or slow up their part of the recovery effort.

2 But notwithstanding, the value of doing
3 this seemed to be pretty widely recognized. There
4 was interest coming from CSNI. Mr. Thadani is the
5 current chairman of CSNI, and so it's kind of an
6 NRC-CSNI interest. Carlo Vitanza, the staff person
7 from NEA, was there, and he now has the assignment
8 of preparing a written proposal which will, I
9 believe, be first reviewed by CSNI and then
10 presented to the Hungarians for consideration.

11 Now, all of this has to happen
12 reasonably fast because the recovery contract calls
13 for completion of that in six months. So the
14 Russians are going to move in and move fairly fast
15 to get this tank defueled and moved out of the way
16 because it's blocking traffic right now.

17 DR. KRESS: Since this is a Russian
18 firm, would these -- I presume these tests have to
19 be done in a hot cell.

20 DR. MEYER: Well, now --

21 DR. KRESS: Would they be done in
22 Russia?

23 DR. MEYER: Now, that's interesting, and
24 I shouldn't speculate too much on this, but you see,
25 from my point of view and the fuels research program

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 at NRC, we have a group in Russia who are working in
2 this very area, and they are Kurchatov and RIAR, but
3 they're not exactly the same people.

4 The Kurchatov people that were part of
5 the TVEL team were not the nuclear safety institute
6 that we deal with.

7 DR. KRESS: I see.

8 DR. MEYER: But they're in the same big
9 institute. So I don't know how this is going to
10 play out. We have our Russian colleagues who we've
11 been working with on oxidation studies who are
12 knowledgeable in this area and placed in the right
13 organizations.

14 And then you have TVEL with the recovery
15 contract who will want things to run smoothly, and I
16 don't know how the pieces will fit together, but I
17 just thought it might be of interest for you to know
18 that there was this effort going on to try and
19 secure -- probably we would like to get one complete
20 fuel assembly. Maybe the top is broken off of it,
21 but this would give us some highly damaged fuel,
22 some not so damaged fuel, and some intact balloons
23 to look at.

24 DR. KRESS: And what would you look for?

25 DR. MEYER: Well --

NEAL R. GROSS

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

1 DR. KRESS: The degree of oxygenation?

2 DR. MEYER: There are several obvious
3 things to look for. The first one to look for, in
4 my opinion, is why did the side of the flow shrouds
5 fall out, just pieces, just big chunks, you know,
6 football size, cross-section areas missing. And it
7 is likely to be from severe hydriding because this
8 is a closed, bottled up system which had oxidized a
9 lot of zirconium, and so you built up a high partial
10 pressure of hydrogen, which also has gone into the
11 zirconium somewhere.

12 And so I think the first thing of
13 interest is going to be to look at hydrogen
14 absorption and effects on the materials.

15 I also think examining these balloon
16 sections will be of value, particularly if what we
17 thought were long, extended balloons are truly long,
18 extended balloons. It will be interest to look at
19 those and see what we can understand from that.

20 I guess going into this our expectations
21 are modest. There's no burning question that we
22 have that we think would be answered by this, but
23 it's certainly an intriguing event. It involves the
24 kind of phenomena that we're studying actively for
25 LOCA behavior and also for spent fuel behavior, and

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 it would just seem to be a shame not to go in and
2 have a look at an event that has preserved some very
3 interesting looking specimens.

4 DR. KRESS: As long as you can get a
5 bunch of people to cooperate and it doesn't cost you
6 too much, it might be well worth it.

7 MS. YANG: May I ask what are the
8 materials for the cladding and for the shroud?

9 DR. MEYER: It's E110.

10 MS. YANG: E110? Okay.

11 DR. MEYER: It's the standard VVER
12 cladding. Of course, there are varieties of VVER
13 cladding. I mean of E110. There are varieties of
14 E110, oxidized, annodized.

15 DR. KRESS: Does that make it less
16 attractive to you?

17 DR. MEYER: No, not really, because you
18 know, E110 is zirconium one percent niobium made by
19 a different company, and it has some very different
20 behavior characteristics, and we're still interested
21 in figuring out what is causing this.

22 I'm sure a lot of people are interested
23 besides us. So it's a very intriguing possibility.

24 DR. KRESS: I guess whenever you get
25 this proposal in late October we might get a look at

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 it?

2 DR. MEYER: I can't say how this is
3 going to go. The negotiations are somewhat delicate
4 because the whole situation is in litigation over
5 the responsibility for this, and we have to make
6 sure that we don't interfere with normal processes
7 of plant recovery and whatever financial recovery is
8 involved.

9 We have to just stay clear of that, and
10 for that reason, some of these things may be done
11 diplomatically and a little discretely. I simply
12 don't know.

13 DR. KRESS: It's not one of the things
14 that this Committee normally looks at anyway when
15 you get into these cooperative programs.

16 DR. MEYER: We're simply asking the
17 Hungarians to let us have an opportunity to look,
18 and we have to be patient and polite about it.

19 DR. KRESS: Sure. Okay.

20 DR. MEYER: I'm finished.

21 DR. KRESS: I guess we're at the dry
22 cask storage conditions. We'll hear from Mr.
23 Billone again.

24 We're also scheduled to take a break at
25 this time. Do you guys feel like this would be a

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 good time to take a 15 minute break?

2 MR. BILLONE: It's a good time to take a
3 break before you let me start talking.

4 DR. KRESS: Yeah, let's do that. Okay.
5 I'm going to declare a break for 15 minutes, and be
6 back at 3:15.

7 (Whereupon, the foregoing matter went
8 off the record at 3:01 p.m. and went
9 back on the record at 3:18 p.m.)

10 DR. KRESS: Could we please come to
11 order and resume the meeting?

12 MR. BILLONE: All right. We're going to
13 switch subjects to dry cask storage, and you'd
14 better let me get started so that you can get to
15 supper tonight.

16 There's two aspects of our program. One
17 is dry cask storage license renewal, and let's call
18 it low burn-up fuel less than 45 gigawatt days per
19 metric ton by this world. Our work has been
20 documented in a NUREG report, CR-6831, which is
21 coming out the end of this month. We are at the end
22 of this month so it should be out now.

23 That's work with Surry PWR fuel rods at
24 36 gigawatt days per metric ton. We're fortunate to
25 have those. They were dry cask storage for 15 years

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 in a helium environment.

2 We took 12 of those rods out of one of
3 the subassemblies, and we did profilometry to look
4 at any interesting possible changes in cladding
5 diameter due to creep while they were in storage.
6 We saw none. All 12 rods looked pretty much
7 identical, and they looked pretty much like they
8 would look as they would come out of a reactor going
9 into the wet pool.

10 We did fission gas analysis on four of
11 the rods. This was done at Argonne West. Fission
12 gas release is half to one percent, which is typical
13 of this kind of rod at this burn-up, and three of
14 the rods were sent to Argonne East -- that's us --
15 for destructive examinations. I'll show you some
16 results on those.

17 We did thermal creep studies from 360 to
18 400 degrees C. to see what kind of residual creep
19 life was left in these samples.

20 The purpose of this is twofold. One,
21 this work was sponsored by EPRI, NRC and DOE-RW. So
22 one purpose was if these rods had gone in at higher
23 fission gas pressure, would they have had residual
24 creep lag to make it the first 20 years.

25 DR. KRESS: Are those typical

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 temperatures in a dry cask?

2 MR. BILLONE: Typical temperatures now,
3 everything is under 400 degrees C. for the whole
4 process. That's the recommendation of ISG-11, Rev.
5 2.

6 So this would be typical of starting
7 temperatures, and we picked those temperatures
8 because we're in a laboratory framework with a
9 limited amount of time. We can't run 15-year tests.
10 So this would be typical of the upper bound
11 temperature.

12 The second purpose of doing this was for
13 DOE-RW because at the end of storage, these
14 assemblies will be reconstituted -- not
15 reconstituted -- reconsolidated and put in a
16 repository site with an elevated temperature.

17 So at the end of 15 years for Surry, it
18 would have started at something like 350 degrees,
19 355 degrees C., ended at something like 150 to 200
20 degrees C. So that temperature would go up for a
21 while in the repository and come down again.

22 We also have axial tensile tests in
23 progress, room temperature to 400 degrees C. We got
24 interested in radial or reorientation and axial
25 redistribution of hydrides and what those effects

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 might be, and we've also proposed and have samples
2 for post-storage post-creep, bending tests, and
3 there's been a request for some kind of impact test
4 to represent possible transportation loads,
5 particularly after the storage when you're going
6 from the dry cask storage to the repository.

7 The second part of our program is high
8 burn-up spent nuclear fuel behavior issues, and for
9 that we're using the Robinson rods. Several of the
10 rods were selected for this part of the study.

11 In progress is fuel actinide and fission
12 product concentration measurements and burn-up
13 analysis. This is for our code people and for burn-
14 up credits, which I'm not an expert on. So I won't
15 elaborate.

16 DR. KRESS: Is this for behavior in
17 spent fuel pools or in dry cask?

18 MR. BILLONE: No, no.

19 DR. KRESS: This is dry cask?

20 MR. BILLONE: This would be in dry cask.

21 DR. KRESS: Okay.

22 MR. BILLONE: However, the DOE-RW is
23 also interested in this kind of analysis. You have
24 to do a criticality analysis and see how tightly
25 you can pack everything.

NEAL R. GROSS

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

(202) 234-4433

www.nealgross.com

1 All right. We chose essentially the
2 same matrix of 360 to 400 degrees C. and tensile
3 test, room temperature to 400. These rods had gone
4 through not the traditional process, but they had
5 seen temperatures as high as 415 degrees C. during
6 vacuum annealing or during vacuum really, being in a
7 vacuum environment.

8 These rods came to us out of the wet
9 pool. So they haven't seen that kind of treatment.
10 So in addition to thermal creep, we're interested in
11 looking at annealing and reorientation,
12 redistribution of hydrides, particularly during the
13 vacuum drying process, and effects of these things,
14 annealing and hydride orientation, on mechanical
15 properties. And by "mechanical properties" I'm
16 including creep in that.

17 So, again, same picture. We need to do
18 something post-storage, post-creep. We're proposing
19 bend tests. Our creep samples would be ideal for
20 three point bend tests.

21 There's no universal agreement on what
22 is the best test to do or series of tests to do
23 following storage such that you can safely handle
24 these things. They're not going to shatter on you,
25 and you can transport them.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 And so, again, some kind of impact
2 tests. There's a couple that we could do. The
3 question is: what do you do with the data?

4 We can generate some data, Charpy impact
5 type data or even pendulum data. Again what do you
6 do with the data?

7 I don't think that's been completely
8 resolved, but it's in our test plan to do something.

9 Let's go back to the earlier slide I
10 showed you; only now let's just focus on those rods
11 which we're going to use in this program, and a lot
12 of the data we're generating here is also going to
13 apply to the mechanical properties data we need for
14 RIA. As you'll see, we're basically going to be
15 using two strain rates, one moderate and one fast,
16 and those data will be useful to both programs.

17 So the Surry rods we'll talk about
18 first, and then we'll talk about the Robinson rods.
19 We do have the TMI-1 rods, thanks to EPRI and Rosa,
20 that we use to benchmark the mechanical properties.
21 But if you look at the next slide, you'll see that
22 we have an interesting range of hydrogen contents
23 and fast fluences, and those are the things that you
24 correlate models to.

25 So we're actually very fortunate. If

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 you ignore the storage at Surry, which appears to be
2 benign, you've got fast fluences in these units from
3 seven to nine to 14. So it's a factor of two and a
4 potential hardening mechanism and embrittling
5 mechanism due to neutron damage.

6 And significantly, forget the oxide
7 content. That's not something we correlate to. We
8 correlate to what's inside the metal, and what's
9 inside the metal is for Surry less than 300 weight
10 parts per million, up to 300 weight parts per
11 million of hydrogen. The TMI is a little bit lower,
12 and then up to at least 800 weight parts per million
13 hydrogen in the Robinson.

14 So we expect differences in mechanical
15 properties and even creep properties and ductilities
16 between those two. So it's actually a nice matrix
17 of materials to work with.

18 Let's start with Surry, and then
19 everything that we study, the metallography, the
20 hydride orientation that I'll show you, everything
21 seemed relatively benign.

22 There's only one mildly interesting
23 thing, and the question is with this long rod and
24 the axial temperature profile over 15 years, does
25 hydrogen move from the hot inner regions or midpoint

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 region of the rod to the colder ends.

2 So there's a temperature profile and
3 storage, and so we had commissioned to do three
4 hydrogen measurements, a midplane, a half a meter
5 above and one meter above, and everything was going
6 fine and the oxide increased the way it was supposed
7 to. The hydrogen increased the way it was supposed
8 to until we got to the last reading, and it
9 decreased.

10 This location happens to be just where
11 you start the down slope in temperature. So what we
12 have in progress is going higher to one and a half
13 meters and then the plenum region, and the only
14 issue here is do you get hydrogen accumulation at
15 the colder ends that would tend to embrittle the
16 colder ends.

17 What's nice about having the Surry rods
18 is DOE-RW happened to have a lot of money this year
19 for sabotage considerations and dry cask, and so
20 they want a little bit of the midplane of this third
21 Surry rod, and they will pay a lot of money for
22 characterization. So we'll get oxide thickness, a
23 couple of hydrogen readings and isotopics at two
24 locations, actinides, and fission products.

25 And TBM means to be measured. That

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 means the money is not there and is not paid for by
2 NRC, but NRC and EPI get the data from that. And
3 they only want a little bit to make rodlets and
4 Sandia is going to shoot shaped charges through them
5 and we see what kind of aerosols come off.

6 I'm not involved in that part of the
7 program.

8 DR. KRESS: I was wondering what you
9 were going to do with that.

10 MR. ROSENTHAL: Wait, wait, wait. I
11 think if we start saying more we're going to have to
12 go into closed session.

13 DR. KRESS: Yeah, okay. We'll leave it
14 at that.

15 MR. BILLONE: Sorry.

16 DR. KRESS: That's okay.

17 MR. BILLONE: My only point is there's
18 more characterization data that will be made
19 available.

20 Okay. I want you to get a good mental
21 image of the hydride distribution and the Surry
22 cladding. This is the OD oxide you're looking at.
23 It's basically circumferential, and at this hydrogen
24 concentration, almost all of this hydrogen would
25 have been in solution at 415 degrees C. during the

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 early period of time where this was in vacuum.

2 However, the stresses were low. They
3 were no more than 50 megapascals hoop stress, and
4 under those conditions when you start cooling you
5 don't get the hydrogen reoriented in a radial
6 direction. So essentially it reprecipitated where
7 it was, maybe with a little bit of extra
8 precipitation here.

9 So at some point early in the history of
10 dry cask storage prior to the actual storage time
11 when they were doing thermal benchmark tests, most
12 of this hydrogen was in solution. It precipitated
13 out in a benign fashion.

14 And let's keep this aside because I want
15 to come back to that because a couple of our creep
16 tests we shut down under very high pressure and
17 stress and got quite a different picture than that.

18 Okay. So we ran a series of creep tests
19 on the Surry cladding, all basically in the range of
20 250 to 300 weight parts per million hydrogen.
21 Temperatures ranged from 360 to 400, and
22 characteristically our stresses are 160, 190, 220.

23 In this particular test we got as high
24 as six percent creep strain, hoop creep strain
25 without any failure, and we're saving this sample

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 for a bend test, and the idea is you take the surry
2 cladding prior to running it through creep, and then
3 you take the Surry cladding after this, and how much
4 damage was accumulated? Is damage due to creep
5 additive to sort of plastic flow or the kind of
6 damage you get from a tensile test or a bend test?

7 Also C8 got to one percent creep strain,
8 and we're saving that for a bend test. These are
9 the two that were very low strains, and it wasn't
10 much advantage based on the creep rates of keeping
11 them going.

12 We shut those down under pressure, under
13 stress and looked at the hydride distribution for
14 those particular samples to see if we got
15 reorientation.

16 DR. FORD: Presumably measuring the
17 strain in real time is not just a grab sample, is
18 it? You are measuring.

19 MR. BILLONE: The strain is measured
20 periodically by shutting down, depressurizing first,
21 and then cooling to room temperature and measuring
22 the strain. It wasn't measured on line.

23 DR. FORD: Okay.

24 MR. BILLONE: Oh, I'm sorry, and I'll
25 show you the histories. These are just the end of

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 life values.

2 All right. With Surry creep tests
3 everything behaved the way it was supposed to
4 behave. I mean, you're supposed to have stress
5 dependency. It's nonlinear. You're supposed to
6 have temperature dependency which is nonlinear.

7 So if you look at a fixed hoop stress
8 and two different temperatures, you see 20 degrees
9 C. temperature difference makes quite a bit of
10 difference in the creep rate, at least a factor of
11 five in the creep rate, and I'll summarize that at
12 the end.

13 So that's --

14 DR. KRESS: Now, is this a (pause) --

15 MR. BILLONE: These are three inch long
16 pressurized tubes.

17 DR. KRESS: These are the test data you
18 got.

19 MR. BILLONE: This is test data. So
20 we've taken Surry, which has already gone through 15
21 years of storage --

22 DR. KRESS: Yeah.

23 MR. BILLONE: -- and we're asking
24 ourselves how much residual creep does it have.

25 DR. KRESS: Yeah, okay.

1 MR. BILLONE: And we're trying to add to
2 the general overall database for irradiated hydrided
3 materials for creep rates. It's something that's
4 useful for the modelers.

5 So 20 degrees C. Particularly, these
6 400 degrees C. temperatures become interesting. As
7 I go on in my presentation, it's becoming more and
8 more interesting because that's set as of August
9 2002. That was the recommended upper limit for
10 beginning of dry cask storage and all of the other
11 processes, and that's part of the reasons why we're
12 concentrating initially on that.

13 Again, temperature dependency at a
14 higher stress level, 380 degrees C. down to 360.
15 That 20 degrees makes a huge difference in creep
16 rate.

17 I don't know if you saw these last year.
18 Some of them were available. So I'm going to go
19 through them quickly until I get to the Robinson,
20 which that's a stress effect of 30 megapascals.
21 Interesting, but let me get on.

22 Okay. Four hundred degrees C. The red
23 curve is new data, and the test, I'll explain why it
24 was terminated at this point in time. It didn't
25 fail, but at this point in time we do not see as

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 strong a stress dependency as we expected at the 400
2 degrees C. level. We'll get into that a little bit
3 later.

4 Okay. Let's try to go through the Surry
5 stuff fast because most of it is in the NUREG
6 report, except for some data.

7 We were able to determine secondary
8 creep rates or steady state creep rates, and we've
9 got a range of more than a factor of 100 in creep
10 rates by varying these temperatures. The 400
11 degrees sample at 190 megapascals after it
12 accumulated one percent strain, we jacked up the
13 stress to 250 megapascals, and that's what took us -
14 - we were creeping too slowly, and we wanted to get
15 up to higher strains. So this took us up to about
16 six percent strain and about five times ten to the
17 minus third.

18 All right. Two of the tests we shut
19 down, and again, let me show you this. This is what
20 you start with before you run the creep test. This
21 is what happens when you shut down under fairly high
22 stress, and this is what should happen because the
23 critical stress for hydride reorientation, we think,
24 is lower than this, but basically the hydrides --
25 and you don't see all of the hydrides when you etch,

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 but basically you've got reorientation in the radial
2 direction, some in that direction, and you broke up
3 the concentration of hydrogen at the boundaries.

4 And one question that we would like to
5 address is what effect does this have on the
6 mechanical properties. Do these effectively act
7 like locations for cracks to easily grow through the
8 radius of the material?

9 How detrimental is hydride reorientation
10 is one questions, and, two, under what stress and
11 cooling conditions does it occur?

12 Those two samples I just showed you were
13 in the process of remeasuring the hydrogen to make
14 sure it didn't actually move out of our sample.

15 That's Surry. Let's move on to the high
16 burn-up Robinson, and again, TBM means to be
17 measured. I've got to be careful here, but
18 basically most of our work is with two of these
19 rods, and that's the fuel and cladding
20 metallography, OD oxide thickness measurements,
21 hydrogen isotopics and burn-up analysis, again, to
22 be measured.

23 The same with BO-1. This is a gamma
24 linear rod, and the interest in giving it to us was
25 to do the isotopic and burn-up analysis of the gamma

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 linear rod. Again, one extra rod will get data at
2 the midplane from this unnamed source of funding.

3 All right. Let's look at the gamma scan
4 for one of the rods and where we've done most of our
5 destructive examination and where creep samples come
6 from. This happens to be rod A02. These are grid
7 spacer locations, and this is the expected profile.
8 These dips are not real. These come to us in
9 approximately a little less than one meter segments,
10 and so what you see here is just the end of the
11 segment, and we're piecing these curves together.
12 So ignore these particular dips.

13 At these locations, roughly the core
14 midplane and roughly .7 meters above the core
15 midplane, that's where our metallography, hydrogen
16 samples, and our burn-up and isotopic samples were
17 taken from these locations. So you had a complete
18 picture.

19 When we get back to this we'll take
20 samples from down here in the lower hydrogen region
21 for the same kind of analysis. So most of our creep
22 samples that I'll show you results from came from
23 these locations.

24 Okay. There's a lot more hydrogen in
25 the Robinson cladding, and the question is how does

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 it affect the mechanical properties, how does it
2 affect the creep behavior, but this would be roughly
3 650 weight part per million hydrogen in this
4 particular location.

5 At the midplane we got roughly 600, 580
6 at the midplane, and 750 about .7 meters above the
7 midplane. This is not the maximum. If you keep
8 going up, you would measure more hydrogen than this,
9 but our samples are taken from this regime, and
10 oxide thicknesses is from 70 at the midplane to
11 about 100 at .7. This might go up another ten to 20
12 microns as you go up the rod.

13 And the hydrides, again, are all
14 circumferentially oriented.

15 Let's save that picture because I want
16 to come back to it.

17 This is more of an RIA issue, but just
18 for those who want to know what the fuel looks like,
19 if you put this in a dry cask, basically this is the
20 fuel rim which is porous and very fine grained, and
21 this is an interaction layer of fission products
22 between the fuel and the cladding. It doesn't
23 really eat away at the cladding or deteriorate the
24 cladding, but it does exist, and it would have a
25 bearing on the response for an RIA, and again, it

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 would have some bearing on the LOCA response
2 depending -- I mean, some of this is oxide, and the
3 question is is any of this protected when hydrogen
4 gets inside and tries to get into the cladding.

5 Okay. We started some creep tests at
6 400 degrees C. Actually I'll be reporting four of
7 the creep test results, two at 400 degrees C. and
8 two at 380 in two different stress levels.

9 DR. KRESS: How do you do these creep
10 tests? Do you pressurize the inside or do you pull
11 them in tension or --

12 MR. BILLONE: No, we pressurize. We
13 have one open end connected to a -- well, it's
14 bound.

15 DR. KRESS: Yeah.

16 MR. BILLONE: So we actively control the
17 pressure.

18 DR. KRESS: So it's creep in the radial.

19 MR. BILLONE: It's basically creep in
20 the radial, almost no axial contraction. So it's
21 all hoop creep strain.

22 One advantage of our system is we can
23 change the stress and pressure at any time during
24 the test.

25 DR. KRESS: It would be easy.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 MR. BILLONE: All right. So far that's
2 very valuable information written down. I can see
3 my signature over here, and there's a cost code
4 number. So hopefully that didn't come across in
5 your slide.

6 At 400 degrees C. and at 380 degrees C.,
7 the same stress level, we got expected behavior,
8 meaning that 20 degrees C. difference in temperature
9 made a significant difference in creep. I'll
10 explain why this starts curving up on us soon.

11 So that result was expected. When we
12 compare the higher hydrogen and higher fast fluence,
13 higher neutron damage, Robinson to Surry, at 380 and
14 220 megapascals, we got the expected result, that
15 both hydrogen and additional radiation hardens the
16 material more. Everything was fine at this point.

17 And then we went to 400. Funny things
18 started happening at 400 degrees C. This is the
19 Surry sample at 190 megapascals and 400 degrees C.,
20 and the Robinson sort of starts like the Surry, and
21 then it takes off on us, almost as if it's going
22 through some annealing during the test time at 400,
23 whereas the Surry did not appear to do that.

24 These are two different samples. C-14,
25 we were trying to see how far in strain we could go,

NEAL R. GROSS

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

1 and C-15, we were trying to get good secondary
2 creep.

3 We stopped C-14 after we got an average
4 strain of 3.6 percent, and if you move 15
5 millimeters above the average point, we've got as
6 much as five percent peak strain.

7 So Robinson, like Surry, even though
8 it's higher hydrided, seems to have the same creep
9 capacity. What's not clear is why this takes off in
10 our tests and also in some of the French tests at
11 this particular temperature and stress level.

12 Just to give you some idea of the
13 temperature sensitivity which is not explained by
14 any of the models which have creep as an erroneous
15 function of temperature, if we take the one sample
16 and just look at three different locations separated
17 by 15 millimeters apart, we have a very small axial
18 temperature gradient. This would be towards the
19 bottom of the furnace, about 402 degrees C. This is
20 401 degrees C., and these are the differences in
21 local creep rates observed at different locations of
22 the sample corresponding to different temperatures,
23 and this kind of temperature sensitivity, as I say,
24 cannot be explained by any of the existing creep
25 models. It's much, much, much too high and much

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 higher than we expected. So we'll call this an
2 interesting result.

3 DR. FORD: Surely if those areas where
4 you're measuring those temperature are fairly close,
5 you're going to have constraint from the adjacent --

6 MR. BILLONE: Then there will be
7 constraint, but the constraint means that these
8 differences would be even larger. In other words,
9 this material here is partially constraining that
10 material.

11 DR. FORD: Yes. Okay.

12 MR. BILLONE: All right. I'm showing
13 you C-15 because we got very cavalier with this
14 sample and things were going extremely well here,
15 and we got to this point in time, and we happened to
16 shut it down under pressure to study hydride
17 reorientation, totally convinced that it would be
18 benign to shut it down under pressure.

19 You can't get too cavalier when you're
20 doing research.

21 MR. CARUSO: I'm just curious. You've
22 drawn all sorts of nice curves that look like maybe
23 swine between these points. Why haven't you done
24 any sort of least squares fit? Why have you drawn
25 the curve?

NEAL R. GROSS

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

1 MR. BILLONE: Why do we connect the
2 points?

3 MR. CARUSO: Well, you don't have --

4 MR. BILLONE: Only for your eye.

5 MR. CARUSO: Well, I mean, I look at
6 them and they're not straight lines between the
7 points. They're curves.

8 MR. BILLONE: They're not straight lines
9 because the material seems to be annealing or going
10 into tertiary creep. What we were looking for was
11 straight lines to determine secondary creep. We
12 never got in that regime. We went from primary
13 creep to a transition, to like a tertiary creep.

14 There's no advantage to doing least
15 squares fit of this because all I'm trying to do
16 here is show you temperature sensitivity of one
17 single sample. So you're not talking about sample
18 to --

19 MR. CARUSO: Is there an error
20 associated with the hoop strain that was measured?

21 MR. BILLONE: The error is very slight.
22 What we do is we measure diameters at 16 locations
23 around one axial location, and then we measure a
24 number of different axial locations.

25 MR. CARUSO: So there's no error bar

NEAL R. GROSS

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

1 associated with each of these points?

2 MR. BILLONE: The error bar is too small
3 to see if we're talking about precision in terms of
4 one sigma deviation from the average. So if I take
5 one location and I measure 16 different diameters to
6 get this point over here, there's very little
7 variation. It's small.

8 What's much larger than the error bars
9 is this temperature sensitivity. That may not be
10 the best answer in the world because I don't think
11 I'm addressing your question.

12 Error bars, I would rather -- if we
13 repeated this test ten times and --

14 MR. CARUSO: If.

15 MR. BILLONE: I said if we did.

16 MR. CARUSO: Yes.

17 MR. BILLONE: Then I would show you what
18 you want to see, which is the error bars. The
19 measurement error is very small, but to do what
20 would be useful is to run a number of different
21 tests and then show the spread and results as a one
22 sigma variation.

23 One single test, one single location,
24 you're not going to see it.

25 So the purpose of that is to show you

NEAL R. GROSS

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

1 temperature sensitivity. Another way of showing you
2 temperature sensitivity is at fixed times let's just
3 look at the axial profile of strain, and again, the
4 temperature, this is our benchmark temperature,
5 looking at this scale, which is very expanded, and
6 at the end of -- when we stop the C-14 sample, this
7 is the strain profile, and we have a constraint on
8 this end and we have a constraint on that end.

9 Again, the only thing different as you
10 go along the sample basically is the temperature
11 difference. So what I'm saying is at 400 degrees C.
12 for the Robinson rods there is a very, very, very
13 high temperature sensitivity, and when you have
14 guidance like we're going to limit such operations
15 to 400 degrees C., you usually don't worry about
16 401, 399 or 402.

17 DR. FORD: I'm just trying to interpret
18 this graph here.

19 MR. BILLONE: Okay.

20 DR. FORD: Does that mean you've got a
21 balloon forming?

22 MR. BILLONE: No, that is an exaggerated
23 scale. I mean, I wouldn't call that a balloon. Our
24 balloons were 60 percent strain, but you have a peak
25 in strain.

NEAL R. GROSS

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

1 DR. FORD: At a certain position..

2 MR. BILLONE: Well, this gets hotter as
3 you go down here, and the only reason it comes down
4 is you're approaching the end, which is welded and
5 constrained.

6 We did not think we needed perfect
7 temperature control to get a flat profile, and of
8 course, when you start out at low strains, you don't
9 see that, but being a spin doctor, what I want to
10 tell you is for a single test we're able to get
11 multiple data points that are very useful to study
12 temperature dependence. That's what a spin doctor
13 would tell you.

14 This was not planned.

15 Okay. Let's go with our cavalier
16 shutting down of C-15, which temporarily shut down
17 our creep program. C-15 developed a rupture during
18 the final shutdown, which involved cooling from 400
19 degrees C. under full pressure, intentional. The
20 old hydride reorientation data, the maximum hoop
21 stress was about 205 megapascals. It started at 190
22 with wall thinning due to creep. The stress would
23 have gotten up to about 205.

24 And I'll show you a picture of that
25 shutdown. Again, one of the things that's happening

NEAL R. GROSS

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

1 during shutdown under these conditions is you are
2 reorienting the hydrides, the radial and you've got
3 them under significant stress, although the stress
4 is maybe one fourth of the yield stress of
5 irradiated material. So it is not huge.

6 At the end of the run at temperature,
7 the sample was intact. It held pressure very nicely
8 for a total of 2,440 hours. Rupture occurred when
9 temperature decreased at 205 degrees C. under full
10 pressure. This is a temperature plot with the
11 scale. This is the pressure plot, and boom.

12 And the rupture was very significant
13 because even though it expanded into the test
14 chamber and the volume, it went through our whole
15 system, wiped out our HEPA filter, blew out the oil
16 in the tank at the end, and contaminated by hot cell
17 standards -- and this is a beta-gamma hot cell --
18 spread a lot of alpha and beta contamination all
19 over that particular cell.

20 So it was not a pinhole failure. We ere
21 designed for a pinhole failure because that's what
22 you're supposed to get in creep.

23 So the status of that particular sample,
24 the rupture caused substantial contamination of the
25 particular beta-gamma hot cell in spite of the

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 following.

2 We had de-fueled the sample with boiling
3 nitric acid to get as much of the stuff out from the
4 inside. We minimized the volume, the gas volume, of
5 the sample by filling it with zircaloy pellets. We
6 had an in-line pinhole in pressurization system to
7 restrict gas flow, a solenoid valve to shut off gas
8 pressure when it sets decrease, and we had a
9 downstream HEPA filter.

10 Unfortunately, with the level of
11 contamination we have to do some clean-up of the
12 cell before the lab will allow us to inspect that
13 sample, open up the furnace, and there's two
14 possibilities.

15 With welding and plugs, there's always a
16 possibility that you blew an end plug weld and got
17 that huge pressure release. If that's the case,
18 then the sample would still be interesting from a
19 hydride reorientation point of view, but not as
20 interesting as if this happened, the second one,
21 rupture due to hydride reorientation, the second
22 possibility.

23 So we're very eager to view this sample.
24 I have to spend some money and some time to clean up
25 the cell before we can view it, and I put off that,

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 but I've been told I have to do it now.

2 Okay. Let me go quickly through this.
3 Basically that cell which has got low value
4 equipment; the furnaces and stuff are low value
5 equipment. it's too contaminated to salvage. We
6 very much need to retrieve this sample to see where
7 it failed, along with our other samples in there
8 that were either being tested or about to be tested.

9 And we need to view the test chamber to
10 see whether or not it bulged or any problems
11 occurred because of the size of this pressure pulse.

12 In a different building we also have
13 beta-gamma cell that we're using. We have the
14 identical system built in that cell ready to resume
15 creep tests.

16 Again, the system is designed for
17 pinhole leaks and shutting off the pressure. That's
18 no problem to redesign for large pressure pulses,
19 but we have to see whether or not we have to
20 redesign the test chamber depending on the
21 inspection of the test chamber up here.

22 So this is setting idle until we can
23 resolve this issue. We'll never be able to convince
24 a safety committee that we won't have a large
25 pressure pulse once we had the large pressure pulse,

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 even if we promised to never ever cool under
2 pressure again.

3 Let me give you an idea of what we're
4 talking about. This is a test chamber that sits
5 inside the furnace. The sample, this is the sample
6 here, three inches long. This leads to the active
7 gas pressurization system.

8 We purge it with an inner atmosphere so
9 that you're not oxidizing the sample. So when the
10 sample blew down in here, expanded into this volume,
11 shut out the purge outlet and then did a lot of
12 contamination damage downstream. Live and learn.

13 Let me give you a little footnote of
14 what could happen, although I don't think this
15 happened. I haven't shown this yet.

16 Prior to this, we had another Robinson
17 sample where the endcap wasn't that well welded. It
18 had gone for about 400 hours, a much shorter time,
19 very small strain, had roughly similar conditions
20 only lower temperature, same pressure, by the way.
21 It was maintained during the next run, 236 hours.
22 We shut down the sample. It held pressure. We
23 depressurized first and followed that by cooling the
24 room temperature, and during inspection we saw a
25 crack in the weld region that obviously occurred

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 during the cooldown.

2 So let's look at that picture because
3 that could be what C-15 looks like, although this is
4 a very different example of something that occurred
5 very early in life, and we've separated these two
6 pieces a little bit so you could see.

7 This is our active creep sample. This
8 is just a hose clamp to keep the weld affected zone
9 from ballooning out on us. This is the end plug and
10 the weld, and this happened at the bottom, the
11 hottest part of the furnace. So it's not hydrogen
12 migrating to the cold region causing this.

13 So that's a possibility for what C-15
14 looks like.

15 All right. Let's move on to the subject
16 of annealing. We've done some I would call them
17 preliminary annealing tests where we've taken the
18 Robinson samples at about 600 weight parts per
19 million hydrogen. This is a no stress type
20 annealing. We're looking at annealing out of
21 radiation damage, and we did tests from 420 to 500
22 degrees C.

23 The reason we didn't do 400 degrees C.
24 is because we were running creep tests at 400. We
25 figured they'd give us the information.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 And these are short time tests designed
2 for the vacuum drying process and the length of time
3 of vacuum drying, and these are temperatures that
4 were relevant at the time before the ISG-11, Rev. 2,
5 fixed that temperature at 400 degrees C.

6 We did post-annealing micro hardness and
7 hydride morphology determinations, and let's see
8 what they look like.

9 I'm going to skip a few slides.

10 Okay. This is a matrix of the hardness,
11 and again, for non-irradiated starting material, the
12 hardness in these units, the micro hardness is about
13 200 for the irradiated material that hasn't been
14 annealed. It's about 250. So that's sort of the
15 range of hardening that you get with irradiation.

16 And we're looking at the decrease in
17 this number versus time and temperature, and you can
18 look at 500 degrees C. for about 48 hours. You're
19 essentially to your unirradiated conditions, and
20 obviously 420 degrees C. you're essentially there.
21 You're essentially back to midway.

22 So we've converted this to percent in
23 the traditional way, percent recovery or percent of
24 annealing, and that top formula is the standard way
25 of doing it. And as I say, 500 degrees C., you

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 recovered about 94 percent of your irradiation
2 damage.

3 So given time, significant recovery will
4 occur at temperatures greater than about 420 degrees
5 C., and this was all done not under stress.

6 If you look at the hydrogen morphology,
7 and again, why don't you keep that picture in mind
8 as it came out of the wet pool, out of the reactor
9 into the wet pool, and what we're going to find is
10 under no stress and time at temperature, essentially
11 you will make the hydrogen distribution a lot more
12 homogeneous, which is no big mystery.

13 So this is the 500 degree C., 48 hours,
14 and hydrogen is much more homogeneous. This is what
15 you started with. So this is one possible effect of
16 vacuum drying if under the old vacuum drying
17 conditions where you were going to more elevated
18 temperatures than the current practices are supposed
19 to be.

20 So you do have a lot of rods in dry cask
21 storage that have gone through treatments like this.

22 Okay. That picture would be essentially
23 what you would get if your stress is below the
24 threshold it takes to change the orientation of the
25 hydrides. We don't know this answer. We have data

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 on unirradiated material. We have a couple of argon
2 data points that need to be put on this plot, but
3 this is the best that existed prior to the start of
4 our data.

5 This would be the stress that you're
6 cooling under, and this would be the starting
7 temperature that you're cooling from. And if you go
8 to 400 degrees C., you see the critical stress is
9 about 100 megapascals, and we shut down that C-15
10 sample at 190 megapascals. So it's no mystery that
11 we would have gotten hydride reorientation, although
12 we haven't looked at it yet.

13 And another sample was at 360. We shut
14 it down at 220 and saw significant hydride
15 reorientation. That's no mystery.

16 So we need to kind of improve on this
17 curve. Most of it is based on unirradiated data or
18 very low burn-up data. We try to find out not only
19 a boundary for when you start reorienting hydrides,
20 but what percent of the hydrides have been
21 reoriented.

22 And then finally mechanically, how much
23 have you weakened the cladding by doing that?

24 Okay. Here's what we are going to do.
25 We've kind of redirected our program a little bit

NEAL R. GROSS

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

1 based on the needs as expressed by NMSS and SBO and
2 RES.

3 It is not a good idea to do these
4 studies in our beta-gamma cell with our creep
5 apparatus because of the contamination issue. It's
6 better to do it in the alpha-gamma hot cell where
7 the contamination would be trivial. It wouldn't be
8 an issue if these ruptured at all.

9 And so what we'd like to do -- also,
10 what we don't want to do is extreme tests because
11 you don't have that high of a pressure constant
12 during cooling. Just due to the ideal gas law
13 you're going to have a decrease in pressure as you
14 cool an actual rod.

15 So we're going to seal pressurized
16 capsules at 400 degrees C. initially in a range of
17 stresses just below what they think is critical for
18 reorientation and just above. I will use a
19 controlled cooling rate, and it will be a
20 corresponding pressure decrease. We're developing
21 under our other funding technology for laser welding
22 pressurized capsules in the hot cell, and the idea
23 is to conduct the test in the alpha-gamma hot cell.
24 It circumvents dose related issues, worker dose
25 issues, and moving samples, and it mitigates all of

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 the contamination issues. There are no
2 contamination issues in the alpha-gamma hot cell.

3 Reorientation during dry cast storage.
4 We have the option of letting these samples cook at
5 pressure sealed, 40 degrees C. to get creep, and
6 then control the cooling and decrease the pressure
7 correspondingly with the cooling.

8 This is something we're working on, and
9 the only thing holding us up is that this is new
10 technology for us, and we're developing that this
11 fall.

12 But that's how we proposed to study the
13 idea of hydride reorientation, and you could follow
14 that with metallography of the hydrogen, and you
15 could also follow that with micro hardness tests.

16 Let me say a couple of words on
17 mechanical properties and then close. We have three
18 kinds of specimens that are relevant to RIA testing.
19 The most relevant for dry cask storage is the
20 uniaxial test looking at axial hoop properties, and
21 this is an axial sample with the machine gauge
22 section about 25 millimeters long, and this happens
23 to be after it fails. This is before it has been
24 stretched.

25 We also have rings with machine gauge

NEAL R. GROSS

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

1 sections to get hoop properties, and as Arthur can
2 elaborate tremendously, we have what I call the PSU,
3 plain string ring stress specimens. These specimens
4 are designed to give you a biaxial loading state in
5 this region here and may be the most applicable RIA
6 type analysis for limits in strain.

7 So for our combined RIA-dry cask
8 storage, all of these samples are relevant. At the
9 moment the dry cask storage people are only
10 interested in the axial tensile tests and not in the
11 hoop properties. I'm not saying they should be or
12 shouldn't be, but that's what exists at the moment.

13 I should have Arthur explain this slide
14 because this is the result of Penn State work, but
15 basically this is the Robinson Zirc-4 hydride
16 distribution. Please do not get confused. This is
17 the oxide layer. It's not a dense hydride rim, and
18 this is a pre-hydrided sample unirradiated, and this
19 is just to show you some of the similarities between
20 what you can do in the laboratory without
21 irradiation and what occurs naturally with
22 irradiation.

23 And the study was to determine ductile
24 versus brittle behavior based on certain criteria.
25 This is one percent strain as a function of the

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 thickness of this dense hydride rim.

2 Basically if you are to the left of this
3 curve, you're brittle, and to the right of this
4 curve you're ductile.

5 So the hydrides are not 100 percent
6 ductile in all temperatures. As you get up above
7 300 degrees C., even the zirconium hydrides have
8 some ductile behavior. So this tells you that
9 somewhere around 100 microns dense rim of hydrides
10 will embrittle material unless you go up to higher
11 temperatures, and then the material behaves more
12 ductile.

13 And it's usually a mixed mode failure if
14 you look at the details of that. So it's good to
15 have those results because those results are for
16 unirradiated hydrided samples. Our results will be
17 for a combination of irradiation and hydrogen.

18 Okay. Let's skip this slide.

19 Basically we've cut a number of samples,
20 both Surry and Robinson, and more in the process of
21 being cut. I don't know what this strange symbol
22 is.

23 These are our axial tensile specimens
24 again, and we'll skip this. This is our machine for
25 operating them. That's not the slide I wanted.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 What I wanted is we thought we were on a
2 roll back a year ago, a year plus. July 2000 we ran
3 our first ring test with TMI cladding, and we got
4 the kind of hardening we would expect and the losses
5 of strain hardening capability we would expect.
6 This is an engineering stress versus strain diagram.

7 Unfortunately, there was enough alpha
8 contamination on the ID of this tiny ring sample to
9 cause serious problems with the Instron
10 contamination.

11 That led to the building of an elaborate
12 glove box, which is supposed to be more like a
13 Chevy, and it turned out to be Cadillac. So this
14 has been completed.

15 This is the glove box encasing the
16 Instron. This is a smaller glove box with an
17 automatic indentation system so that we can index
18 samples and measure strain directly.

19 And we passed all of the hoops and
20 hurdles of that. We're in the process of validating
21 this whole system, and we're trying to move as fast
22 as possible to the irradiated Zirc-4, which would be
23 servient (phonetic) Robinson this month. This month
24 starts tomorrow, October.

25 So we kind of lost a year with various

NEAL R. GROSS

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

1 committees and change in climate and concern about
2 ALARA, and talking to other hot cells, when I
3 complain and moan, they complain more. So I guess
4 it's a generic problem.

5 Let's summarize. Thermal creep tests,
6 we completed five Surry tests, initiated an
7 additional one, but we didn't get far enough, and we
8 have one more to go.

9 We completed two Robinson tests, one
10 intact and one not intact. We initiated two at 380
11 degrees C. and there are six more planned tests.

12 Testing will resume this fall after we
13 can inspect the C-15 sample test chamber. Axial
14 tensile tests, we're doing baseline properties of
15 unirradiated Zirc-4 right now. This would be a
16 Robinson design, room temperature to 400 degrees C.,
17 two different strain rates, .1 percent per second
18 and 100 percent per second, and we'll do a couple of
19 Surry tests, and we're hoping to initiate both of
20 these in the month of October.

21 The only thing holding us back is some
22 problems with the plant facilities in terms of the
23 fans that draw through the glove boxes.

24 All right. Let me continue with what's
25 planned and where we run into sort of a question.

NEAL R. GROSS

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

1 We're ready to do pre- and post-creep three point
2 bend tests at room temperature. We have two Surry
3 samples available, one Robinson sample available,
4 and here's the question:

5 What do we do about impact tests?

6 Impact tests are really high strain rate, three
7 point bend tests. You whack something in the
8 middle. It's supported at two ends. I don't have
9 something long enough to demonstrate, but you have a
10 sample supported at two ends. You either come down
11 with a guillotine in the middle. That makes it a
12 three point bend test at very high strain rate.

13 Usually you groove the opposite side or
14 you swing a pendulum and you whack it and you look
15 at the difference in absorbed energy between the
16 initial energy of the pendulum and the final energy.

17 So our proposal had been for normal
18 Instron three point bend tests. There seems to be a
19 concern that that's not enough and that we should be
20 doing some impact tests.

21 There is a question. Well, we can do
22 impact tests. There's a question of how the data
23 are to be used because this is not a traditional
24 sample of impact tests, such as a Charpy sample
25 where you purposely put a known flaw in and study

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 the crack growth.

2 So are such tests meaningful for
3 unflawed pre- and post-creep tubes? And how will
4 the data be used?

5 We can do the tests. We would like to
6 sort of pursue this further discussion as to how one
7 would use the data because that could dictate what
8 kind of tests we choose to do.

9 So I would call this an area that
10 requires further discussion between the people who
11 need the data and the people who generate the data.

12 And let me end on that note.

13 CHAIRMAN POWERS: Any questions for the
14 speaker?

15 (No response.)

16 CHAIRMAN POWERS: I don't see a lot of
17 questions appearing. Thank you.

18 MR. BILLONE: You're welcome.

19 CHAIRMAN POWERS: We're now scheduled to
20 hear from Mr. Lukic.

21 MR. LUKIC: Lukic.

22 CHAIRMAN POWERS: Lukic.

23 (Pause in proceedings.)

24 MR. LUKIC: Good afternoon. While we're
25 waiting, it's a pleasure to come over here.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 THE REPORTER: Sir, a microphone.

2 CHAIRMAN POWERS: You can use either a
3 clip-on or sit, one or the other.

4 MR. LUKIC: Before starting, it's a
5 pleasure to be here. This is a civilized type of
6 climate, not like Arizona where it's 105 degrees as
7 we left. They tell us it's dry heat, but after 13
8 years we still don't believe it.

9 CHAIRMAN POWERS: Well, in Phoenix,
10 there's no such thing as dry heat, and I thought
11 Arizona was now referred to as Eastern California.

12 (Laughter.)

13 PARTICIPANT: That's probably pretty
14 accurate.

15 CHAIRMAN POWERS: You're just the
16 Californians that don't get to vote. That's it.

17 (Laughter.)

18 PARTICIPANT: Without ocean front
19 property.

20 CHAIRMAN POWERS: Wait till the
21 earthquake.

22 PARTICIPANT: Then we'll all have beach
23 property, yes.

24 CHAIRMAN POWERS: We're looking for
25 technical support here.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 MR. LUKIC: But this is work that has
2 been developed all at Palo Verde. It has to do with
3 our own particular design. I've been asked a
4 question just about an hour ago. We are not going
5 to talk here about boilers. We are not going to
6 talk here about pressure at Westinghouse,
7 pressurized reactors. We are just strictly talking
8 about our particular design today.

9 Jeff Schmidt has been instrumental in
10 coming up with the lattice redesign that has evolved
11 from having a correlation, a model that can predict
12 crud deposition, and hence, his work was optimizing
13 the lattice design to make possible to deal with
14 crud, in fact, to minimize crud.

15 Oh, thank you very much. I appreciate
16 that. Do you want to handle this? How many
17 engineers does it take to run a presentation, I
18 guess, huh? Sounds like a California joke.

19 Okay. Where did you put next slide?
20 And then the next slide?

21 Okay. About six years ago APS has
22 transitioned to a more efficient design philosophy.
23 This transition was driven, in particular, for a
24 desire for a larger capacity factor, as well as
25 cross-reduction pressures that most energy

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 manufacturers have to face.

2 The transition, the shift was from a
3 traditional checkerboard core design to one of a
4 couple of ring type of designs that make it more
5 efficient, in particular, the ring of fire and the
6 Saturn core designs.

7 Next slide.

8 The effects of this transition were
9 pretty well established once we had an inspection.
10 It was quickly seen that there is a crud build-up,
11 something that had not been seen before in the
12 checkerboard core designs.

13 You're probably aware, but crud has some
14 pretty negative characteristics. For one, it
15 inhibits heat transfer. As a result of inhibiting
16 heat transfer, there is a raise in clad temperature,
17 and also there is an oxide layer growth rate
18 increase.

19 Furthermore, it is believed that crud
20 concentrates lithium and enhances it. It is
21 postulated to increase corrosion.

22 Lastly, crud may lead to boron
23 deposition within its own matrix, and that is a
24 precursor of AOA. All of these things are pretty
25 negative.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 CHAIRMAN POWERS: Let me ask a question.

2 MR. LUKIC: Yes.

3 CHAIRMAN POWERS: You indicated that the
4 crud increases the local clad temperature just
5 because it inhibits the heat transfer, and that in
6 itself will be enough to increase the corrosion, but
7 you said there's an additional effect due to
8 lithium?

9 MR. LUKIC: yes.

10 CHAIRMAN POWERS: Do we know why that
11 is?

12 MR. LUKIC: This has been postulated.
13 It has been postulated that there is some
14 concentration of the lithium and that may cause
15 itself some clad corrosion, some damage to the
16 actual cladding.

17 CHAIRMAN POWERS: I'm wrestling with
18 trying to understand how the cation affects the
19 corrosion.

20 MR. SCHMIDT: This is actually
21 postulated to be a LOCA pH increase due to lithium,
22 maybe a lithium borate of some type that is
23 postulated to occur at the crud-clad interface, and
24 that pH effect could enhance corrosion.

25 MR. CHENC: Maybe I should add a little

NEAL R. GROSS

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

1 bit on that issue. When you increase the --

2 CHAIRMAN POWERS: Would you like to use
3 the magic microphone? Those are the ground rules
4 around here.

5 MR. CHENC: Thank you.

6 CHAIRMAN POWERS: We'll listen to
7 anything, but it has to be by microphone.

8 MR. CHENC: My name is Bo Chenc from
9 EPRI.

10 I think there's a lot of testing of
11 zircaloy in this condition when lithium is somewhere
12 like seven ppm by itself without boric acid. You
13 see an increase in the rate of corrosion of
14 zircaloy.

15 When you have boric acid, then it will
16 be neutralized. Even with 100 ppm or 200 ppm of
17 lithium in water, as soon as you add enough boric
18 acid, there is no effect on the corrosion rate of
19 zirconium model.

20 So it depends. You know, you have to
21 have a solid separation of lithium to cause the
22 corrosion enhancement, but as long as in the PWR
23 core, because you already have substantial boric
24 acid, you know, 800,000 ppm, the effects of lithium
25 tend to be very small.

NEAL R. GROSS

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

1 CHAIRMAN POWERS: Okay. Thank you.

2 MR. LUKIC: In 1999, there was a Unit 2
3 outage inspection and fuel inspection, and that fuel
4 inspection indicated the presence of tenacious crud
5 deposits. Peripheral pins of high duty assemblies
6 appear to be most affected.

7 Now, responding to concerns raised by
8 the fuel inspection, there was plans to put together
9 a detailed thermal hydraulic of the selected high
10 duty assemblies. The objective was to try to
11 establish a correlation between localized thermal
12 hydraulic variables to measure crud thickness.

13 And such a correlation it was felt if it
14 could be developed would be a useful adjunct to
15 lattice redesign that will allow us to preclude the
16 type of thermal hydraulic conditions that leads to
17 enhanced crud deposition.

18 During the Unit 2 visual inspection, it
19 was revealed that crud deposits occurred, as I said
20 now, mostly on peripheral rods, such as the assembly
21 P2K410. And so following the inspection, the P2K410
22 was taken apart and selected rods were subjected to
23 eddy current testing to basically gain a trace of
24 the crud and oxide thickness.

25 The measurements that were performed

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 with eddy current testing confirmed that the crud
2 deposits were mostly at Spans 7 to 9. That's pretty
3 much towards the top of the core, and they occurred
4 predominantly in the peripheral rods. That's the
5 first and the second row, and to a much lesser
6 degree, significantly lesser degree, on the
7 interior.

8 This figure basically shows the five
9 rods of the P2K410 starting from the bottom of the
10 reactor to the top of the reactor. A5, rod A5
11 happens to be a peripheral rod in the first row.
12 We'll shortly see where, and the Spans 7 and 8 and 9
13 show the combination of the composite of oxide and
14 crud.

15 A 353 subchannel, four quarter assembly
16 pH model was developed. Axial and radial power
17 distributions for this model were developed using
18 the SIMULATE-3 code, and that data was entered into
19 the VIPER2 code, along with the other extensive
20 required data.

21 In parallel to developing a model, we
22 did analysis of the eddy current test data analysis,
23 test data that was collected, and in order to
24 quantify crud thickness of the selected rods at
25 axial locations that were identical to the thermal

NEAL R. GROSS

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

1 hydraulic model.

2 That basically provided us with all of
3 the information that we need to quantify the thermal
4 hydraulic model.

5 This is a transverse cross-section of
6 that four quarter assemblies that show the northwest
7 corner of P2K410 in the lower right position. Also,
8 I don't know whether you will be able to see it, but
9 this is the position for Rod A5, which is the
10 peripheral rod. B4 would be on the second row. D3,
11 the one right next to the instrument guide tube,
12 that did not show any deposits at all, and there is
13 an E7 and H5.

14 That gave us a very good cross-section
15 about locations and differences in thermal hydraulic
16 characteristics to be able to quantify an
17 appropriate model.

18 One interesting thing out of this. I
19 did mention to you that fuel pin D3 did not show any
20 evidence of tenacious crud build-up. In fact,
21 during the inspection, the visual inspection, the
22 people who were inspecting, it just showed a very
23 shiny rod as opposed to where tenacious crud was
24 present, which is dark brown and fairly obvious.

25 So we used this fact that D3 did not

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 appear to contain any crud deposition. So to first
2 approximation we assumed that it was affected by
3 oxide only.

4 That allowed us to calculate the
5 inferred crud thickness for the other pins, and
6 these were obtained by subtracting the D3 oxide
7 thickness from the other rods.

8 Next slide.

9 This information here is the basis for
10 the regression model that we use. Once we have
11 stripped the oxide information from this data, what
12 remains over here is just a trace of the crud. It's
13 an inferred crud thickness because of all of the
14 assumptions that we made with regard to D3.

15 Again, A5 in blue and B4 in violet are
16 the peripheral rods, and E7 and H5 are interior
17 rods.

18 Go back one more time. Right there.
19 Okay.

20 Again, this is Span 7, 8, and 9, and
21 this is where the deposits were observed
22 predominantly.

23 Next slide, please.

24 This is a formula. This is the
25 regression model that we used. We went through many

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 iterations and lengthy evolution. In fact, we
2 decided that this is the appropriate equation.

3 Data here represents the crud thickness
4 and the subsequent J at various different burn-up
5 intervals. Other important variables here is W sub
6 I, which is the weighting coefficient for a given
7 burn-up interval, I, which is a burn-up interval
8 steaming rate, and chi survived the burn-up interval
9 correction factor.

10 These variables contain, in fact, the
11 parameters for which we do regression analysis.

12 CHAIRMAN POWERS: What is the
13 coefficient that you're optimizing herd?

14 MR. LUKIC: Okay. We are not showing
15 this because it's proprietary in nature, but the
16 burn-up interval weighting coefficient has one
17 parameter that is being fitted. Psi I has three
18 parameters. The burn-up interval correction factor,
19 chi of I, contains one parameter, and the last
20 parameter will be C bar, which is cycle averaged
21 crud concentration.

22 We'll be happy to expand on that in a
23 closed meeting, but we felt that it would be most
24 appropriate if we did not show the details.

25 Next slide, please.

NEAL R. GROSS

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

1 CHAIRMAN POWERS: And you also have a
2 summation over J or something.

3 MR. LUKIC: Yes. W sub I is the
4 summation of the weighting coefficient across all of
5 the burn-up intervals, is equal to one. That is on
6 the next slide.

7 Keep going one more.

8 Again, it has five parameters. The
9 summation of the weighting factors adds up to one,
10 and that's kind of a forced fit when you do the
11 regression analysis.

12 Next, next.

13 It's very interesting to point out that
14 traditionally steaming rate is calculated by
15 subtracting the convective heat flux from the total
16 heat flux. We have gone through that approach
17 initially, but we found that we had some inaccuracy
18 in the prediction, and so we went and did a more
19 untraditional approach and actually did fit the
20 steaming rate parameters as required, let it flow
21 and let the nonlinear regression take care of that.

22 CHAIRMAN POWERS: So your steaming rate
23 is a determined quantity?

24 MR. LUKIC: I'm sorry?

25 CHAIRMAN POWERS: Your steaming rate is

NEAL R. GROSS

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

1 --

2 MR. LUKIC: Yes. The variables that
3 entered into it --

4 CHAIRMAN POWERS: How do you assure that
5 in a fitting process that you get anything?

6 MR. LUKIC: Yes.

7 CHAIRMAN POWERS: You must have to
8 constrain it some way.

9 MR. LUKIC: I'm sorry?

10 CHAIRMAN POWERS: In just a fitting
11 process you're going to have to constrain that
12 variable to keep it in a rational regime.

13 MR. LUKIC: They are in a rational
14 regime, and I can assure you of that, and we'll be
15 happy to go over that after the meeting if you're
16 interested in it.

17 DR. FORD: I was about to ask the
18 question a slightly different way.

19 MR. LUKIC: Sure.

20 DR. FORD: Knowing crud deposition, you
21 can explain it in terms of potentials of zero
22 charge, et cetera. This algorithm you've got here
23 doesn't take into account what is happening
24 physically on the surface, or is it just purely
25 fitting to some data?

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 MR. LUKIC: Actually, yes, I think it
2 does. I think it allows us -- I mean there are
3 certain principles. In this case it's the steaming
4 rate. As you steam, you're depositing the crud,
5 which is in solution, and you know, that adheres to
6 the cladding with a particular efficiency, given the
7 rate of process.

8 So, yes, we are taking care.

9 DR. FORD: Okay.

10 MR. LUKIC: And we found that
11 empirically determined steaming rate provides better
12 results, and hence, that's what we used. And we'll
13 be showing some comparisons between this model where
14 we allow certain variables within the steaming rate
15 to float, and one that we take a hardball approach
16 and define the steaming rate as traditionally is
17 usually used.

18 Next slide.

19 This figure is a comparison. The blue
20 is the inferred value of the crud, and the whatever
21 color this is, the red, is the calculated one.
22 These are span averaged crud thicknesses. This is
23 for Rod A5, and Span 9 has the largest amount of
24 crud deposits. Span 8, we simply go down all the
25 way to Span 6. It becomes a minimum.

NEAL R. GROSS

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

1 This is another peripheral rod on the
2 second row, Rod B4, that experienced somewhat less
3 crud deposition than the entirely peripheral rod,
4 but nevertheless, does experience.

5 Rod E7 and Rod H5 are interior rods, and
6 they experience minimal crud deposition.

7 DR. FORD: So could you tell me what the
8 difference between inferred and calculated?
9 Inferred is observed?

10 MR. LUKIC: That's how we use the word
11 "inferred." We made an assumption regarding D3, Rod
12 E3, that it was only affected by the oxide. So when
13 we subtracted the oxide trace from D3, we were left
14 with a level of crud.

15 Now, that's why we call it inferred,
16 because of the subtraction of D3. I'm saying
17 "measured" because that would be a direct
18 measurement. So we tried to keep that straight so
19 that it's understood.

20 MR. OZER: You also have something that
21 all of the rods oxidize at the same rate.

22 MR. LUKIC: Yes, yes. The temperature
23 is fairly close in that particular high duty
24 assembly area, and it's a first approximation. Now,
25 you can go and further refine this with additional

NEAL R. GROSS

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

1 iterative type of analysis, and we have done that,
2 but --

3 MR. OZER: So if the temperatures are
4 the same, why did D3 have no crud?

5 MR. LUKIC: I'm sorry?

6 MR. OZER: If the temperatures among all
7 the rods are the same --

8 MR. LUKIC: Ah, okay.

9 MR. OZER: -- why did D3 have no crud?

10 MR. LUKIC: The bottom of this is,
11 again, the steam rate. If you had rods that did not
12 experience steam rate at the time when the crud
13 concentration is the largest, which is at the
14 beginning of the fuel cycle, those would not see
15 very much deposits, and I will be showing shortly
16 the assembly P2K410, and you will be able to see the
17 cross-section of all the fuel pins and crud
18 deposition. I think you'll become clearer.

19 CHAIRMAN POWERS: When you do your
20 fitting process, how do you monitor auto correlation
21 in your residuals? They sure look auto correlated
22 to me.

23 MR. LUKIC: I'm sorry?

24 CHAIRMAN POWERS: Do you look for auto
25 correlation errors in the residuals when you do a

NEAL R. GROSS

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

1 fitting process on this regression formula?

2 MR. LUKIC: You do a fitting process
3 basically, yes. This is done --

4 CHAIRMAN POWERS: Do you look for auto
5 correlation?

6 MR. LUKIC: I'm sorry?

7 CHAIRMAN POWERS: Well, it looks to
8 me --

9 MR. LUKIC: Auto correlation is
10 typically for signals. When you do nonlinear
11 regression analysis, you are basically searching for
12 the absolute minimum in that multiple dimension
13 curve.

14 CHAIRMAN POWERS: Well, the problem is
15 that you get a parameterization that makes your
16 residuals auto correlated, and that's usually the
17 mark of your physical phenomena just aren't being
18 reflected in your formula.

19 And when I look at what you put up
20 there, it looked like they were auto correlated. So
21 I wondered, do you monitor something like a Durban-
22 Watson statistic or something?

23 MR. LUKIC: Yes. Well, you monitor.
24 Once you develop the model, once you quantified
25 through regression analysis the model, then you

NEAL R. GROSS

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

1 compare it with data that he hasn't seen.

2 CHAIRMAN POWERS: But do you have a
3 Durban-Watson statistic?

4 MR. LUKIC: Oh, absolutely.

5 CHAIRMAN POWERS: And what does that
6 number run around?

7 MR. LUKIC: I don't remember right
8 offhand, but I mean, that's certainly something
9 that's available. That plus rho squared, which will
10 just give you --

11 CHAIRMAN POWERS: That's just a global
12 measure. It hardly tells you anything.

13 MR. LUKIC: Exactly, exactly.

14 This slide, in response to your
15 question, this slide shows the northwest corner of
16 P2K410, and it shows that crud, span average crud
17 deposition. This will be the peripheral rods
18 together with these. This will be rod A5, and this
19 will be rod B4. Rod D3, if I can point out, this
20 will be rod D3, and rod, let's see, E7 would be
21 here, and what's the next one? H5 would be here.

22 The important thing to see from all of
23 this is that these calculated values of the crud
24 match very well what was observed during the
25 inspection. The interesting part is that there is

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 hardly any deposition at all around instrument guide
2 tubes, and this was the first indication about the
3 mechanics of how the model worked.

4 Okay. Next slide.

5 This is an interesting slide. On the
6 left, we see the APS crud correlation. The error
7 bands are 90 percent confidence level, five percent
8 on the bottom, 95 on the top. It shows a reasonably
9 good fit on the average between the measured crud
10 thickness and the calculated crud thickness with the
11 model.

12 We have performed as a comparison; we
13 have performed -- we calculated the values of the
14 correlation that is strictly based on the steaming
15 rate, and then displayed effectively the same data
16 that we have here.

17 It can very easily be noted that for
18 measured thickness, low measured thickness, the
19 correlation that's based on steaming rate alone
20 tends to show higher values than it should.

21 Likewise for larger measured
22 thicknesses, it really under evaluates the magnitude
23 of the thickness. It should be here, and yet it is
24 showing here. In fact, it seems like it is stuck at
25 the level of ten. So it doesn't show any value

NEAL R. GROSS

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

1 higher than ten, which is not a problem over here on
2 the other one.

3 I hope that maybe begins to shed some
4 light with the motivation for modifying it.

5 Beyond the one quarter assembly, we
6 developed a lump subchannel one-eighth core T-H
7 model, and the objective for this was to be able to
8 quantify crud deposition on the assemblies. If you
9 used the four one-quarter model, you are just
10 limited to finding out what happens in four adjacent
11 assemblies.

12 But if you have a one-eighth core model,
13 then you can pretty much identify what is your lead
14 assembly, the assembly that produces the most crud,
15 and then if you're interested, you can go in more
16 detail with the four one-quarter assembly T-H model
17 and develop information on a rod basis.

18 The first model, one-eighth core model,
19 that we developed was consistent with a resolution
20 of the traditional lattice. Traditional lattice
21 recall is what we used before we redesigned the
22 lattice, and that effectively had the interior --
23 was pretty much dead as far as crud deposition.

24 Once we started moving that crud,
25 spreading it evenly across the lattice, it become

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 more important what happened on the inside, and
2 hence the second model of the eighth core model
3 provides the enhanced resolution of the assembly
4 interior. That has been very, very useful.

5 However, the price, this is a
6 comparison. This is the original one-eighth core T-
7 H model with very gross resolution in the center,
8 and here is a very detailed model.

9 Now, everything comes at a price, and
10 the quantification of the T-H model like that takes
11 about ten times as much CPU time as the other one,
12 but well worth the time.

13 Next slide.

14 A computer program was written to read
15 VIPER output data. The program calculates crud
16 assembly deposited on -- crud deposition on all the
17 assemblies, as well as the core. It helps us
18 identify assemblies with the highest crud deposits.
19 These are the lead assemblies, and then, again, as I
20 mentioned earlier, if we need more detail, we go to
21 the four one-quarter assemblies to obtain that kind
22 of detail.

23 Now, as far as crud model application
24 results, the crud model has been fully integrated
25 into the core design process. In fact, it has been

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 used so far in six reloads, and there has been no
2 evidence of AOA or crud induced failures, which we
3 feel is not a direct measure because we have not
4 measured the crud on any of these. It's a very
5 costly proposition, but an indirect indication has
6 been that we do not have crud induced failures or
7 AOA.

8 The model application has been a real
9 success. It helped prevent crud deposition. It
10 eliminated potential for crud induced corrosion in
11 AOA, and as we feel, as we like to think about it,
12 it prevents the cause and avoids having to treat the
13 symptoms.

14 Jeff will continue from here on the
15 lattice redesign that basically is an evolution of
16 what we were doing before. By modifying the lattice
17 design, we can really take advantage of the ability
18 to measure the crud and optimize the lattice such as
19 to spread the crud and otherwise minimize the crud
20 level in the entire core.

21 So Jeff Schmidt.

22 MR. SCHMIDT: Good afternoon. I'm Jeff
23 Schmidt, like Yovan said, section leader of Nuclear
24 Analysis Group.

25 And I want to talk today about basically

NEAL R. GROSS

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

1 the application of Yovan's model to a lattice
2 redesign to try to basically reduce crud deposition.

3 As Yovan mentioned, six years ago Palo
4 Verde made a transition in in-core fuel management.
5 That transition was driven by a desire to increase
6 the plant capacity factors while maintaining or
7 managing fuel costs. The basic transition was a
8 switch from a checkerboard loading pattern to a ring
9 or a pre-type loading that Yovan mentioned.

10 Here are some examples of that. On the
11 left you'll see a traditional checkerboard pattern.
12 The blue assemblies are the feed locations.

13 Let me get this together here. I didn't
14 get your laser pointer.

15 MR. LUKIC: Oh, my laser pointer didn't
16 work.

17 MR. SCHMIDT: Given defective material.
18 There we go. All right. Go back to the pictures,
19 please.

20 MR. LUKIC: Okay.

21 MR. SCHMIDT: Okay. We see here the
22 traditional checkerboard loading pattern. Basically
23 the dark blue are the feed assemblies, and they're
24 surrounded basically on four of adjacent faces by
25 burned assemblies.

NEAL R. GROSS

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

1 We transitioned to a ring type design
2 where, again, the blue assemblies, the darker blue
3 assemblies are the feed assemblies. You can see
4 basically two pronounced rings, an inner and an
5 outer ring surrounding the interior checkerboard,
6 and that placement of fuel led to increased crud on
7 peripheral assemblies or filled pins on the
8 assemblies.

9 So following the fuel inspections, when
10 we transitioned to a ring pattern, as Yovan
11 mentioned, basically it was a deposition on
12 peripheral pins with the high duty assemblies.

13 The contributing causes were basically
14 the highest pin powers and the lowest flow locations
15 in the assembly, and degrading thermal hydraulic
16 conditions due to conservatively plugging steam
17 generator tubes. What's happening basically is we
18 are plugging tubes, and flow was reducing, and over
19 time that contributed to the enhanced crud
20 deposition.

21 Effective fuel management. Basically
22 the current Palo Verde designs are limited by crud
23 deposition and not traditional peaking factors, such
24 as DNBR, linear heat rate.

25 Crud deposition has led to AOA and fuel

NEAL R. GROSS

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

1 failures at some locations or some plants, as you're
2 aware of.

3 Basically after we observed the crud
4 induced AOA, we created an integrated fuel
5 performance plan, which was to address in a global
6 perspective the crud deposition that we were seeing.

7 One of the key components of that plan
8 was to evaluate the current lattice design and its
9 performance in these ring type loadings. Our
10 current lattice design has two intra-assembly
11 enrichments, which are basically a high and a low
12 pin enrichment. The low enrichment pins are
13 typically surrounding the guide tubes and the corner
14 pin of the assembly, and then the high pins or
15 higher enrichment make up the rest of the assembly
16 design.

17 This enrichment split in our design
18 effectively pushes power to the peripheral pins of
19 the assembly, and that's aggravated when you load
20 them in feed, face feed location.

21 That is further exaggerated when you
22 load additional erbia. Erbia is our burnable
23 poison. In a ring type design you're loading more
24 erbia, which again enhances the push toward the
25 peripheral pins.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 Why don't we go ahead and show a
2 picture? Go ahead, Yovan.

3 Here is a typical, fairly high erbia,
4 which is our burnable poison type quarter of
5 assembly. This is the northwest quadrant of an
6 assembly. This would be the center of the assembly.
7 That's a quarter of the center guide tube. Here's
8 your full guide tube.

9 As you can see, the box marks where the
10 max relative pin power is, and if you examine this
11 slide, it's pretty much predominantly along the face
12 of the assembly is where power is being pushed. All
13 of the rest of the assembly locations are pretty low
14 in relative power, and this is at beginning of
15 cycle, and that's important to know.

16 The goal basically of the redesign was
17 fairly straightforward. It was to avoid any plant
18 operational challenges or pin integrity challenges
19 due to crud and try to attempt to reclaim some of
20 the efficiencies in ring type loading.

21 Redesign aims to reduce basically total
22 crud mass and also for the crud that remains is to
23 homogenize the crud within the assembly so that we
24 don't have it localized all on certain surfaces to
25 yield a very thick crud layer.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 The redesign was basically we looked at
2 enrichment, changes in enrichment and splits and
3 burnable poison locations because, one, that we felt
4 was the best understood and lowest risk, while at
5 the same time being quickly available to implement
6 instead of doing other design changes.

7 The redesign effort consisted of three
8 phases basically, as I mentioned: examining the
9 current lattice design in a ring type loading, which
10 was very interesting; perform calculations to modify
11 the intra-assembly enrichment to see if we can
12 improve or reduce the crud deposition; and then also
13 kind of modify the burnable poison locations for
14 that same result.

15 And then once we had some candidate
16 lattice designs, is go ahead and throw them into
17 various test core designs and see what the crud
18 deposition yielded.

19 Basically two approaches or two design
20 philosophies were used in the design of the lattice.
21 One is to lower early cycle peak pin powers. We
22 felt that deposition curve primarily early in cycle,
23 and that if we delayed higher pin powers to later in
24 cycle, that would have a reduce crud benefit, and
25 even if we did have crud deposition, there would be

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 less boron to have an AOA. So that was kind of one
2 of the design philosophies.

3 The other one was just simply to match,
4 better match assembly flow, basically subchannel
5 flow to pin powers.

6 Basic steps were as I mentioned, is to
7 modify the two. First we started with what we could
8 do with the two enrichment, say, limitation on the
9 assembly. So we used that. We designed difference
10 splits of enrichment. Then when we found something
11 that looked reasonable or would lead us in the right
12 direction, we would modify burnable poison
13 placements to fine tune it.

14 And then really one of the early tests
15 is is the BOC beginning a cycle pin power
16 distribution roughly equal to what you would see
17 when the erbia burned off and you got a mid-cycle
18 peak. Because we didn't want to artificially reduce
19 BOC and then pay the penalty later on in middle
20 cycle or end of cycle. We just didn't want to move
21 the problem basically.

22 And then step four was once we got some
23 candidate loading patterns is to go ahead and set up
24 some core design models and actually design various
25 core designs and predict the crud deposition, and

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 then basically we extended -- we usually work from
2 like a pallet of 16 to 20 lattice designs where the
3 differentiation is the number of erbia pins.

4 So then we basically concentrated on
5 ones we typically use in a design. Once we found
6 the designs we liked there, then we expanded it to
7 the whole range of erbia loadings basically from
8 zero to some number.

9 Basically we had very good success. We
10 got to step three, and we had two two enrichment
11 designs with different burnable poison placements
12 that yielded some significant crud deposition.

13 When we further studied those designs
14 though, we decided to implement a third enrichment
15 to fine tune the design, and that's really where we
16 ended up with our final lattice design. That extra
17 degree of freedom we were able to tailor the power
18 distribution to the flow a little better.

19 Here's a picture of a fairly heavily
20 poisoned assembly. What you have here is a relative
21 peak pin power of the assembly versus burn-up and
22 EFPD. The top line up here that starts high and
23 goes low is our current lattice design, and the what
24 we're calling the Lattice F -- it was my F try --
25 was basically very similar, BOC peaks to MOC peaks.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 So we weren't --

2 CHAIRMAN POWERS: Pretty good if you can
3 get it by try F, presuming you started at A or did
4 you start at Z?

5 MR. SCHMIDT: No, no. I started at A,
6 but there were probably A1s, A2s, A3s before --

7 CHAIRMAN POWERS: Oh, I see.

8 MR. SCHMIDT: No, I think Lattice F was
9 mainly to -- kind of branched off into the third
10 enrichment. The other ones were the two enrichment
11 designs.

12 Here's another representation of that.
13 It's basically comparing our current design with 72
14 erbia to our new design with 76. We don't have a
15 one-to-one comparison. This is the closest we could
16 do.

17 You basically see along the outer edge
18 is about a three percent reduction in pin powers,
19 and that was really what we were looking for.

20 What's also important here is that we
21 didn't -- even though we reduced powers along the
22 face, we didn't really peak it up at least at BOC
23 significantly anywhere because the max location,
24 which is this red box for the redesign pattern, is
25 almost identical to that similar pin in the current

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 lattice design.

2 So we were able to reduce this edge face
3 where we were seeing the crud deposition, but we
4 didn't put a big pin power somewhere else that we'd
5 just basically be moving the problem.

6 At MOC, you have still a reduction in
7 the outer row of pins, but what you're seeing now is
8 that you're seeing a pin power increase towards the
9 center of the assembly or really towards the -- this
10 is the center down here, but this would be the guide
11 tube locations.

12 But if you look at the absolute value of
13 the new lattice, it's still very low relative to the
14 BOC pin powers of the current lattice. They were
15 about six percent, seven percent. We're still
16 talking four percent here. It's a seven percent
17 increase, but as Yovan noted, we're seeing almost no
18 crud deposition around the guide tubes, and there's
19 a reason for that. That's our highest flow location
20 within the assembly. So that's really where we
21 wanted to push the power to.

22 Phase three of the design was take our
23 pallet of new redesigned lattices and put it into
24 our Unit 2, Cycle 12, which is our up rate cycle.
25 Unit 2, Cycle 12, is a three percent power up rate,

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 but a degree and a half inlet temperature increase,
2 and with new steam generators.

3 So we basically took a parallel design
4 pass, saying, okay, we take our new lattices and we
5 take our current lattices and make the best designs
6 possible out of each one and see where we end up in
7 crud deposition.

8 Go ahead, Yovan.

9 We compared those to Unit 3, Cycle 9,
10 where we had mild localized AOA in the high powered
11 assembly. So that was kind of considered our
12 threshold. Do not go past that mild AOA.

13 Here's the results. You basically have
14 Unit 3, Cycle 9, which is our benchmark. Unit 2,
15 Cycle 12, with the C stands for the current lattice,
16 and this is the revived or redesigned lattice. Here
17 you basically have maximum pin -- that should be
18 crud thickness. Sorry about that. There should be
19 "crud" in there, and that's basically a span average
20 crud thickness.

21 And so you can see that with our best
22 design on our current lattice, we were going to go
23 over our three/nine threshold. So we felt we had
24 some risk associated with that.

25 And the revised lattice, we had a

NEAL R. GROSS

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

1 significant reduction in crud deposition. So we
2 felt pretty comfortable with that.

3 This is just another way of looking at
4 it. This look at total core crud. That was kind of
5 a localized maximum even though it's a span average,
6 but it's kind of a criteria of potential for pin
7 failure if you got too much crud.

8 This is kind of a global AOA indicator
9 we tend to use it as. Again, you can see three/nine
10 here. The current lattice did pretty well in terms
11 of current, and the revised lattice did
12 substantially better.

13 These, I should mention that the two-12
14 designs have different design assumptions than the
15 three/nine. Because we're getting new steam
16 generators, we have to assume an increase in source
17 term, basically the crud concentration coming off
18 the bare metal of the new steam generator before it
19 is basically pacified.

20 So what we did is for the two/12 designs
21 we assumed basically a source term or a crud
22 concentration of twice that would be assumed in the
23 three/nine design, and because we don't know how
24 basically the RCS crud concentration or nickel and
25 iron will fare with time, we assume an equal

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 weighting of deposition all through the cycle. So
2 that adds conservatism to the two values represented
3 for the cycle 12 designs.

4 The redesign lattice is predicting
5 significantly reduced crud deposition, as you saw.
6 Palo Verde has decided to implement the redesigned
7 lattice in all future core designs.

8 And then we have a multi-cycle fuel
9 inspections plan for multiple cycles of Unit 2
10 coming up to further validate the crud model and to
11 make sure the revised lattice is behaving as
12 predicted.

13 Just a couple other points that Yovan
14 had talked about was we have been using this crud
15 prediction model for six cycles now, and we have had
16 an opportunity to look at one assembly visually that
17 was a high powered feed assembly, and that fell --
18 you know, visually it's tough to tell, but we did
19 not see the tenacious crud that we had been seeing
20 on prior visual inspections of our fuel. So that's
21 another indication that we seem to be moving in the
22 right direction.

23 So we have had some data. The Unit 2
24 data is going to be -- excuse me. I'm not used to
25 talking this much. The Unit 2 data will include

NEAL R. GROSS

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

1 oxide thickness measurements and basically visual
2 inspections to, you know, further validate the
3 model. So that's going to be ongoing.

4 Do you have any questions?

5 DR. KRESS: I have a question about one
6 of your earlier slides.

7 MR. SCHMIDT: Okay.

8 DR. KRESS: The one on your crud
9 thickness regression model.

10 MR. LUKIC: Do you want to know the
11 formula?

12 DR. KRESS: Yeah. It doesn't reproduce
13 very well.

14 CHAIRMAN POWERS: Here we go. We've got
15 it all written out here.

16 DR. KRESS: Okay. That takes care of my
17 question.

18 MR. CARUSO: We copied the formula from
19 the paper. Is that the same formula?

20 MR. LUKIC: Yes, absolutely. Would you
21 like to keep the disk?

22 MR. CARUSO: Sure, that's fine.

23 MR. LUKIC: I'd be happy to give it to
24 you.

25 MR. SCHMIDT: For some reason it didn't

NEAL R. GROSS

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

1 print out when we went to print out this.

2 MR. CARUSO: That's right.

3 CHAIRMAN POWERS: That always seems to
4 happen.

5 Any other questions for the speakers?

6 Are we going to have any data on how
7 this new core load behaves?

8 MR. SCHMIDT: Sure, if you want.

9 Absolutely. Be happy to.

10 CHAIRMAN POWERS: I mean if nothing
11 else, send us a note some time and tell us how it
12 works, I mean, what the outcome is. This is like
13 one of those mystery stories. I'm waiting for who
14 done it here.

15 MR. LUKIC: And if you could invite us
16 for when the cherry blossoms are on, that would be
17 even better.

18 CHAIRMAN POWERS: Oh, yeah. We would
19 love to do that, except they carefully schedule ACRS
20 meetings so that that doesn't happen. We work for
21 the government. So you've got to suffer. It's one
22 of the requirements of the job here.

23 MR. SCHMIDT: Just as an aside, we'll be
24 looking at ZIRLO performance as well.

25 CHAIRMAN POWERS: Oh, okay.

NEAL R. GROSS

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

1 MR. SCHMIDT: But we will be looking at
2 a lot of things coming up, including oxide and crud
3 deposition and ZIRLO performance. So we're going to
4 get a lot of data out of it basically. In the next
5 three cycles we are planning on fuel inspections.

6 CHAIRMAN POWERS: Okay, yeah. I think I
7 would enjoy hearing how it all comes out and get --

8 MR. SCHMIDT: I will, too, if it comes
9 out well.

10 (Laughter.)

11 CHAIRMAN POWERS: No, see, I'm
12 interested regardless, but you only --

13 MR. SCHMIDT: Maybe somebody else will
14 be up there if it doesn't come out well.

15 (Laughter.)

16 CHAIRMAN POWERS: Well, thank you very
17 much.

18 MR. LUKIC: A pleasure.

19 CHAIRMAN POWERS: Let me now walk around
20 the committee and see if people have any first
21 thoughts here. I'll keep doing this throughout the
22 meeting in order to give you a chance to revise your
23 thoughts.

24 Peter, any thoughts on what all you've
25 heard here?

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 DR. FORD: You've said there are two
2 questions.

3 CHAIRMAN POWERS: Well, I've got about
4 five here.

5 DR. FORD: The whole topic of the
6 structure and temperature and fuel cladding, there's
7 a complex interaction diagram shown, and I'm
8 concerned that there was nothing related to the
9 primary and secondary interactions to distinguish
10 them. We only heard about the RAI, the LOCA, and
11 the transportation cost or the plan. Your question,
12 Dana, was how complete is the plan. We only had
13 about three of them.

14 We didn't hear any about ATWS for the
15 BWRs.

16 I was concerned that FRAPCON and
17 FRAPTRAN do not predict corrosion and hydrogen
18 embrittlement effects very well, and yet the
19 embrittlement of the fuel cladding is a prime
20 variable, and yet the FRAPCON and FRAPTRAN does not
21 take into account corrosion effects.

22 As far as the RAI aspects are concerned,
23 there's obviously some disagreement with EPRI about
24 the question of the pulse, the size. That concerns
25 me because it seems to me two of the experts

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 disagree, and we don't know which one is --

2 CHAIRMAN POWERS: They're a hell of a
3 lot closer now than they were last time.

4 DR. FORD: Yeah, true. I was a little
5 bit concerned that in the plan we were talking about
6 three approaches to the RAI, and yet it now looks as
7 though because of the stretch of time coming up to
8 resolving this by the end of this year, that we're
9 only going with one, which was really to modify the
10 paintbrush data using modifications of pulse width
11 aspect. It seemed as though they're shoving the
12 Vitanza multi-parameter code to one side, and maybe
13 that's a mistake, but that's what I thought I had
14 heard.

15 I think it's going to be optimistic that
16 we're going to have a believable modification by the
17 end of this year, 2003.

18 As far as the LOCA is concerned, my
19 first question really was or concern was are we
20 absolutely sure the compression ring test is the
21 right test to do. I am not a mechanical engineer,
22 but I keep hearing these murmurs that maybe it's not
23 the right one to use, and yet the whole approach
24 depends on that particular test.

25 I was puzzled somewhat to see how from

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 the basis of some of the pictures we saw, how the
2 pellets were going to be contained in the
3 ruptured -- if the tube does rupture and swings
4 around in a somewhat chaotic, thermal hydraulic and
5 mechanical condition, how the pellets are going to
6 be contained.

7 The LOCA thing I thought was a very
8 ambitious program which I think can be done by the
9 summer of next year, which is what I had heard. I
10 don't know how the gaps in the questions that
11 obviously still abound, how they were going to be
12 answered by the other cooperative partners that you
13 have. You mentioned the Russians and the fact that
14 they had corrosion aspects for E110. I don't know
15 the specifics of those interactions.

16 I will write this all down, Dana, for
17 you, but your final question was, I believe, how
18 much should be done by NRC versus other parties,
19 primarily industry. If you remember in our last
20 year's research report, we made a case for crucial
21 areas, such as neutronics codes and fuels, NRC must
22 have an independent research capability in the
23 crucial area of fuels.

24 I tend to agree. However, looking at
25 the number of questions that still abound, I can't

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 see how they're going to be resolved without there
2 being some sort of cooperative arrangement with
3 industry. I'm not quite sure that exists currently.

4 I'll write this all down, Dana, but
5 those are my first --

6 CHAIRMAN POWERS: That's good. You've
7 been thinking hard. We'll report to Bonaca that you
8 didn't dally around in this meeting; that you worked
9 diligently.

10 DR. FORD: Thank you.

11 CHAIRMAN POWERS: And he'll undoubtedly
12 give you a gold star.

13 Dr. Kress?

14 DR. KRESS: Well, let me address the
15 RIA, and I'll the initials in the right order.

16 DR. FORD: Oh, I got them wrong?

17 DR. KRESS: First, we did see basically
18 two approaches, one by the staff in readjusting
19 their basically empirical paintbrush model in order
20 to come up with a boundary for the failure insertion
21 rate and one by EPRI, which I haven't seen the
22 details of yet, but I understand it's a look at the
23 methodology of failure due to the loads and the
24 stresses and the material properties and getting
25 some sort of failure rate.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 I see no reason why both of those
2 wouldn't work. I mean there's no reason both of
3 those in principle couldn't work. I think the
4 paintbrush approach we heard from Ralph will very
5 nicely settle the issue of do we have the right
6 regulatory bound on the reactivity insertion and
7 will the calculations show that we're below that
8 bound for the ones.

9 I think it will handle that for the
10 existing clads and fuels. I think though that if
11 we're going to look at new clads and new fuels, that
12 you are either going to have to have a lot more data
13 to do that process, and I worry that you may miss
14 some of the fundamental issues.

15 So I think I'm leaning towards both
16 approaches. I like the EPRI approach for the new
17 materials, and I think the staff's approach to show
18 that the current regulatory level is okay is the way
19 to go.

20 So I like both approaches. I think in
21 order to extrapolate this to the different materials
22 you're going to have to go with EPRI's approach
23 because I think it will take too much new data to
24 get a new paintbrush curve for the new materials.

25 May I'm wrong there, but I think I would

NEAL R. GROSS

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

1 look very strongly at the EPRI approach and review
2 their stuff when it comes in. I haven't really
3 seen it in detail yet.

4 With respect to the LOCA stuff, I think
5 I like all of the fundamental data they're getting
6 on the materials properties and the effects of
7 hydrides and oxides on the strength of the material
8 and on its ductility. It seems to me there is a
9 missing step, and that's how you convert that into
10 what would sufficient -- the word "sufficient," I
11 guess, is in there.

12 I didn't really see that step being
13 closed yet, and I think some more is needed on that.

14 I guess I thought all of that work done
15 by Argonne was good work and nice stuff to have and
16 have no real complaints about it.

17 There is this issue that you brought up
18 about single rods versus bundle behavior, and I
19 don't know how to deal with that right now. I think
20 it's still an issue and will have to be dealt with
21 at some time.

22 That's about it, I guess.

23 CHAIRMAN POWERS: Good. Thanks.

24 Vic.

25 DR. RANSOM: Mine is going to be pretty

NEAL R. GROSS

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

1 minimal. This is kind of a new area for me, but
2 from what I heard it certainly sounded like the
3 models were the right way to go to extrapolate the
4 data, and I guess I sort of felt like there wasn't
5 an awful lot of difference in the high burn-up
6 compared to the normal fuels as far as the least
7 failure criteria were concerned.

8 And I would say that uncertainty was
9 brought up a couple of times, but not really
10 addressed very well, and any of this modeling, and I
11 think in general that should be addressed in either
12 approach.

13 That's about all I would have to say.

14 CHAIRMAN POWERS: You make the point;
15 you and Dr. Kress both made the point that modeling
16 is the way to extrapolate. What I would pose to you
17 is a question that you don't have to answer right
18 now, but it's a question we have to think about, is
19 can we do on the unconstrained modeling
20 extrapolation or do we have to have some sort of
21 benchmarks again of those models, and how big does
22 that modeling database have to be?

23 When we look at the database we have,
24 you can see that one data point as a benchmark could
25 be either wildly optimistic or wildly pessimistic.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 The tests have a natural scatter to them of some
2 magnitude. So what's the magnitude of database that
3 you have to have to benchmark your models, if indeed
4 you think you have to have a database to benchmark
5 your models? And I would be stunned if you didn't
6 think that, but I'm always willing to be stunned.

7 DR. RANSOM: Well, I think the problem
8 also would be similar if you simply tried to take
9 the empirical approach. You've got to prove that
10 you have enough data to evaluate the uncertainty
11 associated with any prediction you made from that.

12 CHAIRMAN POWERS: I guess the point I'm
13 trying to make is that the two are not different in
14 the magnitude of the data.

15 DR. RANSOM: True, but I guess from my
16 own personal point of view, I tend to -- if you have
17 a model, you know, that involves the phenomena that
18 you pretty much know are present and does explain
19 the trends of the data, I would tend to trust that
20 more than simply an empirical model.

21 CHAIRMAN POWERS: We used to have a
22 model, right up until REP-Na1 was done.

23 Okay. On that note, I guess we'll
24 recess and resume again tomorrow at 8:30. So we are
25 recessed.

NEAL R. GROSS

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

(202) 234-4433

www.nealrgross.com

1 (Whereupon, at 5:18 p.m., the
2 Subcommittee meet was adjourned, to reconvene at
3 8:30 a.m., Tuesday, September 30, 2003.)
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25

CERTIFICATE

This is to certify that the attached proceedings
before the United States Nuclear Regulatory Commission
in the matter of:

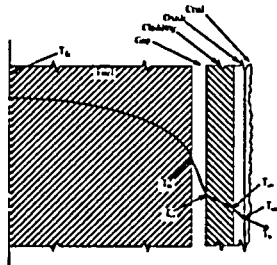
Name of Proceeding: Advisory Committee on
Reactor Safeguards
Reactor Fuels Subcommittee
Docket Number: n/a
Location: Rockville, MD

were held as herein appears, and that this is the
original transcript thereof for the file of the United
States Nuclear Regulatory Commission taken by me and,
thereafter reduced to typewriting by me or under the
direction of the court reporting company, and that the
transcript is a true and accurate record of the
foregoing proceedings.



Rebecca Davis
Official Reporter
Neal R. Gross & Co., Inc.

Fuel Rod Temperature Profile



J. Vignatiello - ACNH

9

September 28, 2005

Other Performance Characteristics

- Fission gas release
 - Principally temperature dependent
 - Affects temperatures by reducing gas thermal conductivity
 - Increases rod internal pressure
- Fuel densifies then swells
 - Affects fuel cladding gap, fuel-cladding mechanical interaction
- Cladding creeps, grows, corrodes, and hydrides
 - Affects fuel cladding gap, strength

J. Vignatiello - ACNH

8

September 28, 2005

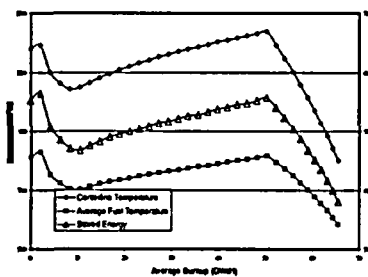


Fig. 9-1 Fuel temperature and stored energy for a PWR 15x15 fuel rod with initial peak power of 9 MWd

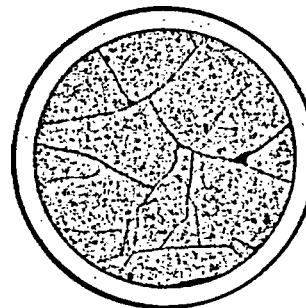
NUREG-1764

J. Vignatiello - ACNH

9

September 28, 2005

Example of Irradiated Material: Medium Burnup

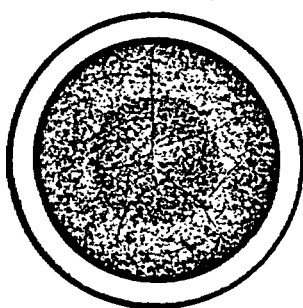


J. Vignatiello - ACNH

10

September 28, 2005

Example of Irradiated Material: High Burnup



J. Vignatiello - ACNH

11

September 28, 2005

Necessary Information to Calculate Fuel Rod Performance

- Fuel rod design
 - Dimensions
 - Fuel density and enrichment
 - Initial gas pressure and composition
- Materials properties
 - Often temperature and other parameter dependent
 - Some are burnup dependent
 - Material and physical properties generally correspond with MATPRO-11 Rev.2 (1981)
- Coolant conditions
 - Can be time dependent
- Power history
 - Time dependent

J. Vignatiello - ACNH

12

September 28, 2005

**Problems running the codes
can usually be traced to user
errors with the input files!**

J. Vignone - ACPS

13

September 29, 2005

NRC HAS TWO FUEL CODES

- **FRAPCON-3.2**
 - NUREG/CR-4534, Volume 1 (Code Modifications for High-Burnup)
 - NUREG/CR-4534, Volume 2 (Code Description)
 - NUREG/CR-4534, Volume 3 (Integral Assessment)
- **FRAPTRAN-1.2**
 - NUREG/CR-4739, Volume 1 (Code Description)
 - NUREG/CR-4739, Volume 2 (Integral Assessment)

J. Vignone - ACPS

14

September 29, 2005

NRC Fuel Codes

**are developed and maintained by
the U.S. Department of Energy's
Pacific Northwest National Laboratory**

J. Vignone - ACPS

15

September 29, 2005

FRAPCON-3.2 Steady-State Performance

J. Vignone - ACPS

16

September 29, 2005

FRAPCON-3.2

- **FRAPCON calculates steady-state fuel rod performance for the life of a rod**
- **Changes on the order of hours or greater**
 - **Temperature history**
 - Function of (design, thermal properties, power, dimension changes)
 - **Gas pressure history**
 - Dependent on fission gas release and void volume changes
 - **Cladding strain history**
 - Elastic and permanent strain
 - Cladding creep-down from pressure differential
 - Cladding outward strain due to mechanical interaction with pellets
 - **Steady-state cladding oxidation (also called corrosion)**
 - Function of (clad surface temperature, time)
 - **Crud buildup**
 - User-defined rate

J. Vignone - ACPS

17

September 29, 2005

FRAPTRAN-1.2 Transient Performance

J. Vignone - ACPS

18

September 29, 2005

FRAPTRAN-1.2

- Calculates fuel rod performance in response to a rapid power and/or cooling transient
 - Requires initial conditions (dimensions, gas, axial and radial power and burnup profiles)
- Transients on the order of milliseconds to minutes
 - Temperature history
 - Gas pressure history
 - Cladding strain history
 - Elastic and permanent strain
 - ballooning
 - High temperature cladding oxidation

J. Vignone - ACNH

16

September 26, 2005

Transients Analyzed by FRAPTRAN

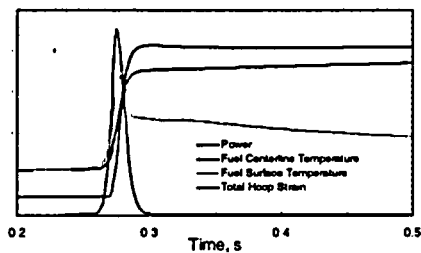
- Some of transients analyzed are:
 - Loss-Of-Coolant Accident (LOCA)
 - Reactivity Initiated Accident (RIA)
 - Anticipated Transient Without Scram (ATWS)
 - Power - Cooling Mismatch

J. Vignone - ACNH

20

September 26, 2005

Example time history of RIA



J. Vignone - ACNH

21

September 26, 2005

Calculations Common to Both Codes

- Same general computational model
- Temperature
 - Axial and radial profiles
 - Time and power dependency
- Rod internal gas pressure
 - Dependent on temperature, void volume, gas release, dimensional changes (but no transient fission gas release)
- Dimensional changes
 - Cladding thermal strain from thermal expansion
 - Cladding elastic strain from pressure differential
 - Cladding elastic and plastic strain from fuel-cladding mechanical interaction
 - FRAPCON3
 - Fuel desiccation and swelling
 - Cladding creepdown from pressure differential
 - Cladding irradiation growth
 - FRAPTRAN
 - ballooning

J. Vignone - ACNH

22

September 26, 2005

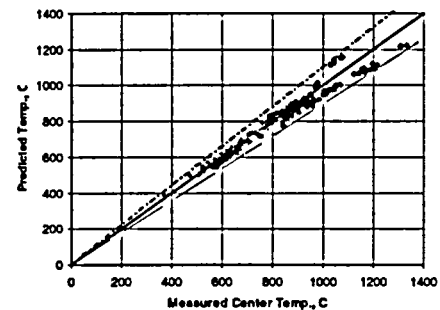
Sources of Data/Model Development

- Non-irradiated testing
 - Properties
 - Components
- Irradiated testing
 - In-reactor measurements
 - Temperature, pressure, dimensions
 - Post-irradiation examination
 - e.g., dimensions, gas pressure, metallography
- Separate effects vs. integral behavior

J. Vignone - ACNH

23

September 26, 2005

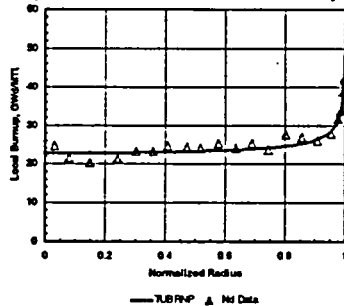


J. Vignone - ACNH

24

September 26, 2005

TUBRNP Radial Burnup Profile (PWR Rod at ~25 GWd/MTU)



J. Vignone - ACPS

29

September 29, 2003

Program Office Use of Fuel Codes

- NRR Uses Fuel Codes in Audits of Vendor Codes and Methods
 - NRR currently reviewing the EPRI FALCON code
- NMSS Uses Fuel Codes for Fuel Conditions in Storage
 - Per Interim Staff Guidance No. 11 (Rev 2), SPFO calculates fuel rod internal void volume and gas pressure in spent fuel
- Fuel Code Training for Program Offices
 - Two-day training session in August 2003

J. Vignone - ACPS

30

September 29, 2003

International Use of Fuel Codes

- Fuel Code User Group
 - 29 organizations and 15 countries represented
 - Peer review of NRC codes
 - Periodic User Meetings (ANL in July 2003)
- Fuel Code Information Available on the Internet
 - <http://www.pnl.gov/fapcon3>
- International Use of NRC Codes
 - Finland
 - Russia
 - Spain

J. Vignone - ACPS

31

September 29, 2003

FUEL CODE REPORT CARD

Steady-State		Transient
A	Fuel Temperature Distribution	B
A	Fuel Densification/Swelling	C
A	Fission Gas Release	D
A	Radial Power and Burnup Distribution	B
B	Fuel Material Properties	C
C	Cladding Material Properties	C-
C+	Cladding Mechanical Response	C-
D	Fuel and Cladding Chemistry	F
B	Cladding-to-Coolant Heat Transfer	C
F	Channel/Fuel Assembly Effects	F

J. Vignone - ACPS

32

September 29, 2003

PROBLEM AREAS

Transient Fuel Swelling and Fission Gas Release
Grain Boundary Evolution, Rim Effects and Burst Releases

Fuel and Cladding Material Properties
New Cladding Alloys

Cladding Mechanical Response
Pellet-Cladding Mechanical Interaction

Fuel and Cladding Chemistry
Corrosion, Hydrogen Embrittlement

Clad-Coolant Heat Transfer and Channel Effects
CHF modeled but limited transient capability, GENFLO

J. Vignone - ACPS

33

September 29, 2003

SUMMARY

- Fuel Codes Used By NRC
 - To study transients and accidents
 - To audit vendor submittals
 - To evaluate the influence of new experimental results
- NRC Fuel Codes Used By Others
 - As a research tool
- NRC Fuel Codes Continue to Evolve
 - Model development to support areas of current regulatory interest

J. Vignone - ACPS

34

September 29, 2003



United States Nuclear Regulatory Commission

SCALING METHOD FOR RIA DATA (Reactivity Initiated Accidents)

Ralph Meyer
Office of Nuclear Regulatory Research

ACRS Subcommittee
September 29, 2003

PRESENTATION OUTLINE

- Description of the issue, which includes the need for a high-burnup data base
- Identification of problems with test conditions in current programs
- Two numerical examples of a scaling method to correct problems in the data base
- Conclusions with estimates of correction magnitudes
- Discussion of how this scaling method will be used to resolve the issue

THE ISSUE

Irradiation effects, especially corrosion, reduce the ductility of cladding on high-burnup fuel. Because of this, cladding failure with fuel dispersal can occur at fuel enthalpies well below the 280 cal/g limit currently used in licensing analyses (e.g., Regulatory Guide 1.77). An experimental data base needs to be established from which a revised limit can be determined for high-burnup fuel. And a confirmatory assessment is needed to show that operating reactors at the current limit of 62 GWd/t burnup still meet the requirements of General Design Criterion 28 with respect to coolability and pressure pulses.

PROBLEMS WITH TEST CONDITIONS IN CURRENT PROGRAMS

- Nuclear Safety Research Reactor (NSRR, Japan)
 - 4.5 ms half-width of pulse at 100 cal/g
 - 20°C test temperature
- Cabri Test Reactor (France)
 - >30 ms half-width in artificially broadened pulses at 100 cal/g
 - 280°C test temperature
- PWR
 - 10 ms half-width of transient at 100 cal/g
 - 280°C hot standby temperature

EFFECT OF PULSE WIDTH AND TEMPERATURE ON CLADDING FAILURE

Pellet expansion is largely a function of fuel enthalpy increase, regardless of pulse width, but ...

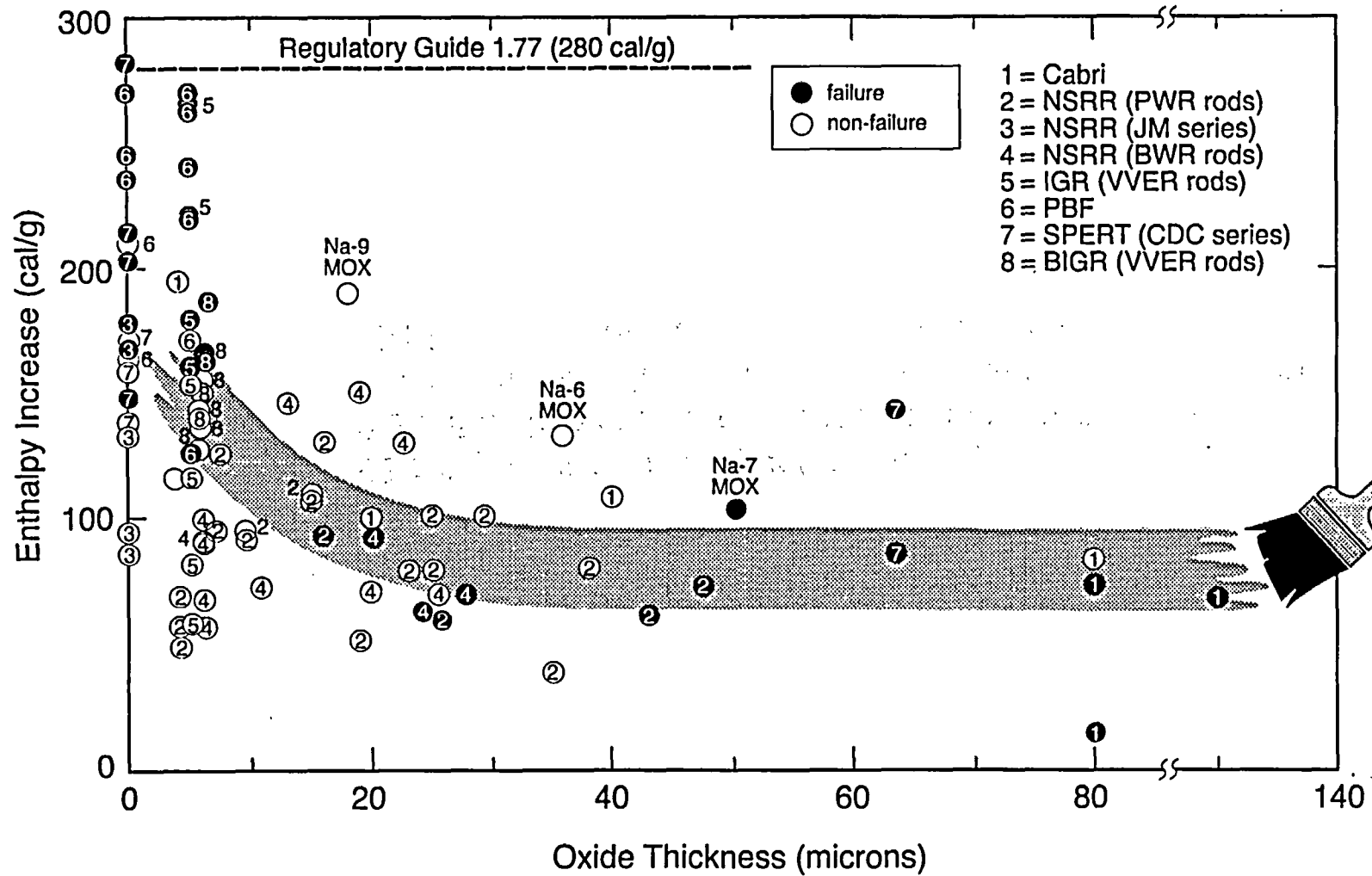
- More heat flows to the cladding during a broad pulse than during a narrow pulse so the cladding temperature at the time of failure will be affected by pulse width.
- Initial coolant temperature in a test rig will also affect the cladding temperature at the time of failure.

and ...

- Mechanical properties are a function of temperature and thus sensitive to the temperature of the cladding at the time of failure.
- Cladding temperature will also determine the amount of thermal strain (thermal expansion) of the cladding at the time of cladding failure.

THE METHOD OF RESOLUTION

- Use FRAPTRAN calculations and mechanical properties data to make adjustments for these temperature effects.
- Two examples will be shown (HBO-1 from NSRR, and REP-Na10 from Cabri).
- HBO-1 failed in the plastic region, after reaching the yield stress.
- REP-Na10 failed in the elastic region.



HBO-1 TEST PARAMETERS

93 cal/g total energy input (measured)

0.2045 s time at failure (measured, but arbitrary zero)

4.4 ms pulse width (measured full width at half maximum)

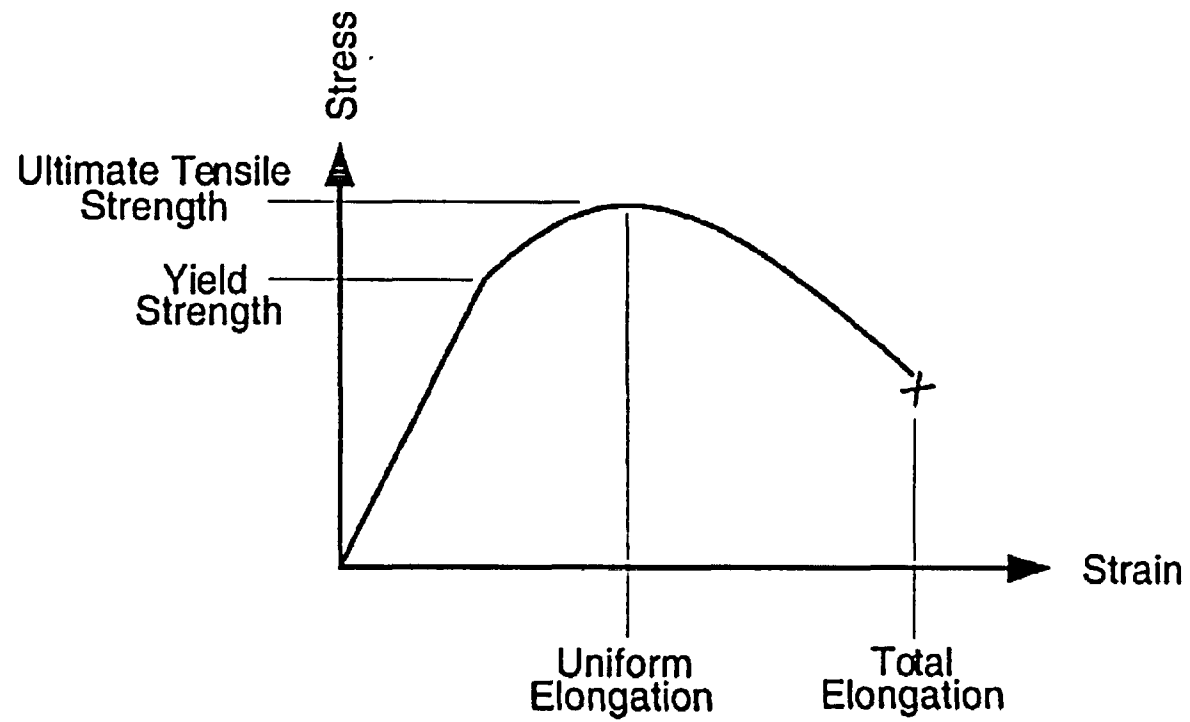
291 K initial coolant temperature (measured)

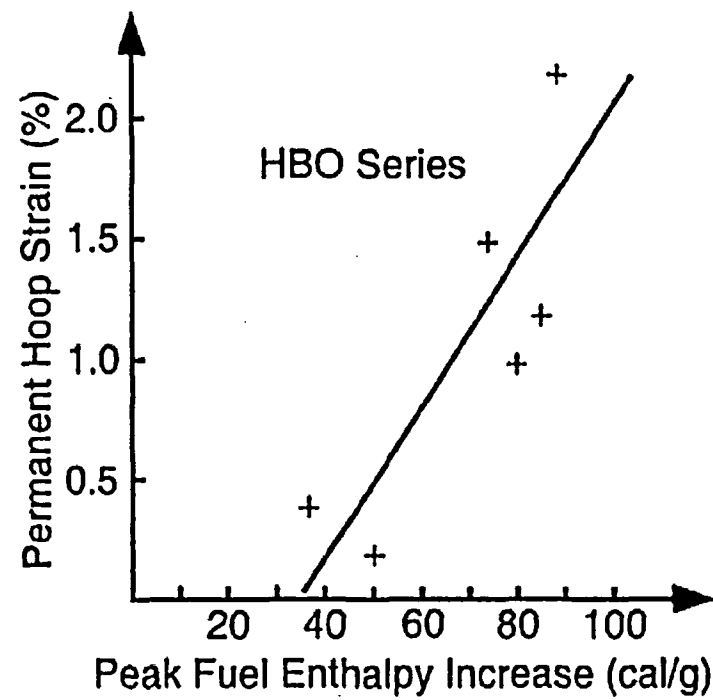
CALCULATED HBO-1 PARAMETERS AT TIME OF CLADDING FAILURE

60 cal/g fuel enthalpy increase at failure

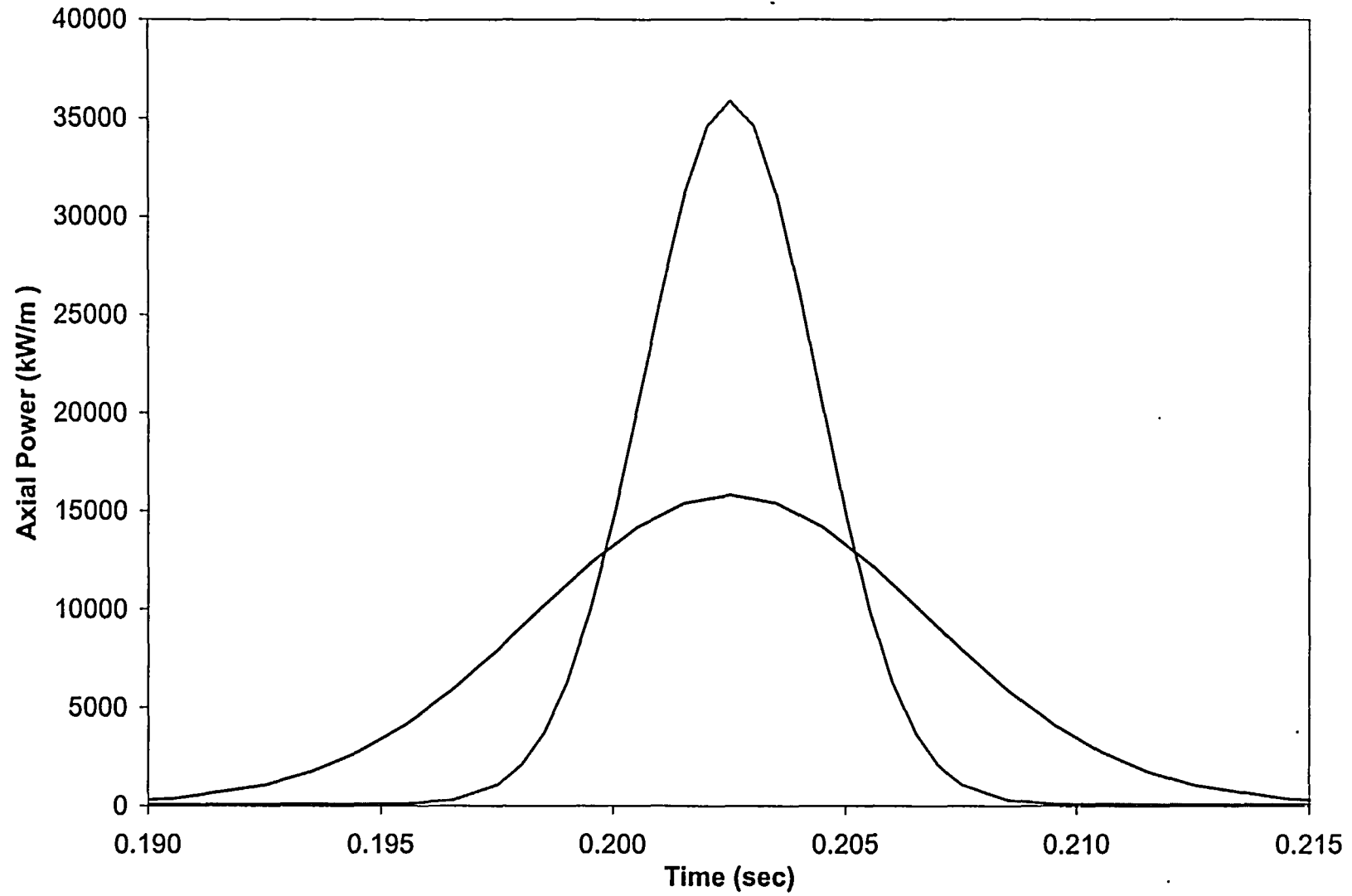
0.62% cladding permanent hoop strain = Failure Strain

337.5 K cladding average temperature

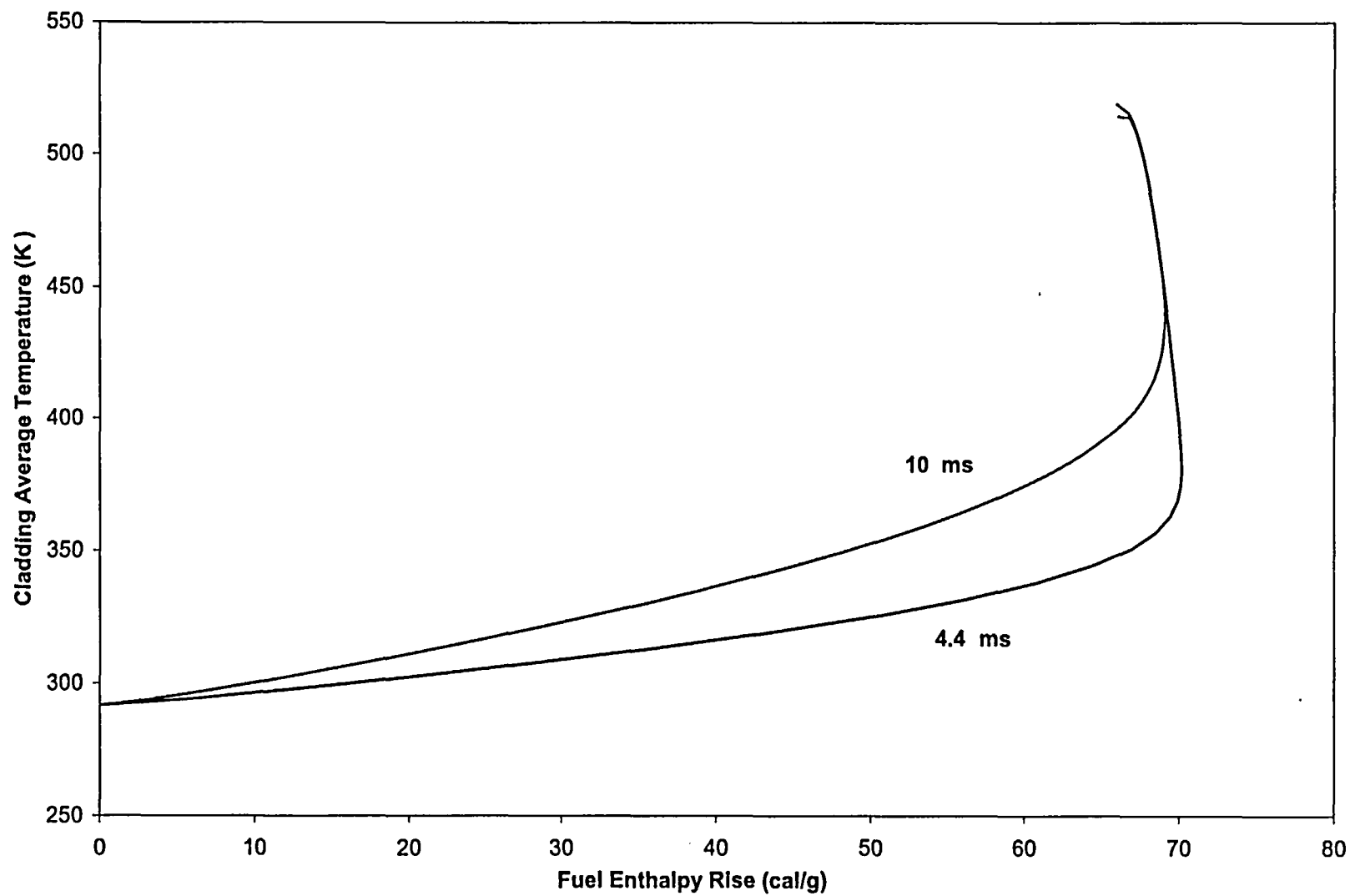




HBO-1 and HBO-1-10ms



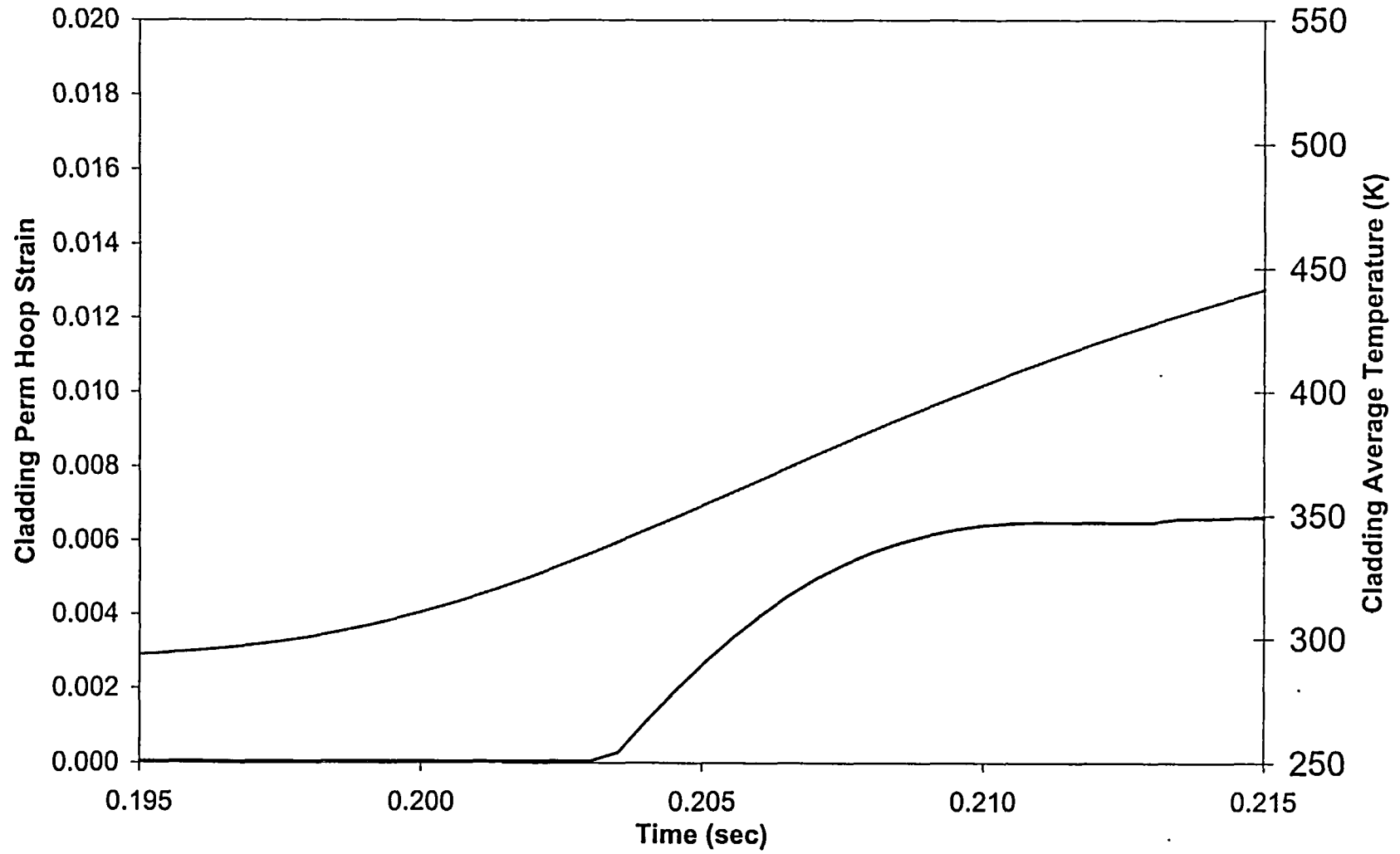
HBO-1 and HBO1-10ms (Fixed Coolant Temperature)

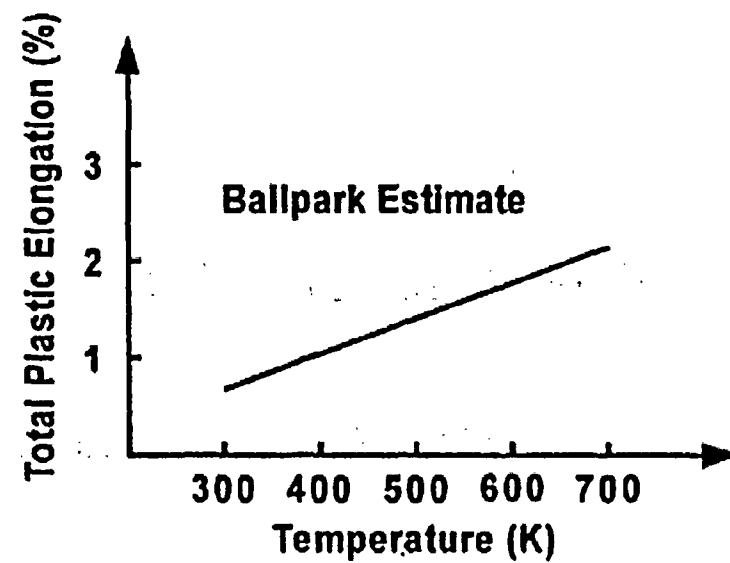


**OBSERVATIONS FOR 10-ms PULSE CALCULATION SIMILAR TO HBO-1
(HYPOTHETICAL TEST WITH HBO-1 SPECIMEN)**

- Cladding temperature is 400 K at time corresponding to 0.62% permanent strain
- Cladding would not fail at 0.62% strain because it has more ductility at 400 K than at 337.5 K
- Cladding failure will occur at a higher strain and hence at an enthalpy > 60 cal/g

HBO-1-10ms





FAILURE STRAIN AS FUNCTION OF TEMPERATURE

$$\epsilon(T_2) = \epsilon(T_1) TE(T_2)/TE(T_1)$$

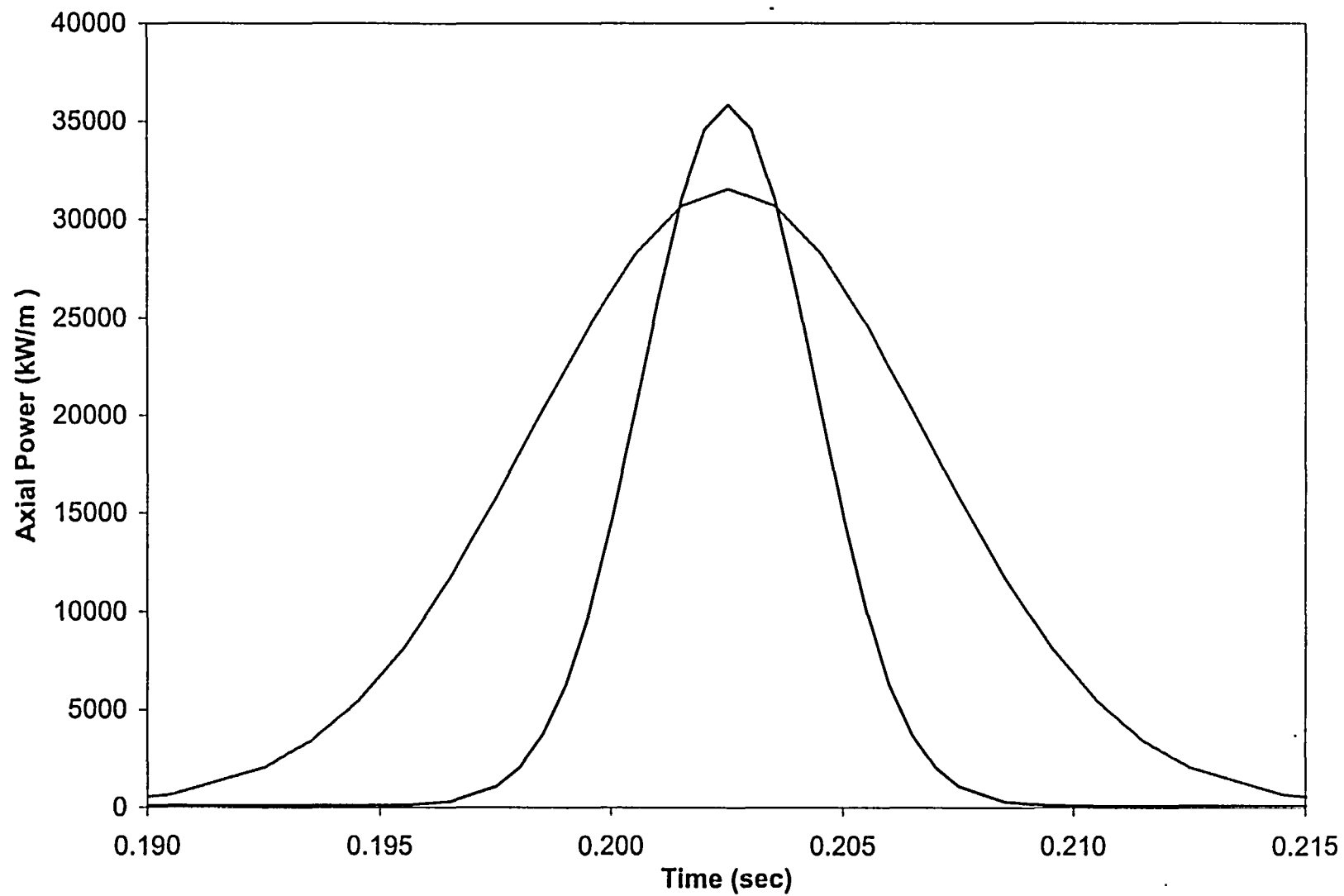
$$\epsilon(T_2) = 0.62 TE(T_2)/TE(337.5)$$

**CALCULATED PARAMETERS AT TIME OF FAILURE FOR 10-ms PULSE
SIMILAR TO HBO-1
(HYPOTHETICAL TEST WITH HBO-1 SPECIMEN)**

69 cal/g fuel enthalpy increase at failure
0.75% cladding permanent hoop strain
380 K cladding average temperature

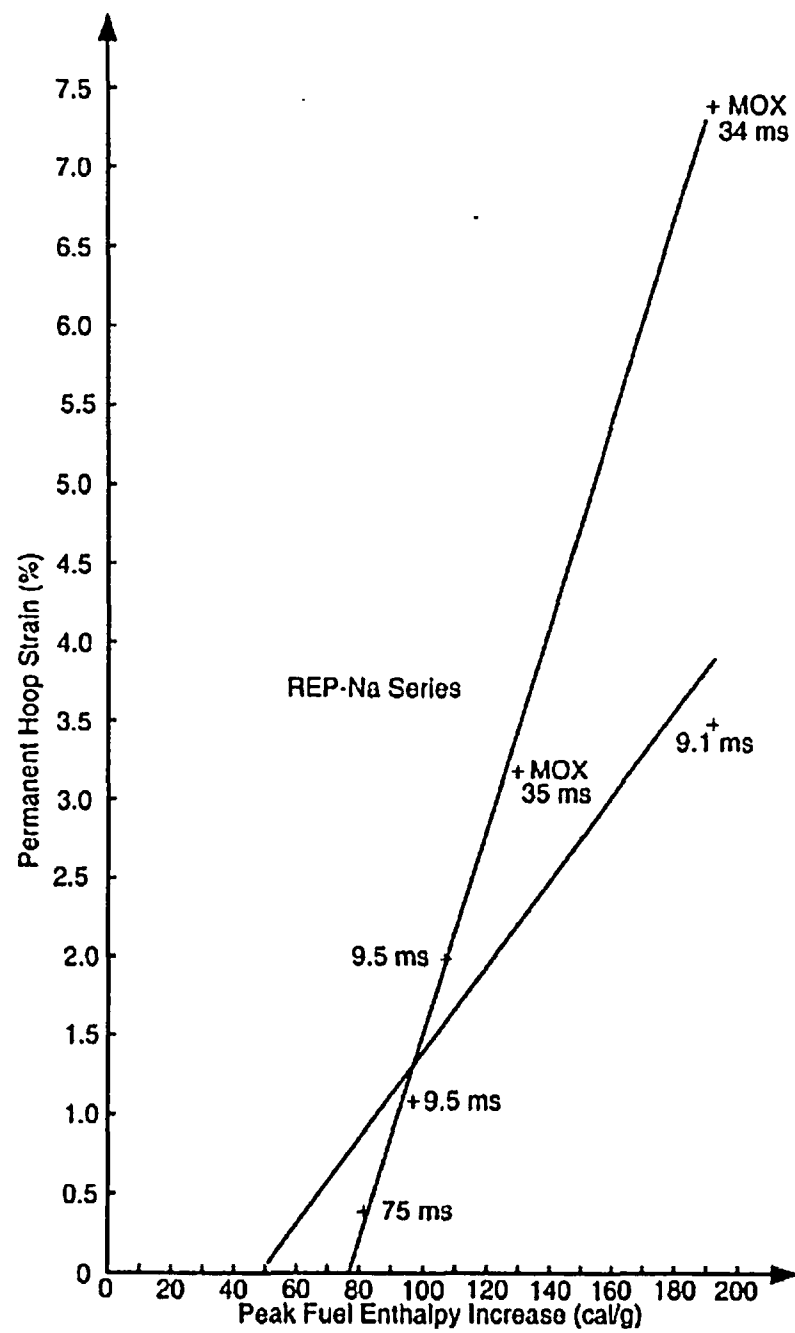
Note: 10-ms pulse with same deposited energy as HBO-1 will not produce 0.75% strain. Pulse energy had to be increased about 20%. (Out in the tail of a pulse, the cladding temperature increases faster than the strain increases.) Above result is relatively insensitive to energy in the larger pulse above the level needed to get 0.75% strain.

HBO-1 and HBO-1PWRX2



**CALCULATED PWR PARAMETERS AT TIME OF CLADDING FAILURE
(HYPOTHETICAL TEST WITH HBO-1 SPECIMEN)**

100 cal/g fuel enthalpy increase at failure
1.71% cladding permanent hoop strain
707.5 K cladding average temperature



REP-Na10 TEST PARAMETERS

107 cal/g total energy input (measured)

0.456 s time at failure (measured, but arbitrary zero)

31 ms pulse width (measured full width at half maximum)

553 K initial coolant temperature (measured)

CALCULATED REP-Na10 PARAMETERS AT TIME OF CLADDING FAILURE

68 cal/g fuel enthalpy increase at 0.456 s

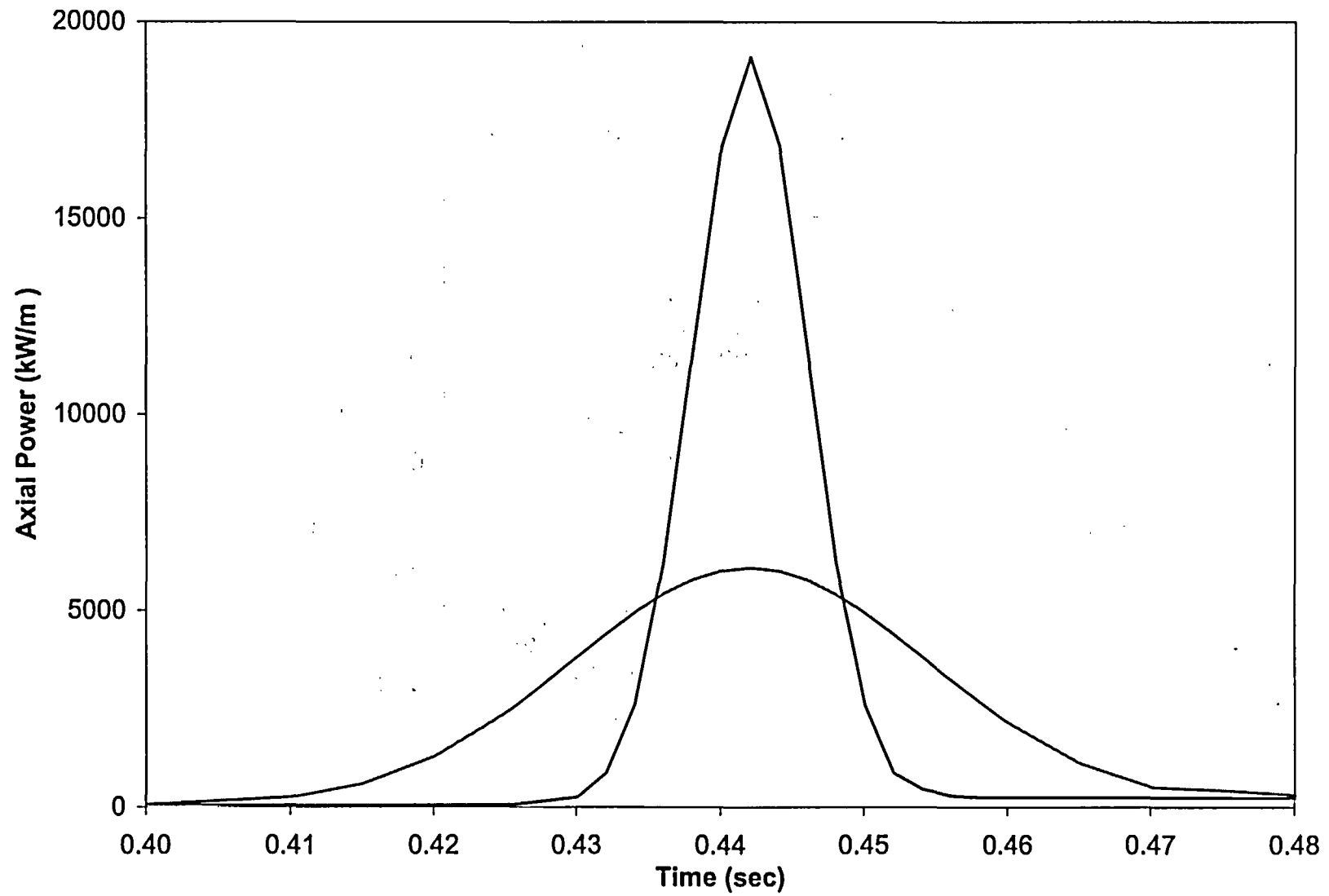
59 cal/g fuel enthalpy increase at failure

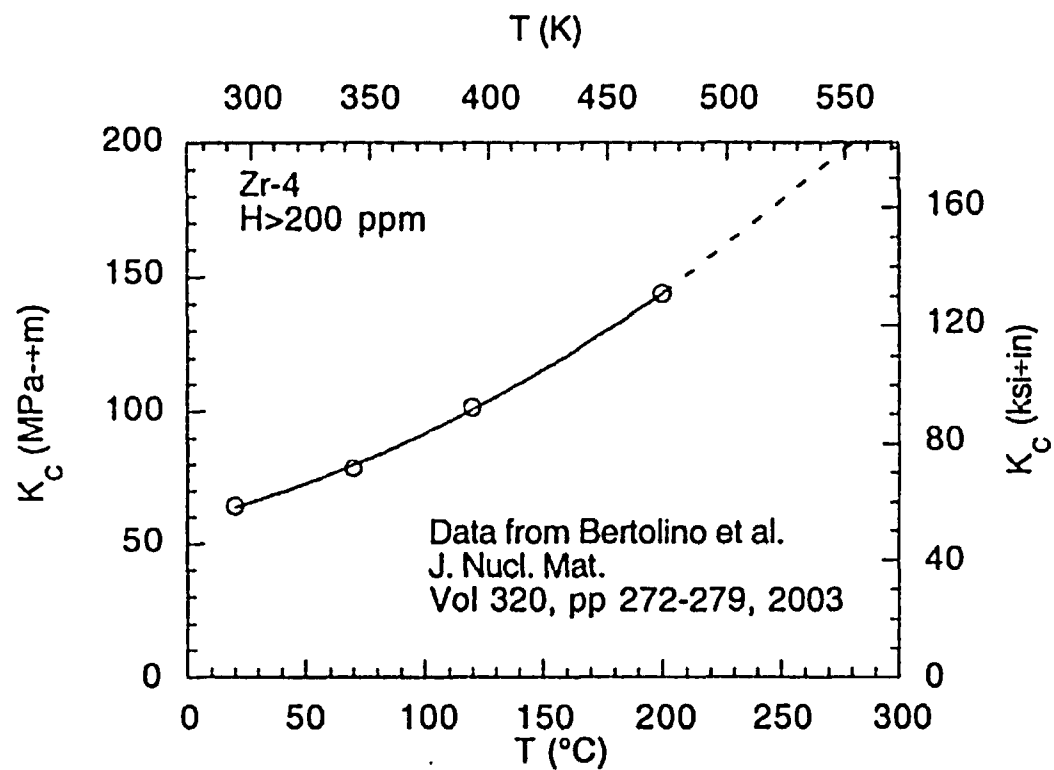
450 MPa cladding hoop stress = Failure Stress

743 K cladding average temperature

Note: Our calculation shows some plastic strain at the reported time of failure. Data for REP-Na series suggest that there should be no plastic strain, and IRSN reports that failure occurred at the end of the elastic region. We took the failure time in our calculations to be at the end of the elastic region for this demonstration of the scaling method.

REPNa10 and REPNa10PWR





*Variation of fracture toughness of Zr-4
with >200 ppm H as a function of
temperature*

**CALCULATED PWR PARAMETERS AT TIME OF CLADDING FAILURE
(HYPOTHETICAL TEST WITH REP-Na10 SPECIMEN)**

40 cal/g fuel enthalpy increase at failure
350 MPa cladding hoop stress
662 K cladding average temperature

CONCLUSIONS

- Effects of pulse width and test temperature depend strongly on the temperature dependence of the mechanical properties
- Mechanical properties are not well known at this time
- Effect of pulse-width broadening in Cabri (30 vs 10 ms in PWR) is large (~ -20 cal/g)
- Effect of pulse-width atypicality in NSRR (4.5 vs 10 ms in PWR) is modest (~ +10 cal/g)
- Effect of low test temperature in NSRR (20 vs 280°C in PWR) is very large (~ +30 cal/g)
- PWR test specimens in NSRR might not have failed by PCMI at PWR temperatures
- This scaling method will allow us to adjust test data for PWR conditions and then determine a realistic cladding failure boundary

CONFIRMATORY RIA ANALYSIS

- Improvements in analysis and mechanical properties will be made, and our best estimates as of end of CY 2003 will be used to define a cladding failure boundary as a function of oxide thickness for high-burnup fuel.
- In our assessment, we will use this cladding failure boundary as a limit to preclude:
 - energetic fuel-coolant interactions
 - loss of fuel and questions about coolable geometry
- Estimates of control rod worth needed to reach this cladding failure boundary will be made with generic 3-D neutron kinetics analyses.
- Based on preliminary work, we expect to show that typical control rod worths in commercial reactors are not large enough to cause cladding failure.
- This will resolve the confirmatory RIA issue for high-burnup fuel up to 62 GWd/t burnup and will be documented in a Research Information Letter around the end of this year (2003).



United States Nuclear Regulatory Commission

TECHNICAL BASIS FOR PERFORMANCE-BASED REVISIONS TO 10 CFR 50.46

Ralph Meyer
Office of Nuclear Regulatory Research

ACRS Subcommittee
September 29, 2003

THE PROBLEM

- Ductility of cladding is reduced by burnup and related corrosion. Because 50.46 uses embrittlement criteria, the adequacy of current licensing analyses should be confirmed.
- Oxidation-related LOCA evaluation models might be affected by fuel burnup, and this needs to be checked out.
- 50.46 is currently limited to two cladding alloys (Zircaloy and ZIRLO), and other alloys need to be accommodated.

THE METHOD OF RESOLUTION

- **Generate a data base for high-burnup fuel and new cladding alloys**
- **Make a confirmatory check of current licensing analyses**
- **Develop a basis for a more inclusive rule**

R. Meyer — ACRS — September 29, 2003

3

THE FORM OF THE SOLUTION

- **Research Information Letter summarizing laboratory results**
- **Confirmed and grandfathered rule (or revision if necessary)**
- **New performance-based option in 50.46 (SRM 3/31/03)**

R. Meyer — ACRS — September 29, 2003

4

BASIS FOR EMBRITTLEMENT CRITERIA IN 50.46

Maintain coolable geometry

→ Keep fuel pellets inside the cladding

→ Don't let the cladding fragment or break in several pieces

→ Retain some ductility in the cladding

→ Limit cladding oxidation and temperature

CURRENT FORM OF EMBRITTLEMENT CRITERIA IN 50.46

- (1) Peak cladding temperature shall not exceed 2200°F
- (2) Maximum cladding oxidation shall nowhere exceed 17% of cladding thickness
 - Includes ruptured cladding balloons, with double-sided oxidation
 - Oxidation should be calculated with the Baker-Just correlation
 - Corrosion thickness should be subtracted from 17% ("total oxidation")

These criteria only apply to Zircaloy and ZIRLO cladding.

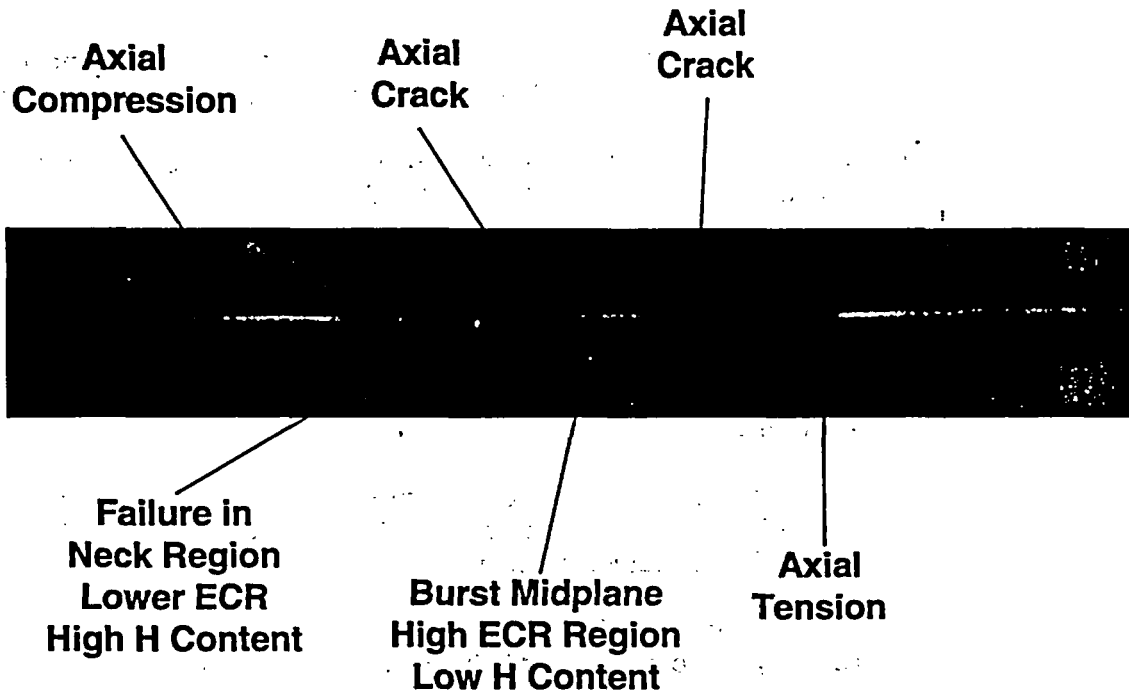
TYPES OF DATA BEING GENERATED IN CURRENT PROGRAM AT ANL

- Ductility tests (ring-compression tests) to determine the dependence of ductility on burnup, corrosion, and alloy type — similar to original approach
- Integral tests, followed by 4-point bending, to confirm that application of ductility data to ballooned region achieves objective (Do you retain sufficient ductility if you follow directions in 50.46 and Appendix K?)
- Oxidation tests to see if burnup, corrosion, and alloy type affect kinetics correlations
- Current data base for resolution includes (a) high-burnup rods with Zircaloy cladding and (b) unirradiated M5 and ZIRLO cladding
- Future data base for confirming burnup behavior and developing a pre-hydrided surrogate will use high-burnup fuel with M5 and ZIRLO cladding, subject to the availability of fuel rods and the continued cooperation of the industry

DUCTILITY "SINGULARITIES"

- There are three local areas where we expect ductility to be lost even when applying the ductility criteria as intended:
 - (1) Just above the balloon, where the hydrogen concentration is high
 - (2) Around the rim of the burst opening where oxidation is 100%
 - (3) Just below the balloon, where the hydrogen concentration is high
- We expect the integral tests to show that fuel loss will be minimal if the cladding cracks in one of these locations.

July 16, 2003 4-Point-Bend Demonstration Results



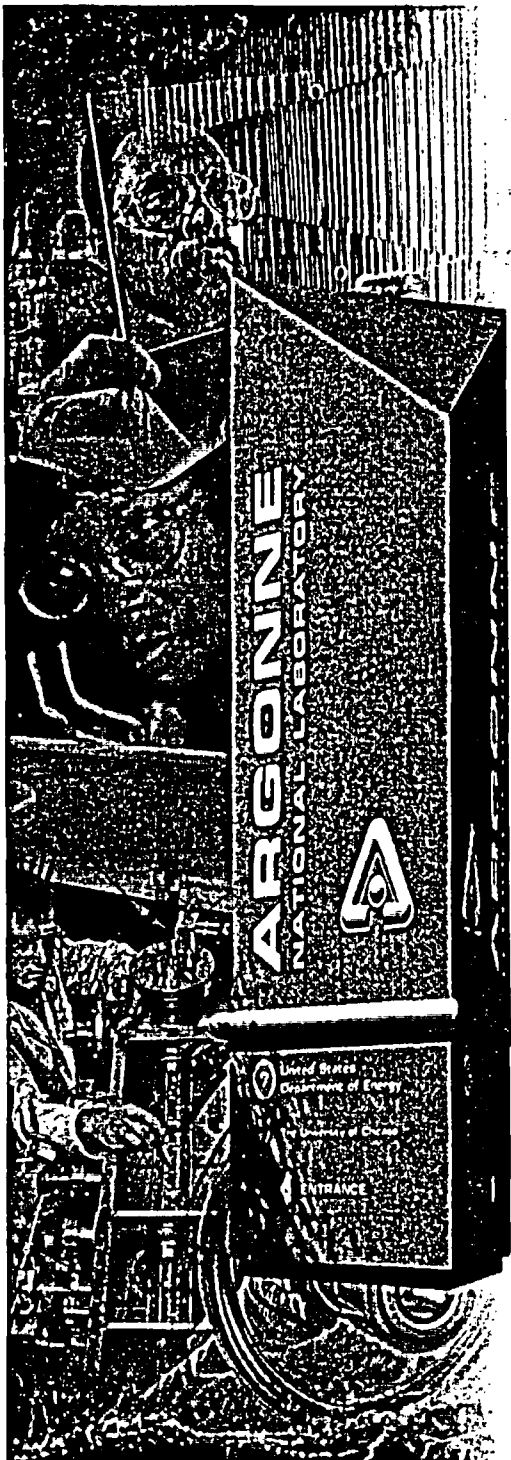
CONFIRMED AND GRANDFATHERED RULE

- Data are being generated for Zircaloy, ZIRLO, and M5 cladding to determine if sufficient ductility is retained in the ballooned region when the current embrittlement criteria are applied.
- This demonstration would apply for burnups up to 62 GWd/t and corrosion up to 100 μ .
- Results will be documented in a Research Information Letter
- M5 could then be added to the grandfathered rule, if that were desired.

OPTIONAL PERFORMANCE-BASED EMBRITTLEMENT CRITERIA

- Ring-compression tests, which are being used for the confirmatory activity, are being qualified as a general test for all alloys, burnups, and corrosion thicknesses.
- This ring compression test can be used to find the temperature and oxidation conditions corresponding to zero ductility.
- A test procedure with this test could be specified in 50.46 instead of fixed values for temperature and oxidation limits (details in a Regulatory Guide).
- Appropriate temperature and oxidation limits could be determined from this performance-based procedure by the fuel manufacturer for use in LOCA safety analyses.
- Because this performance-based procedure would permit cladding temperatures above 2200°F, an independent temperature limit might be needed to ensure against runaway temperatures from excessive metal-water reaction heat.

NB. Metal-water heat calculated by Baker-Just at 2200°F equals metal-water heat calculated by Cathcart-Pawel at 2307°F (discussion in RIL-0202).



LOCA Test Results

M.C. Billone, Y. Yan and T. Burtseva
Energy Technology Division

ACRS Meeting
NRC Headquarters
September 29, 2003

Argonne National Laboratory



A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago



Summary of Programs

- **LOCA-Relevant**

- Advanced alloy post-quench ductility testing (unirradiated)
- Steam oxidation of high-burnup BWR and PWR cladding
- LOCA Integral Tests with fueled BWR and PWR cladding
- Post-quench ductility of high-burnup LOCA Integral Test specimens
- Ramp-to-burst tests with fueled BWR and PWR cladding

- **RIA- and LOCA-Relevant**

- High and low strain-rate tensile properties: axial and hoop
- PSU biaxial “plane-strain” tests: limit and failure strains

- **Dry Cask Storage**

- Burnup ≤ 45 GWd/MTU: PWR rod characterization after 15-y storage
- High burnup: tensile, bending & creep properties, annealing, hydride reorientation/redistribution, post-storage ductility, fuel isotopes

Cladding Alloys and Irradiated Fuel Rods at ANL

- **Unirradiated Cladding Alloys**

- Zry-2: 8x8, 9x9 (Limerick BWR “archive”); 10x10 (to be provided)
- Zry-4: 15x15 (Robinson “archive”); 17x17 low-Sn (W and [F-ANP])
- ZIRLO: 17x17
- M5: 17x17 (two lots)
- E110: tubing and cladding (etched/anodized or lightly oxidized)

- **Irradiated Fuel Rod Segments (see Table)**

- Robinson 15x15 PWR rods (7 for LOCA/RIA + 3 for Dry Cask + 2)
- Limerick 9x9 BWR rods (7 for LOCA/RIA)
- TMI-1 15x15 PWR rods (2 for verification/validation tests)
- Surry 15x15 PWR rods (3 rods dry-cask stored for 15 years)

Commercial LWR Fuel Rod Segments at ANL

Reactor (Design)	Burnup GWd/MTU	²³⁵ U wt.%	Gd ₂ O ₃ wt.%	Clad.	React. EOL	Dry- Stored
Robinson 15×15 PWR	64-67	2.90	0	Zry-4	1995	No
	63	3.85	0	Zry-4	1995	No
	47	1.95	10	Zry-4	1995	No
Limerick 9×9 BWR	54-57	3.95	0	Zry-2 Lined	1998	No
TMI-1 15×15 PWR	48-50	4.00	0	Zry-4 Low-Sn	1997	No
Surry 15×15 PWR	36	3.11	0	Zry-4	1881	15 y



Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



Irradiation Parameters Relevant to Models & Correlations

Reactor (Design)	Burnup GWd/MTU	Clad.	Fast Fluence 10^{25} n/m^2	Oxide μm	H wppm
Robinson 15×15 PWR	67	Zry-4	14	≤ 110	≤ 800
Limerick 9×9 BWR	57	Zry-2 Lined	11	$\approx 10 +$ $\approx 10 \text{ crud}$	≈ 70
TMI-1 15×15 PWR	49	Zry-4 Low-Sn	9	≤ 30	≤ 200
Surry 15×15 PWR	36	Zry-4	7	≤ 40	≤ 300



Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



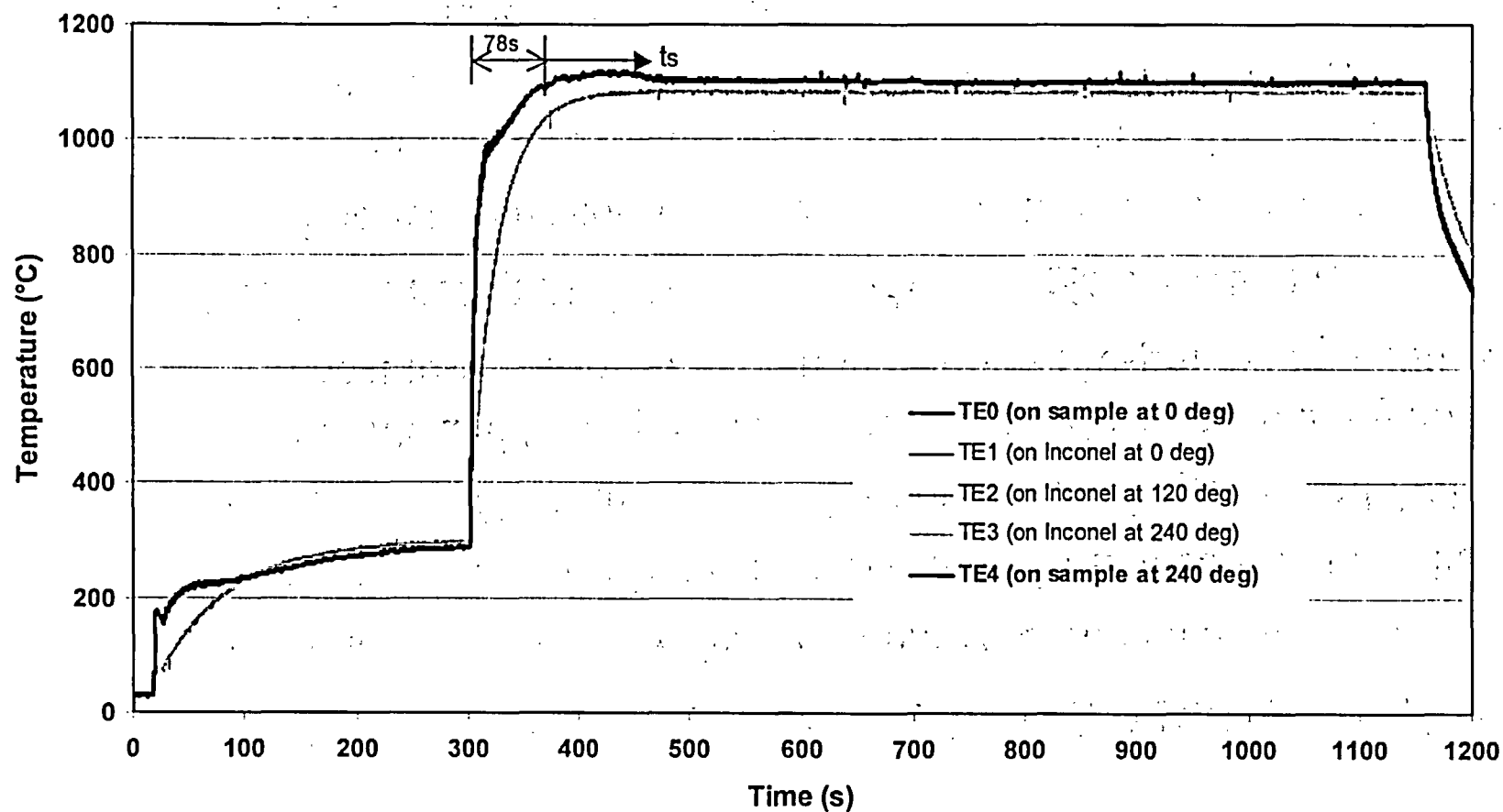
Advanced Alloy Post Quench Ductility Summary

- **Receipt of Cladding and Tubing**
 - June 2002 – June 2003
 - GNF 10×10 Zry-2 and F-ANP Zry-4 to be provided (???)
- **Verification and Validation Phase for Oxidation/Quench**
 - Two-sided oxidation of 25-mm-long samples
 - Thermal benchmarking, metallography, O & H determination (LECO)
 - Comparison of weight gain kinetics to CP-Model & published data
 - Ring compression tests: off-set displacement, H pickup, metallography
- **Data for (1000-1260°C) Oxidized/Quenched Samples**
 - Completed for all alloys oxidized at 1000°C and 1100°C to ≤20% ECR
 - Completed E110 study with emphasis on oxidation at 1000°C
 - 4-point-bending of LOCA Integral Test samples (ballooning, burst, hydriding), followed by local ring-compression tests (in progress)



Temperature History for Controlled Ramp to 1100°C

Thermal Benchmark Test (M5 Sample in Steam) at 1100°C Hold Temperature for 780s

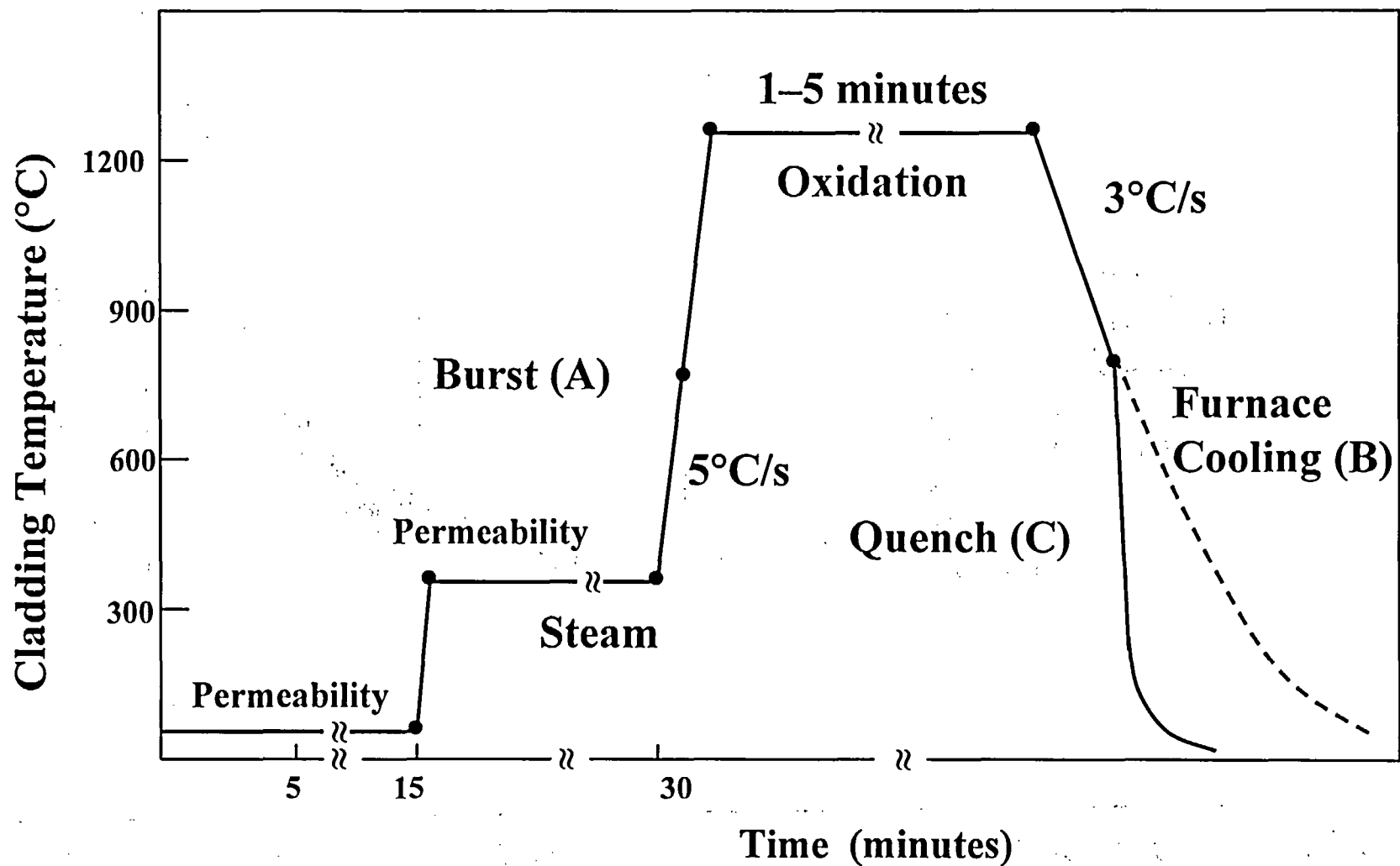


LOCA-Relevant High-Burnup Test Summary

- **Oxidation Kinetics Studies (1000°C, 1100°C, 1200°C)**
 - Limerick (10-μm oxide, 70-wppm H) completed (see NSRC papers)
No significant difference observed for irradiated vs. unirradiated Zry-2
 - Robinson (100-μm oxide, 750-wppm H) to begin in Fall 2003
 - If oxide and hydrogen have significant effect on weight gain kinetics, repeat tests for lower elevation samples (50-μm oxide, ≈400-wppm H)
- **LOCA Integral Tests (1204°C for ≤5 minutes)**
 - Limerick ramp-to-burst and oxidation tests completed (Sept. 2002)
Non-destructive results show more similarities than differences between unirradiated (with pellets) and irradiated (with fuel) Zry-2
Determination of axial profiles for H and O is in progress
 - Run Limerick test with quench (October 2003)
 - Initiate Robinson (100-μm oxide, 750-wppm H) tests in Fall 2003



LOCA Integral Test Sequence



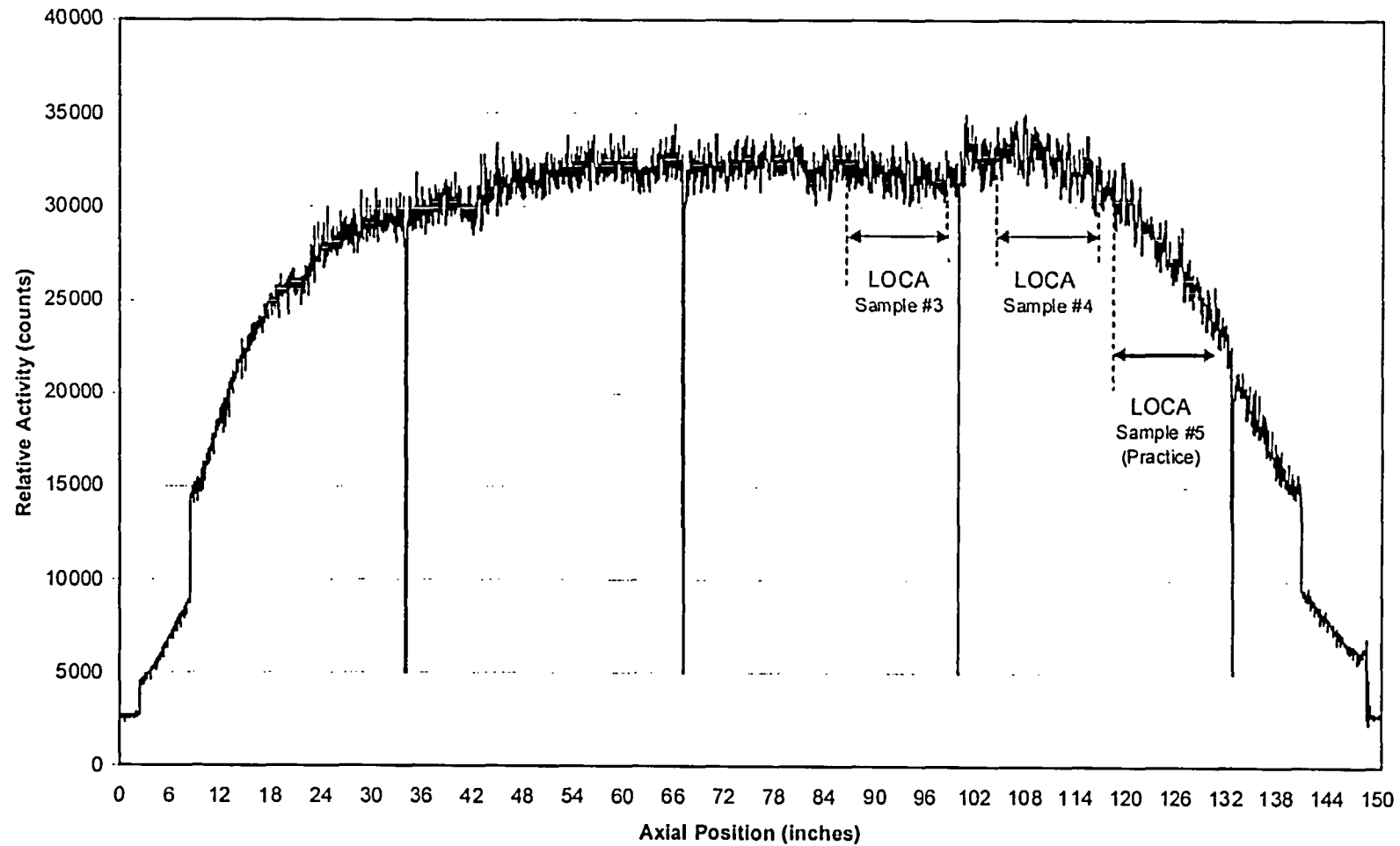
Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



Limerick BWR Samples for LOCA Next LOCA Tests

Limerick Rod J4



Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



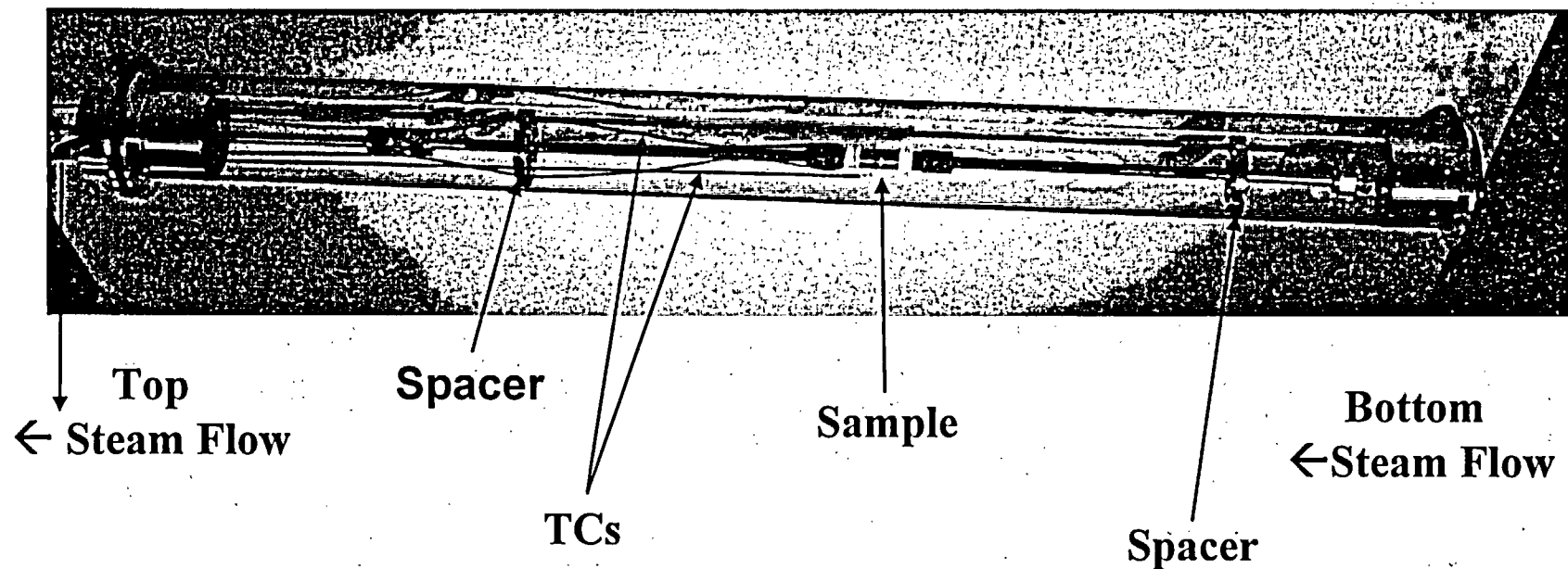
LOCA-Relevant High-Burnup Test Summary (Cont'd)

- **Post-Quench Tests with High-Burnup LOCA Specimens**
 - Four-point-bend test: uniform bending moment along ballooned-and-burst, ballooned, neck and beyond-neck regions
 - Local ring compression tests of neck and beyond-neck regions
 - Decrease test time (<5 min.) and ECR if both tests indicate nil-ductility
- **Additional Robinson LOCA Integral Tests**
 - Lower elevation samples with 50- μ m oxide layer and 400-wppm H
 - Consider running tests at lower hold temperature (e.g., 1100°C)
- **Number of Tests in Test Matrix**
 - ≥ 4 for Limerick (ramp-to-burst, 5-min.-oxidation, 2 with quench)
 - ≥ 6 for Robinson (all with quench, vary ECR, H-content, hold T)

Approach to Advanced-Alloy Post-Quench Ductility Tests

- **Oxidize Alloys for Same Test Times to $\leq 20\%$ ECR (0.57-mm Wall and Cathcart-Pawel WG Model) and Quench**
 - ≤ 3400 s (1000°C), ≤ 1100 s (1100°C), ≤ 400 s (1200°C), ≤ 230 s (1260°C)
- **Determine “Measured” ECR Based on Weight Gain**
- **Oxidation Kinetics and Post-Quench Ductility Data**
 - Compare results for ZIRLO and M5 to Zry-4 (and Zry-2) data
- **Explore Factors that may Contribute to E110 Behavior**
 - Confirm poor post-quench ductility performance at low test times (ECRs)
 - Explore effects of surface roughness and chemistry on oxide instability
 - Characterize: bulk chemistry, metallography, SEM, TEM

Steam Oxidation Test Train with Quartz Tube

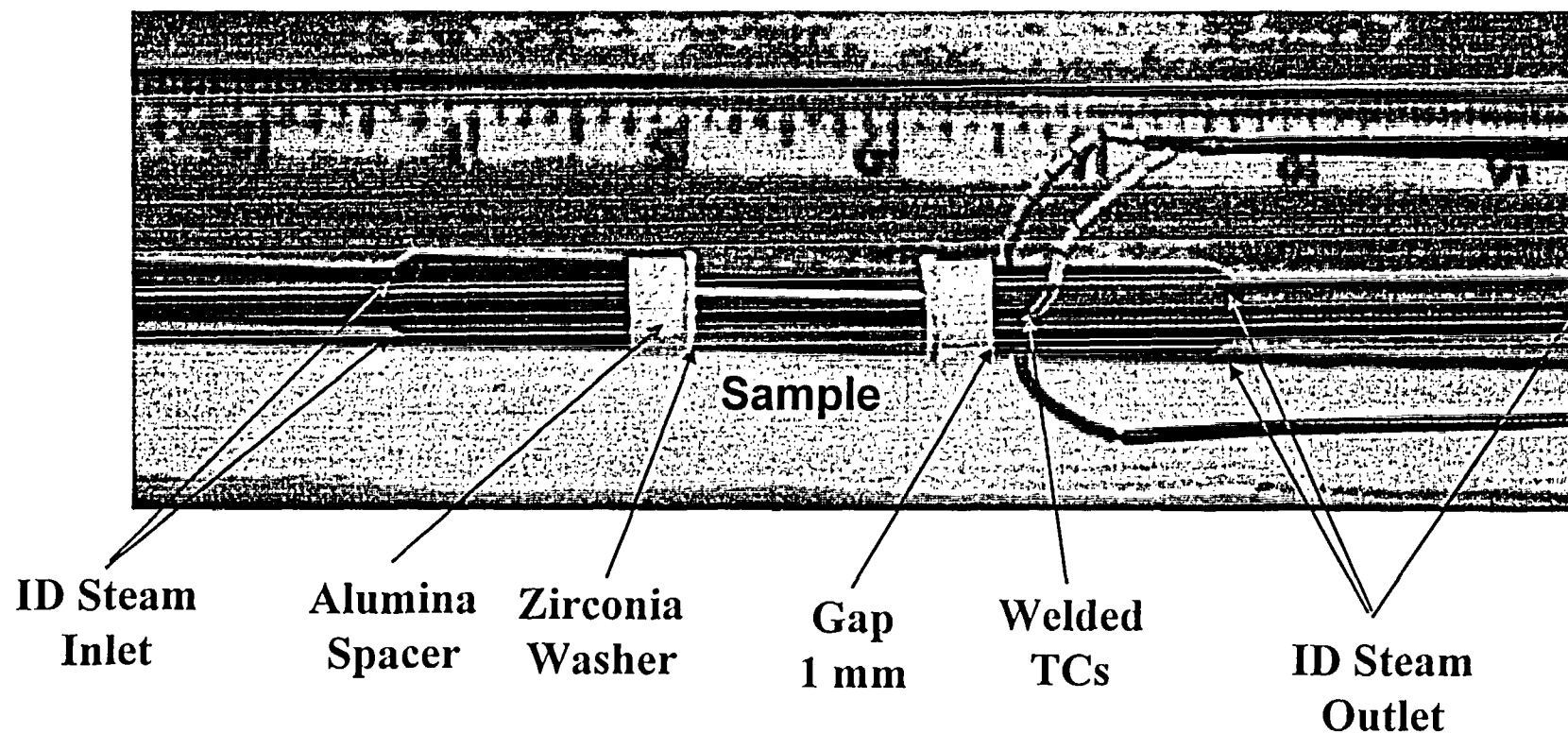


Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



Two-Sided Steam Oxidation Test Train



Pioneering
Science and
Technology

Nuclear
Regulatory
Commission

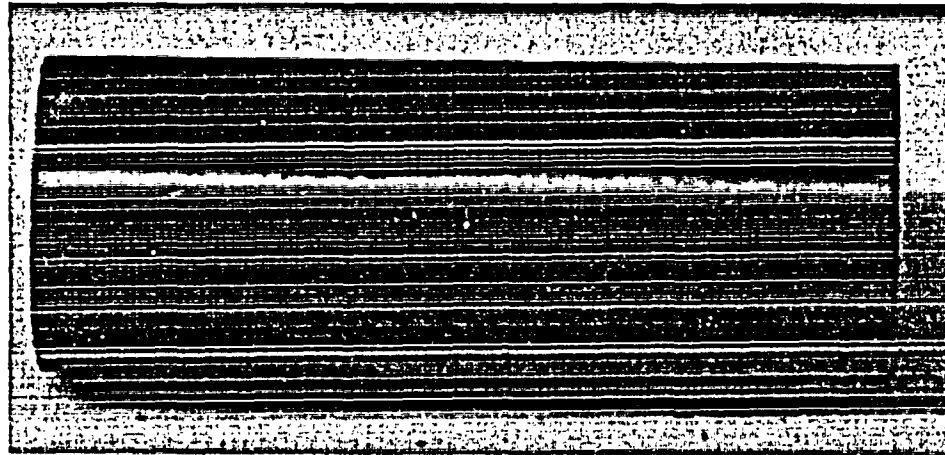


Embrittlement Mechanisms

- **Protective Oxide Layers: Lustrous Black, Tetragonal, ZrO_{2-x}**
 - Thinning of effective ductile (prior-beta layer) with t at T , WG and ECR
 - Increase in oxygen content in prior-beta layer with increasing T
 - Effect of hydrogen from in-reactor corrosion; LOCA ballooning/burst
- **Classical Breakaway Oxidation for Zry-4 and M5**
 - Black (tetragonal)-to-white (monoclinic) transition on outer oxide surface
 - Increase in oxygen pickup rate; possibly hydrogen uptake
 - Generally not within LOCA-relevant times (e.g., after 3 h at 1000°C)
- **Nodular Breakaway Oxidation for E110**
 - Local enhancement of oxidation rate (e.g., E110 at 1100°C)
 - Local enhancement of hydrogen uptake (e.g., E110 at 1100°C)
 - Global enhancement of O and H uptake (e.g., E110 at 1000°C)

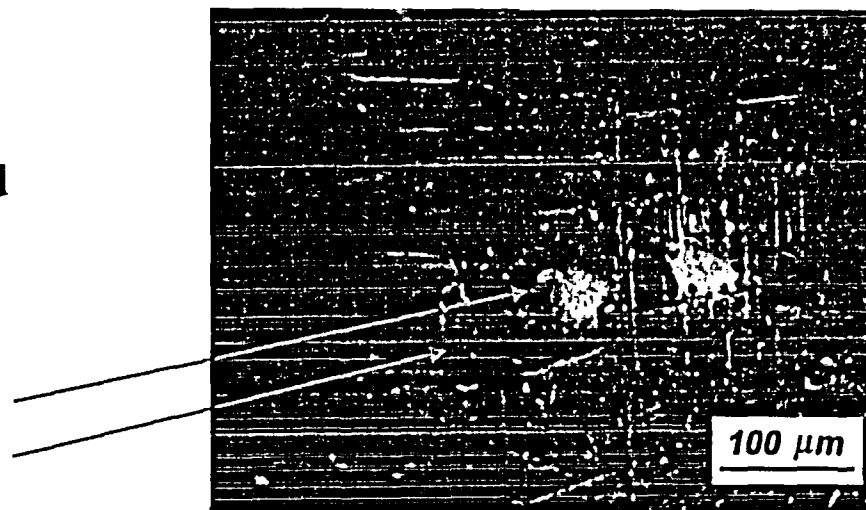
Protective Lustrous Black Oxide Layers

Zry-4
After 868 s (18% ECR)
in Steam at 1100°C



E110
After 75-s Ramp/5-s Hold
in Steam at 1000°C
(high magnification)

White Spots in
Lustrous Black Matrix



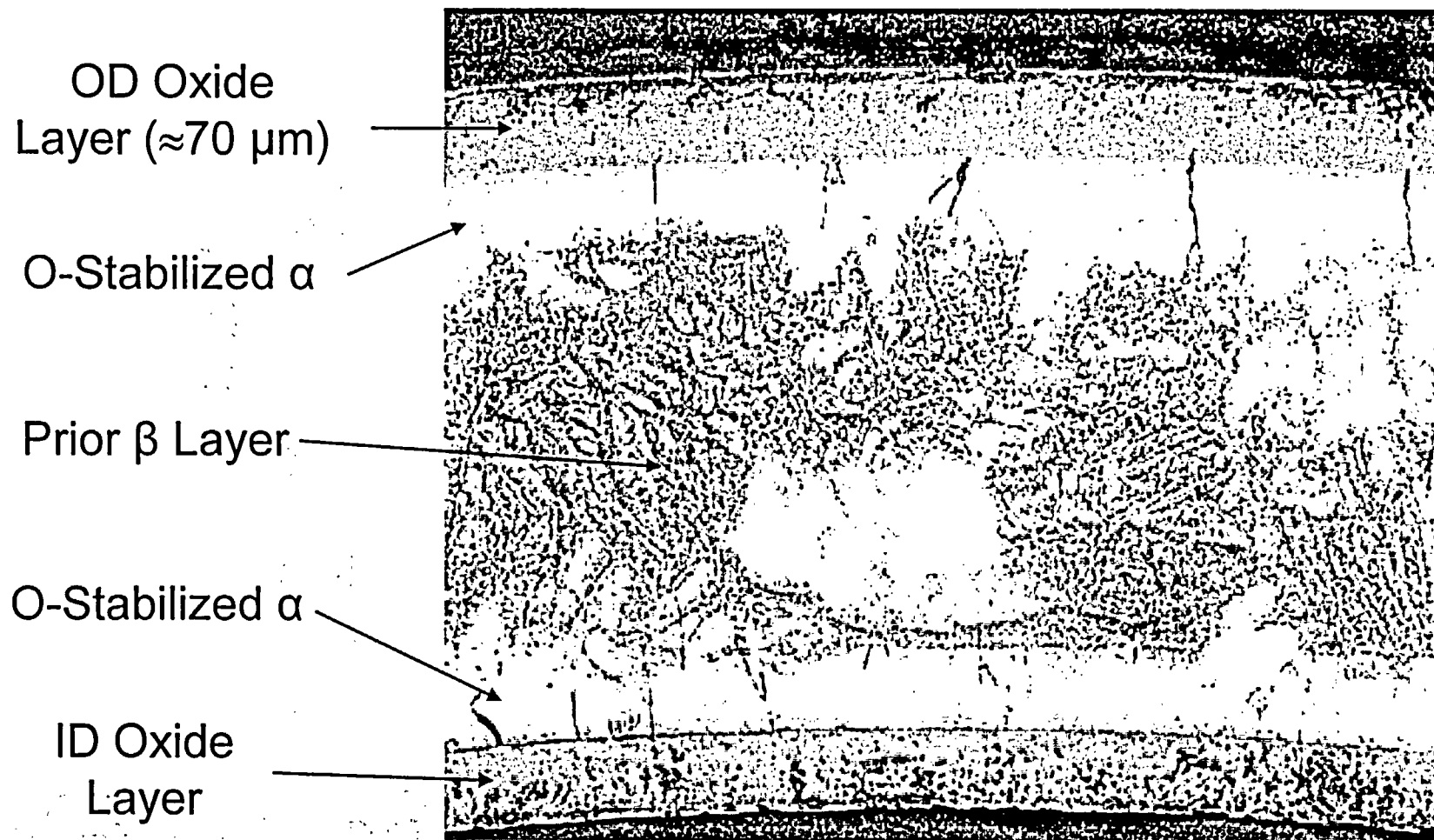
Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



High Magnification of Protective Oxide Layers

Zry-4, 1100°C for 868 s, 18% ECR, $\Delta H = 8$ wppm

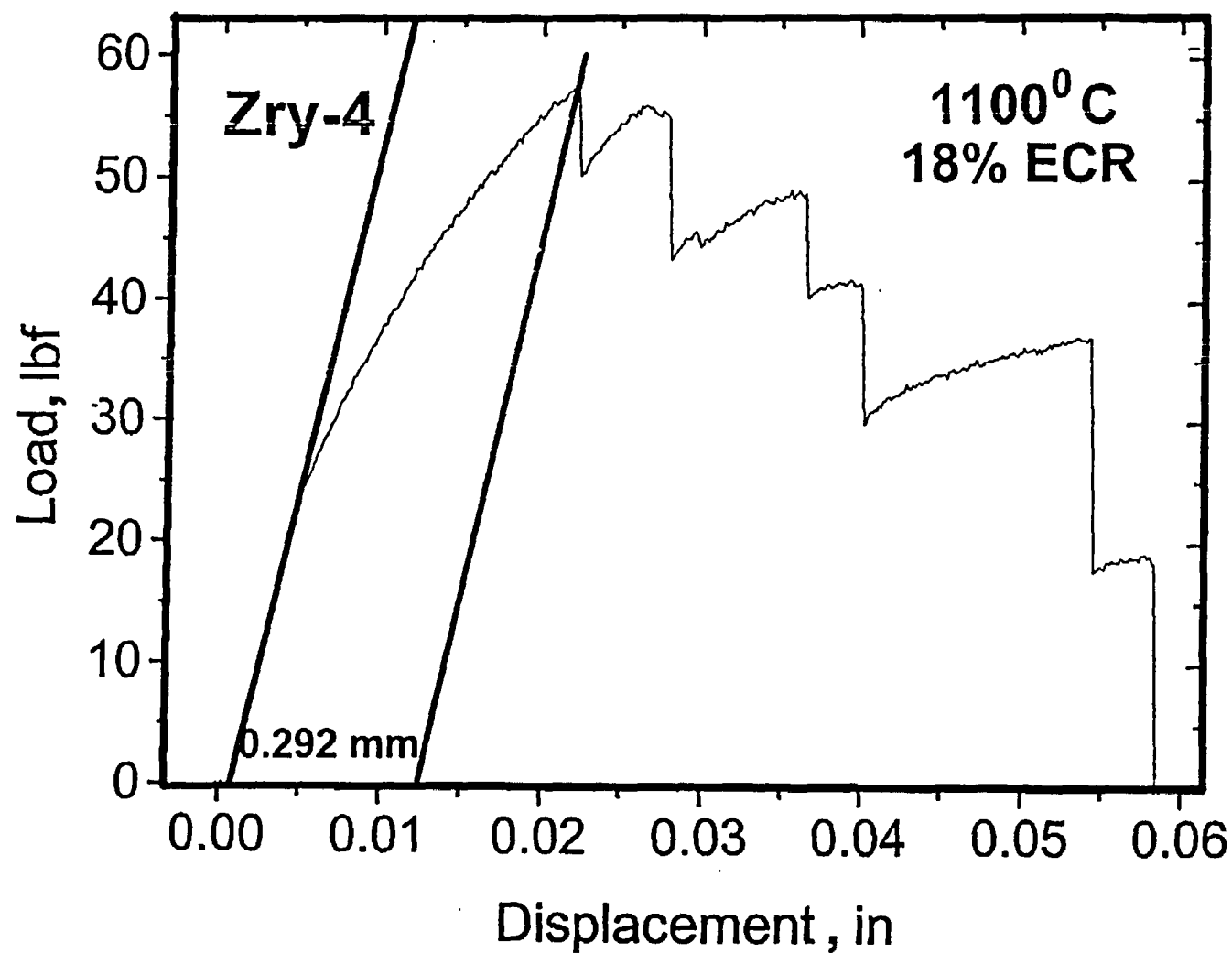


Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



Zry-4 Ring-Compression Results after 18%ECR at 1100°C

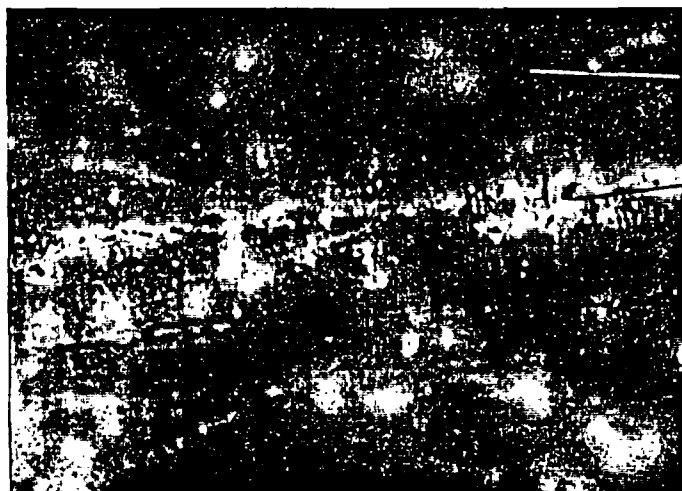


Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



Nodular Breakaway Oxidation in E110 at 1100°C



1100°C for ≈ 2500 s
(1-sided)
200 wppm H



Black Oxide
Tetragonal
 ZrO_{2-x}

White Oxide
Monoclinic
Near- ZrO_2

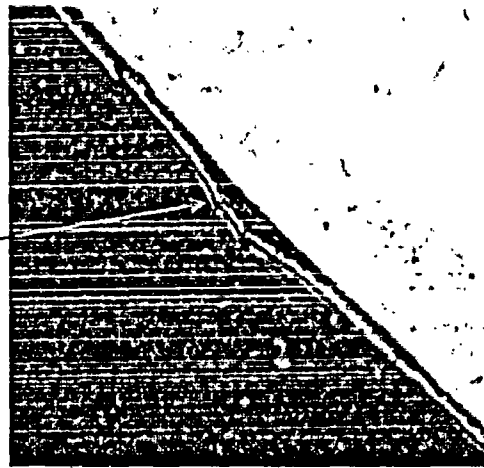
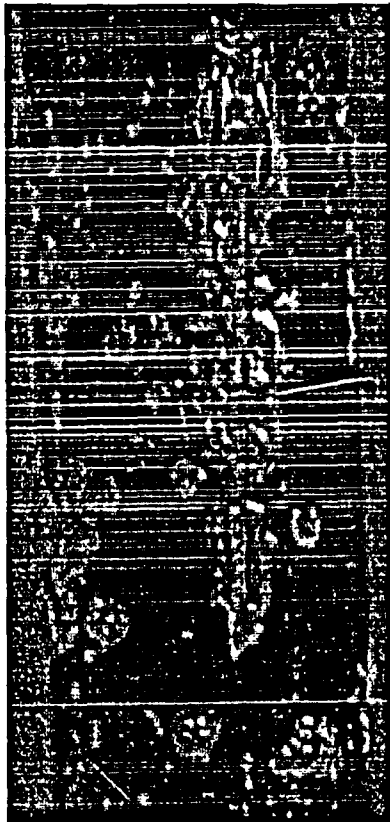


Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



E110 after 300 s and 1400 s at 1000°C



Delaminated
Oxide Layer
after 300 s

5% ECR
 ≈ 300 s
 120 ± 50 wppm H



10% ECR
 ≈ 1400 s
 > 4000 wppm H



Pioneering
Science and
Technology

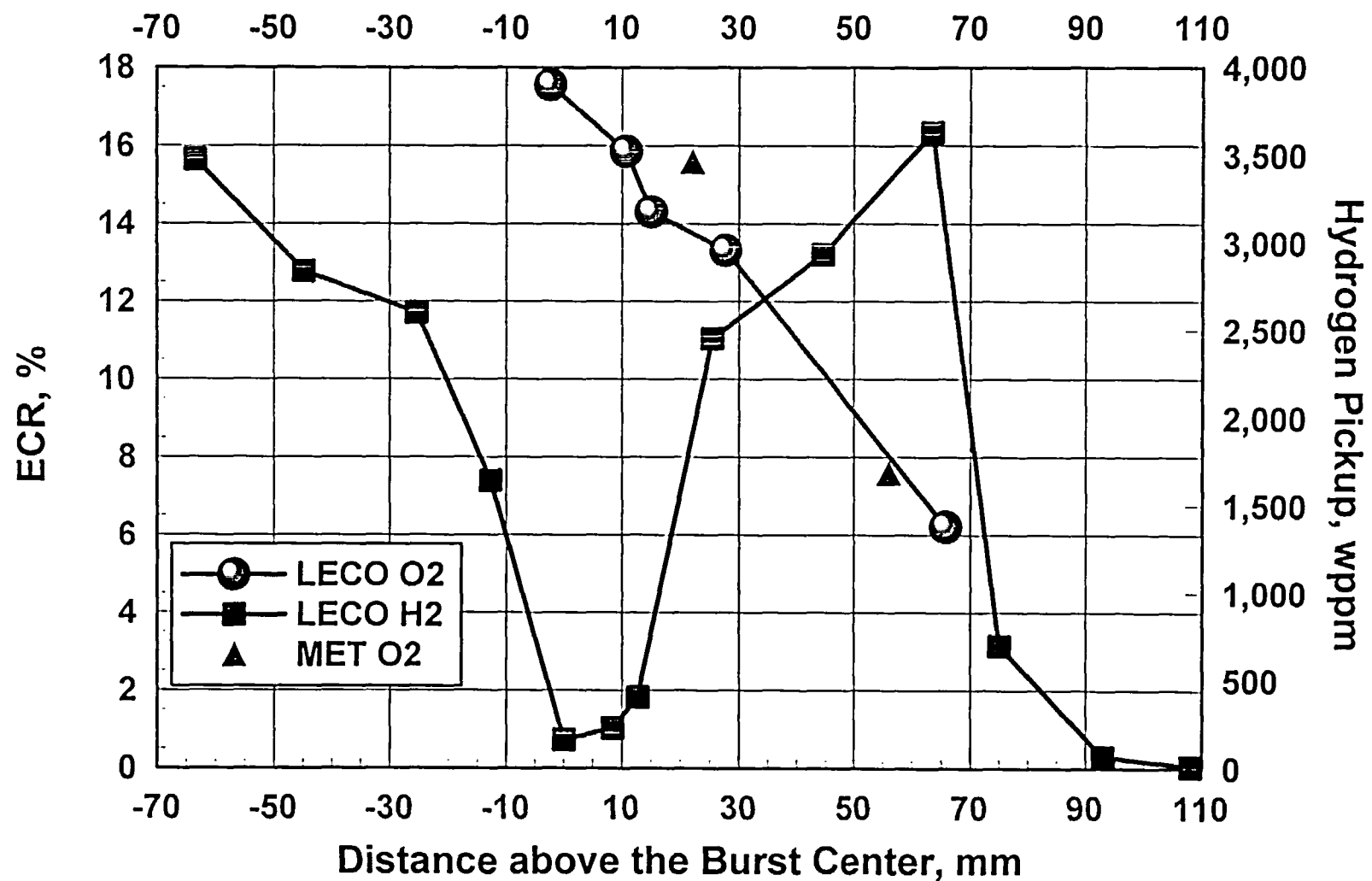
Nuclear
Regulatory
Commission



Post-Quench-Ductility Test Methods

- **Ring Compression Tests on Undeformed Samples**
 - RT screening tests at 2 mm/min (0.35%/s) for 8-mm-long rings
 - Measure off-set displacement (δ_p) vs. ECR (5, 10, 15, 17, 20%)
 - Convert to “nominal” strain ($\epsilon = \delta_p/D_o$) vs. ECR
 - For alloys that embrittle at <17% ECR, repeat test at 135°C
- **4-Point-Bend Tests following LOCA Integral Tests**
 - Potential failure locations and modes under uniform bending moment
 - Burst region: thin, flawed cladding; high ECR, O-embrittlement
 - Neck region: thick, unflawed cladding, low ECR, H-embrittlement
- **Ring Compression Tests for Neck-and-Beyond Regions**
- **Testing of Pre-Hydrated Cladding (Phase 2) and High-Burnup Cladding (Phase 3) would Yield Valuable Data**

LOCA Integral Test Results for Zry-2: 1200°C for 5 Min.



Pioneering
Science and
Technology

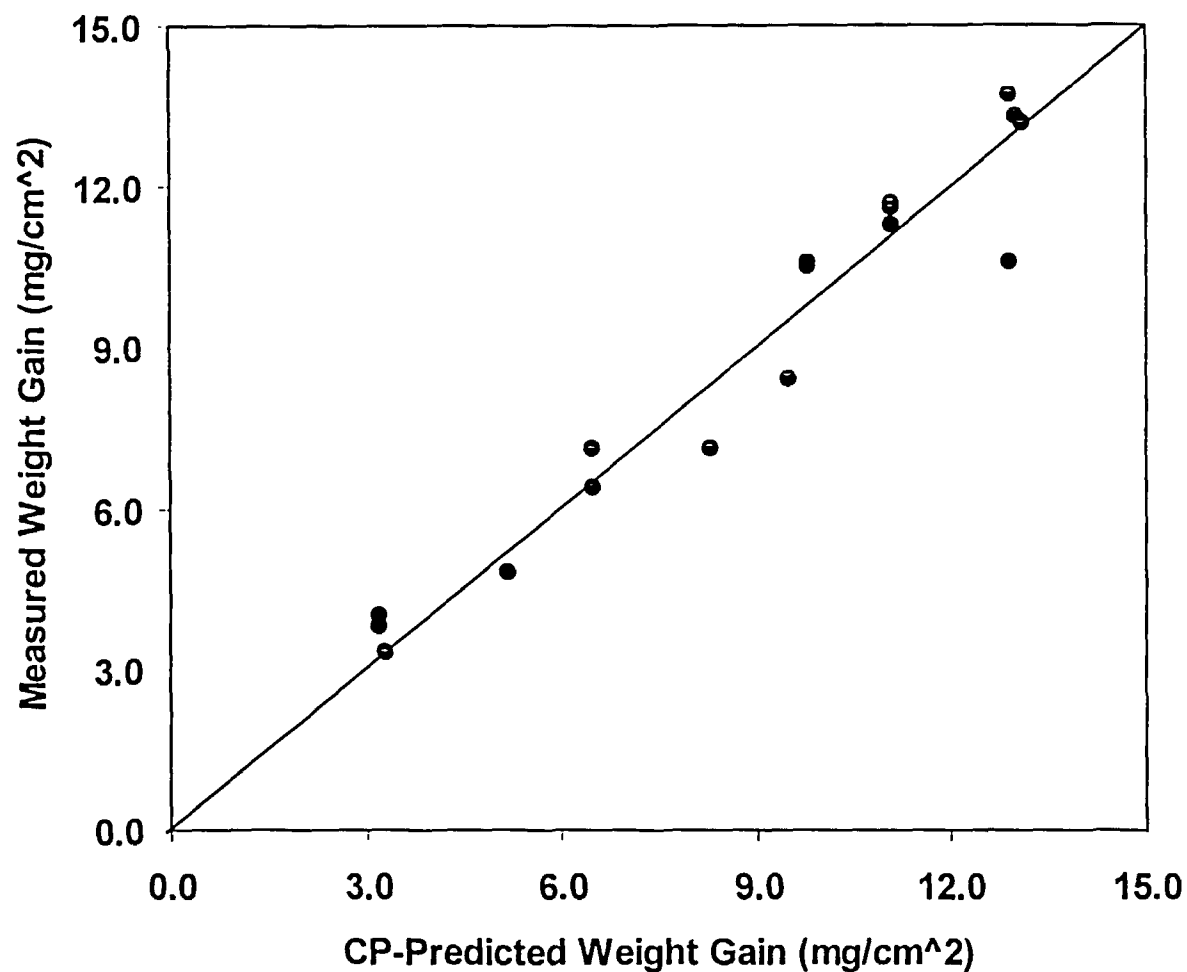
Nuclear
Regulatory
Commission



Weight Gain Kinetics for Advanced-Alloy Program

- **Weight Gain Kinetics at 1100°C**
 - Zry-4, M5 and ZIRLO data are in agreement with Cathcart-Pawel (CP) model predictions (within $\approx \pm 10\%$)
 - Could not get meaningful data from as-received E110 (oxide instability)
 - Data for machined-and-polished E110 agrees well with data for other alloys up to point of E110 oxide instability
- **Weight Gain Kinetics at 1000°C**
 - Zry-4 and ZIRLO have similar weight gain kinetics; M5 is lower
 - Meaningful data for machined-and-polished E110 up to oxide instability
 - M5 and polished E110 have similar weight gain (WG) kinetics
- **Tests at 1200°C and 1260°C are in Progress**
- **No Effects of Quench at 800°C on Weight Gain**

ANL Weight Gain Data for All Alloys at 1100°C



Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



Post-Quench-Ductility Data for Zry-4, ZIRLO, and M5

T °C	CP ECR %	Material	Measured ECR %	δ_p mm	δ_p/D_o %	ΔH wppm	Met.
1100	20	Zry-4	20.3	0.455	4.8	19	*
		ZIRLO	21.1	0.318	3.3	18	*
		M5	19.2	0.170	1.8	12	*
1000	20	Zry-4	22.5	≈ 0.36	≈ 3.8	*	*
		ZIRLO	18.0	≈ 0.27	≈ 2.8	*	*
		M5	13.4	≈ 0.31	≈ 3.3	*	*

*In progress



Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



Summary of E110 Results

- **Instability of Oxide Layer Confirmed at Low Test Times**
 - Alloy is more “challenged” at 1000°C than at 1100°C
 - 1100°C: *nodular oxidation* → *oxygen + hydrogen embrittlement*
 - 1000°C: *delamination/spallation* → *hydrogen embrittlement*
 - Performance at 950°C appears worse than at 1000°C
 - Roughness, grooves, TCs, ends are initiation sites for oxide transition (black to white) and instability: disturbance of compressive stress field
- **Studies of Surface Roughness and Surface Chemistry**
 - Surface polishing significantly improves E110 oxidation performance
 - Etching (HF+HNO₃+H₂O), polishing/etching, and etching/polishing
 - Etching as-received E110 significantly degrades initial oxide (due to F)
- **Bulk Chemistry, Metallography, SEM, TEM Results**
 - In progress: indication of non uniform distribution of Nb-particles



Advanced-Alloy Post-Quench-Ductility Results

- **Current Oxidation/Quench Study: As-Received Cladding**
 - Basically oxygen-induced embrittlement of Zry-4, ZIRLO, and M5
 - All 3 alloys retain ductility at 1000°C and 1100°C up to 20% ECR
 - Based on ring compression data, hydrogen pickup and metallography
 - H- and O-induced embrittlement of E110 confirmed at 1000-1100°C
- **Ductility Tests of Post-Quench LOCA Integral Test Samples**
 - LOCA Integral Tests are in progress (1 per alloy per T at $\leq 17\%$ ECR)
 - RT four-point-bend tests will follow sample preparation
 - Local (neck-and-beyond) ring-compression tests will follow bend tests
 - Hydrogen concentration will be measured on ring-compression samples that exhibit low or nil-ductility

LOCA Integral Test Results for Limerick Zry-2

- **Temperature History**

- Stabilize at 300°C and 1200 psig (8.3 MPa) internal pressure
- Ramp at 5°C/s through ballooning & burst to 1204°C
- Hold for 1-10 minutes, cool to 800°C at 3°C/s and quench

- **Detailed Examinations**

- Profilometry, metallography, H&O determination
- 4-Point-Bend Tests & Ring-Compression Tests (in progress)

- **Results of Post-Quench-Ductility Demonstration Tests**

- Brittle failure of 10-min. sample (30% measured ECR) in burst region at 100°C following quench due to dead weight loading
- Brittle failure of 5-min. sample (18% ECR) during bending tests

Bending with burst region under tension: burst region failure

Bending with burst region under compression: neck region failure

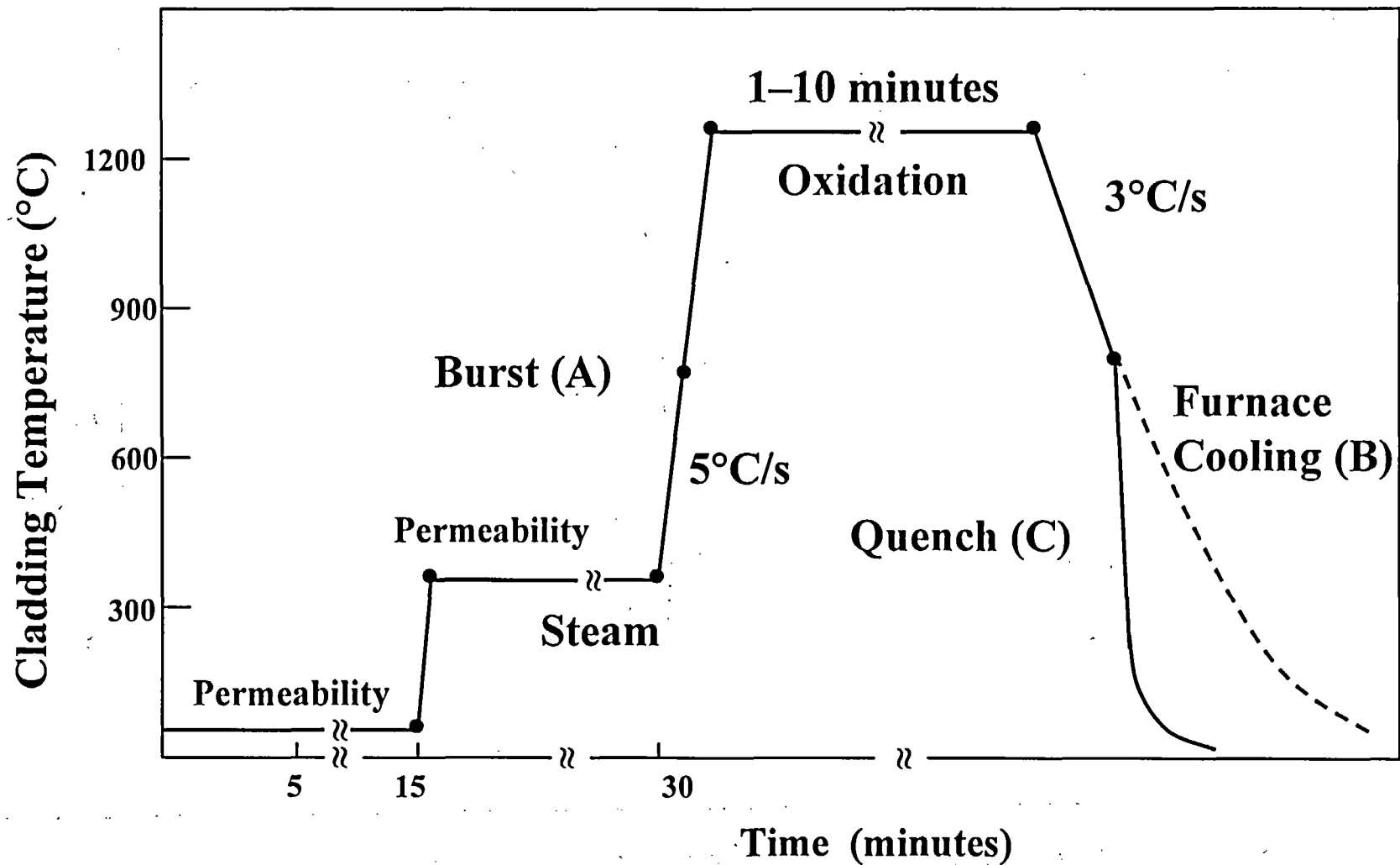


Pioneering
Science and
Technology

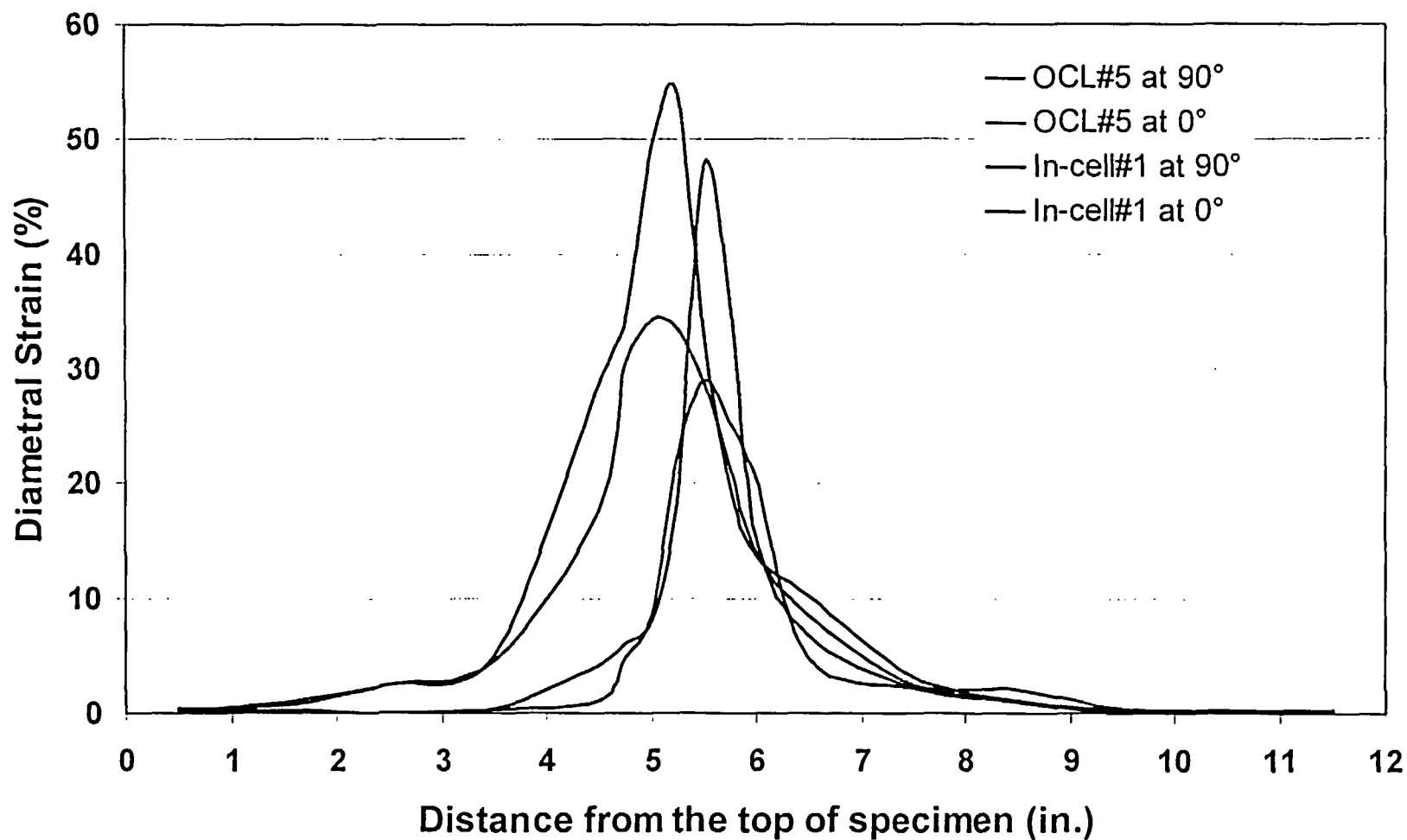
Nuclear
Regulatory
Commission



LOCA Integral Test Sequence



Profilometry Results for ICL#1 vs. OCL#5

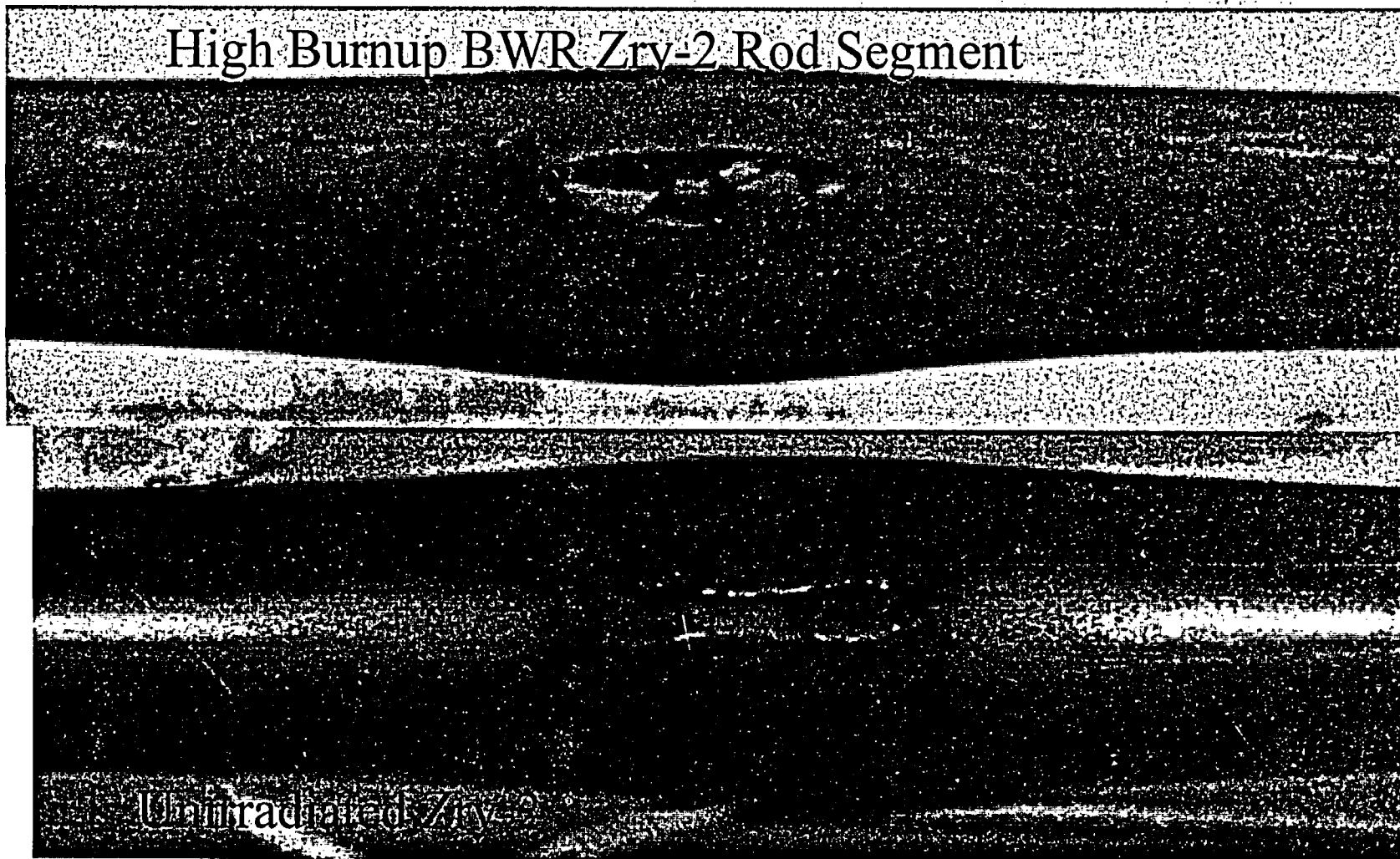


Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



Ramp-to-Burst Opening Comparison

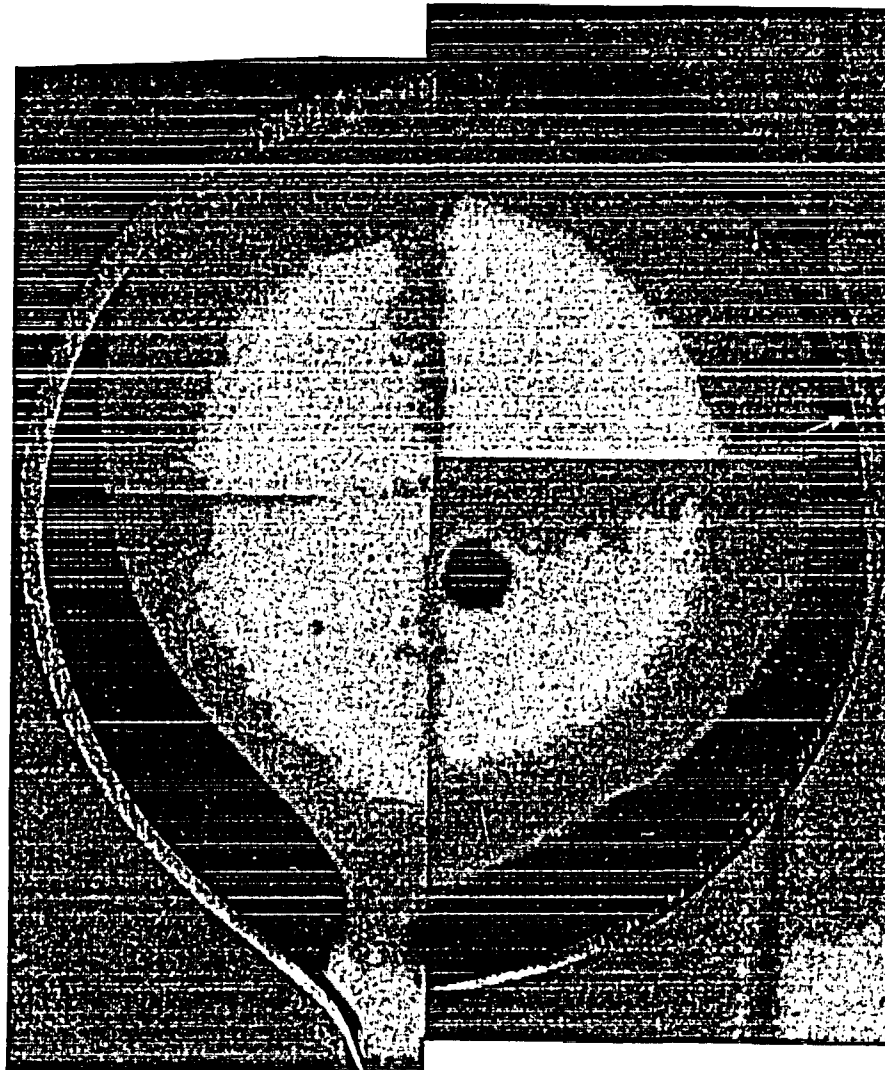


Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



Burst Cross-section: Unirradiated, Unoxidized Zry-2



h

OCL#8

$$\Delta C/C_o = 60\%$$

$$\Delta h/h_o = -39\%$$

C = average
circumference

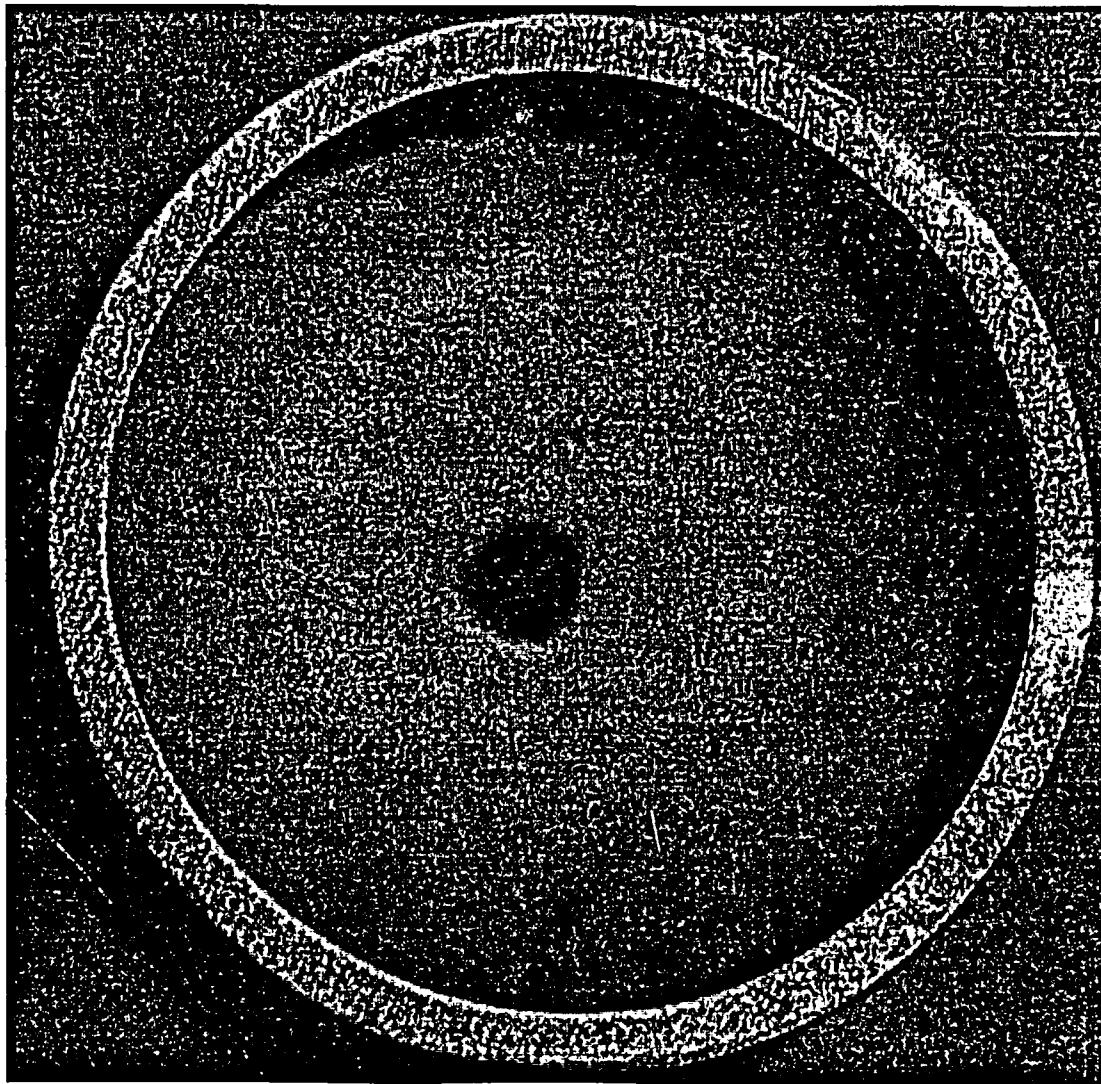


Pioneering
Science and
Technology

Nuclear
Regulatory
Commission

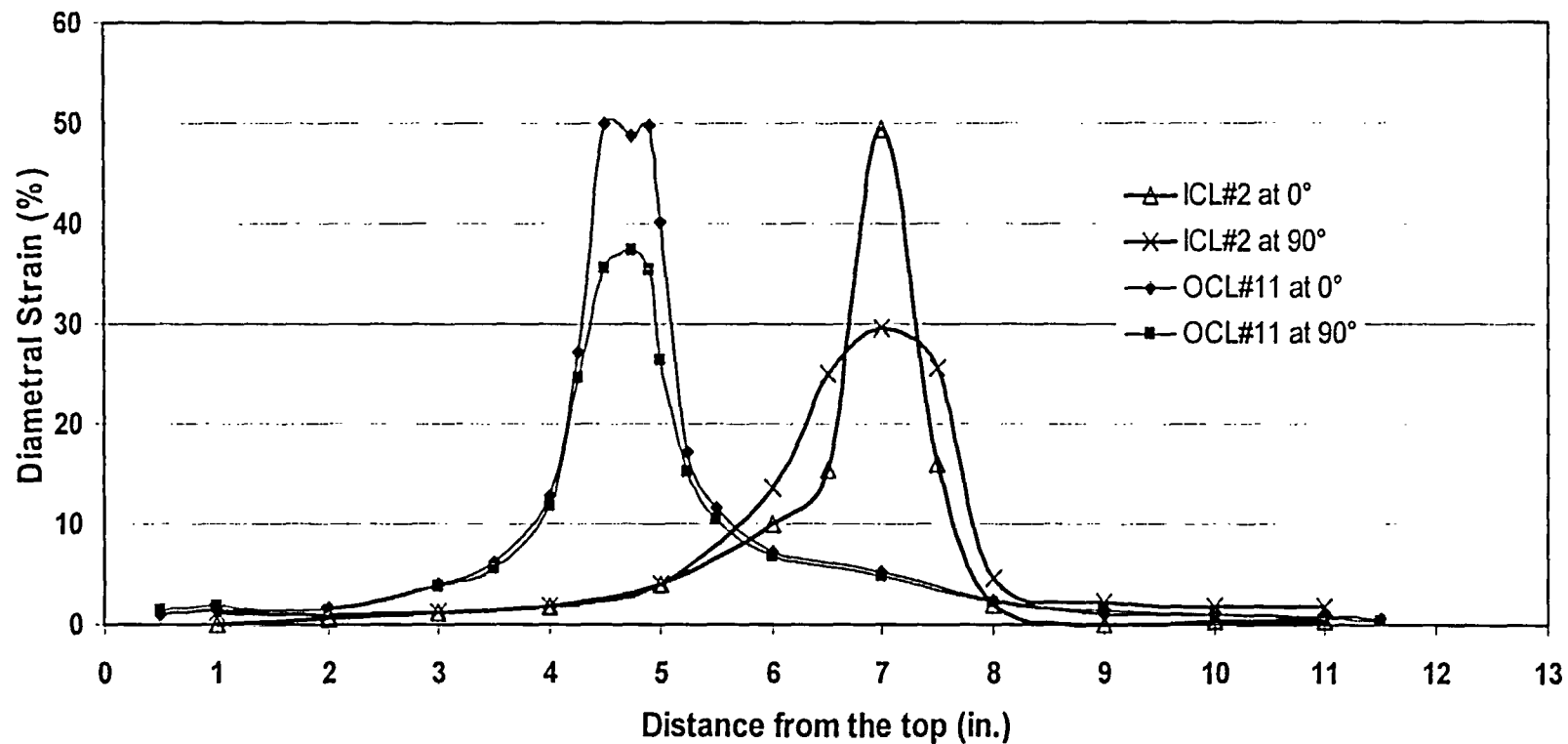


Neck Cross-section: Unirradiated, Unoxidized Zry-2



OCL#8
 $\Delta C/C_o = 6\%$
 $\Delta h/h_o = -6\%$

PROFILOMETRY ICL#2 and OCL#11 Specimens

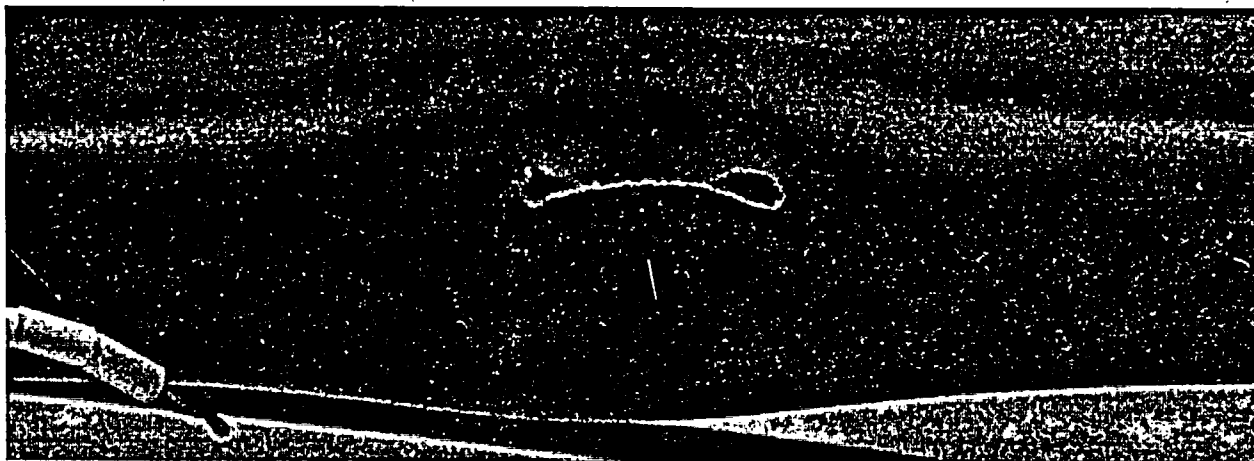
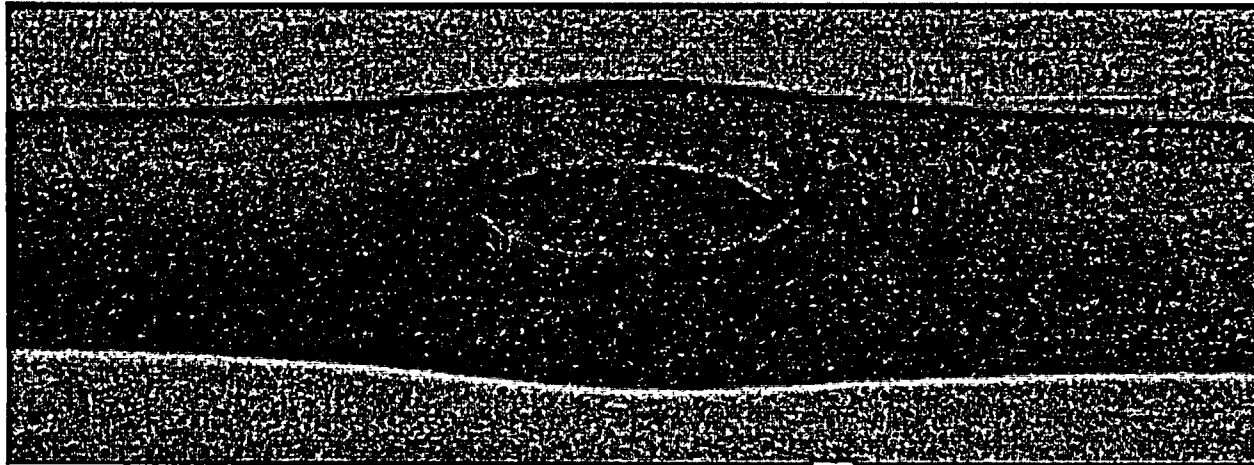


Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



Comparison of Burst Openings for ICL#2 and OCL#11

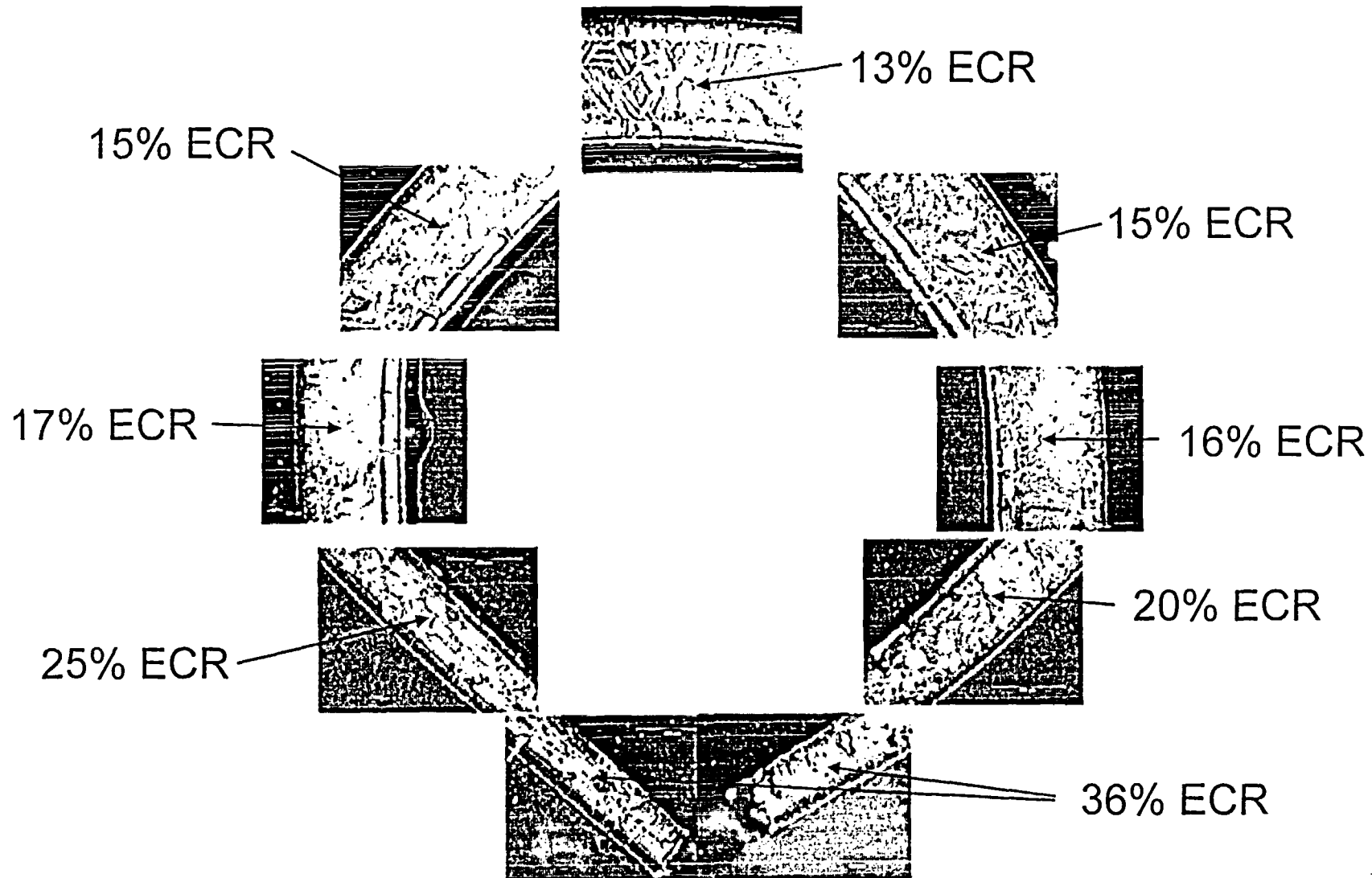


Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



OCL#11 Burst Cross-Section: 1204°C, 5 min., 18% ECR

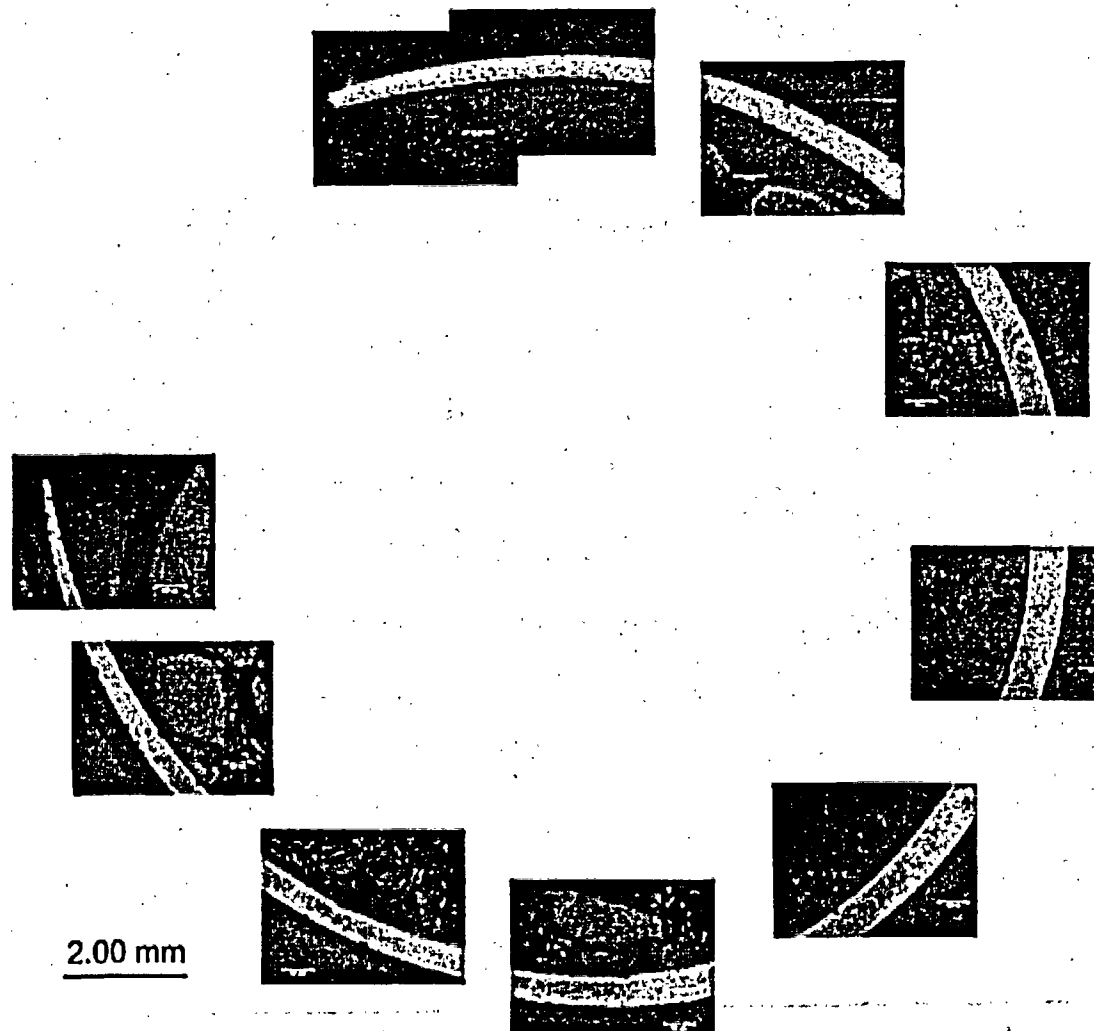


Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



Burst Cross-Section for High-Burnup ICL#2 Test

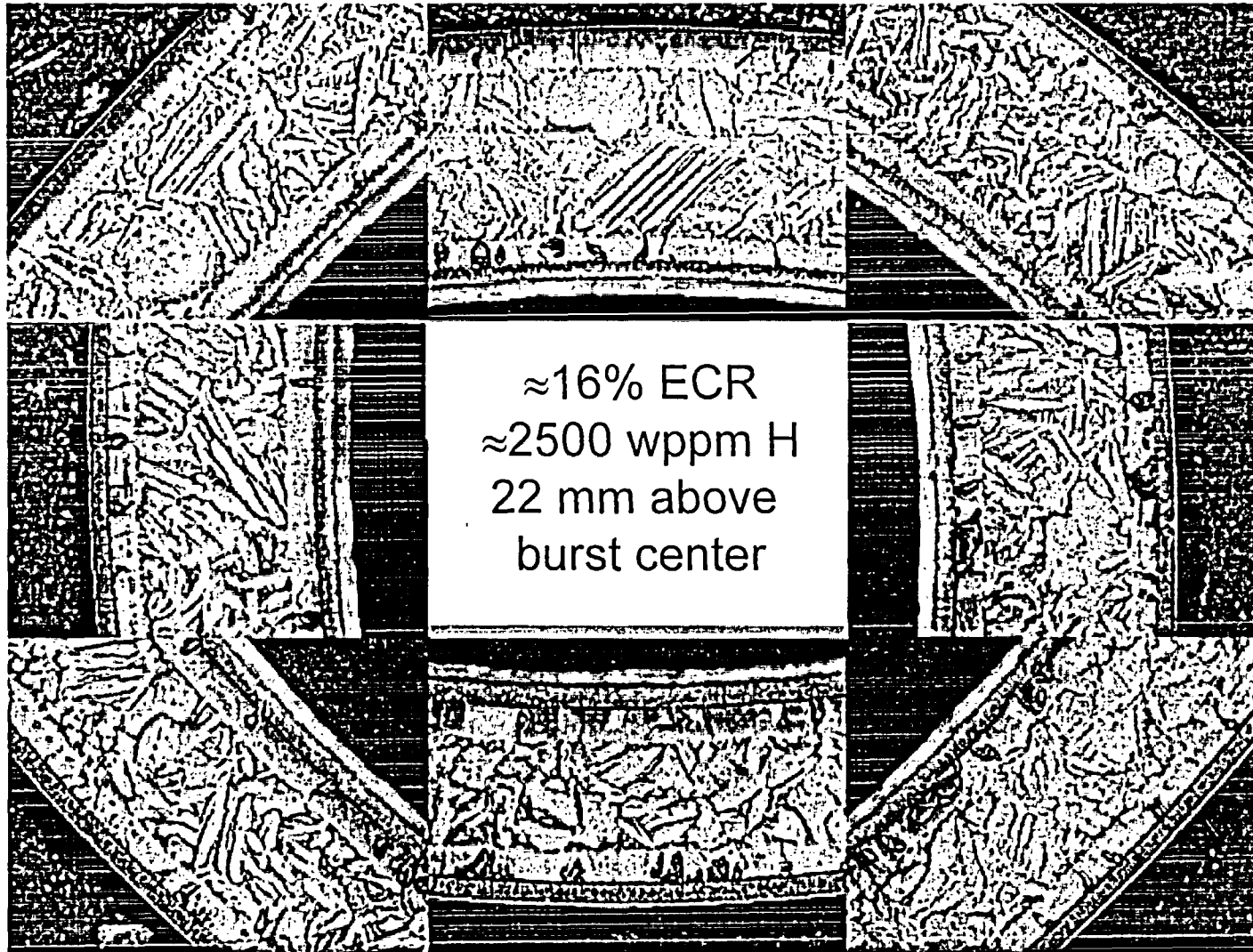


Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



OCL#11 Balloon Region: 1204°C, 5 min., 16% ECR

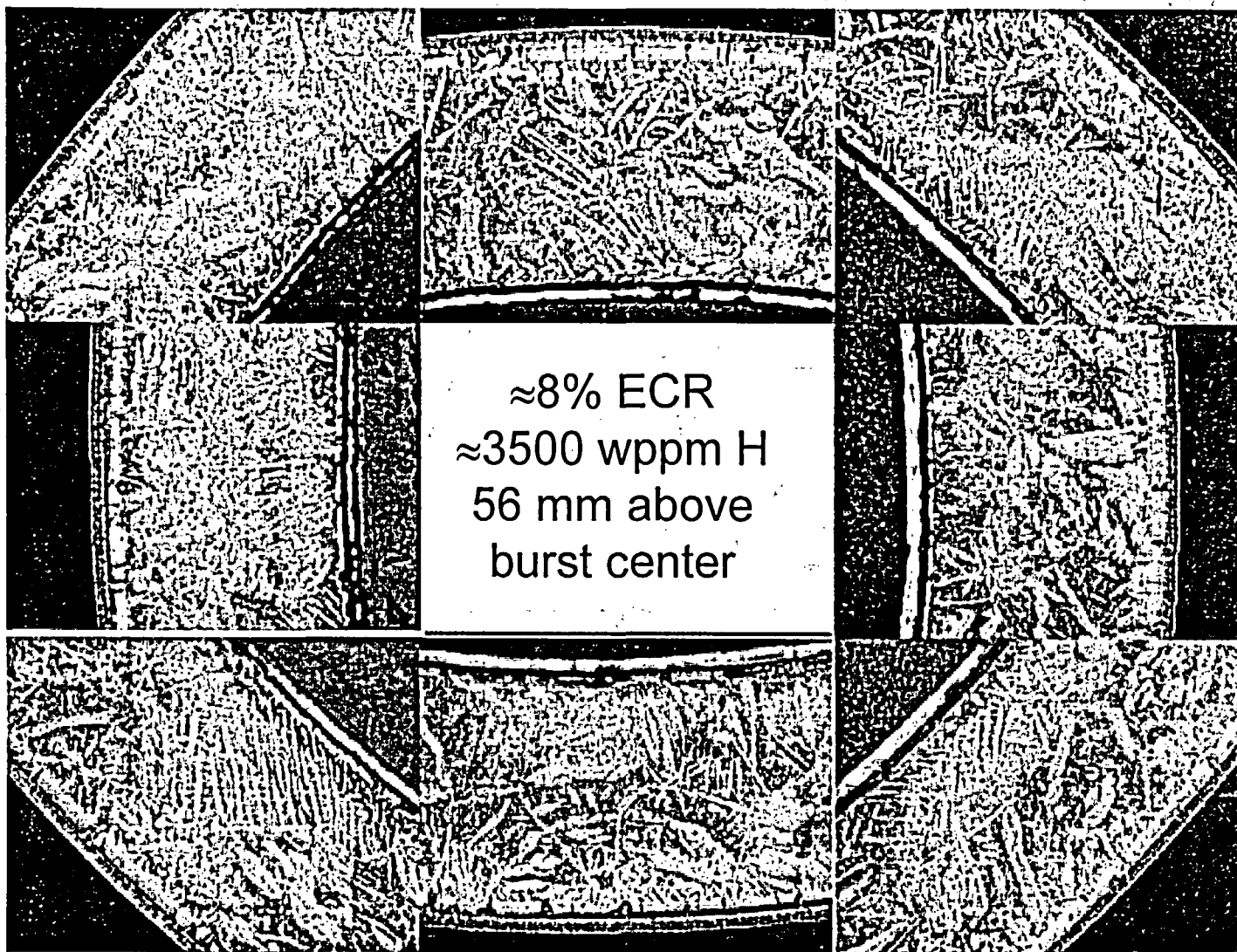


Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



OCL#11 Neck Cross-section: 1204°C, 5 min., 8% ECR

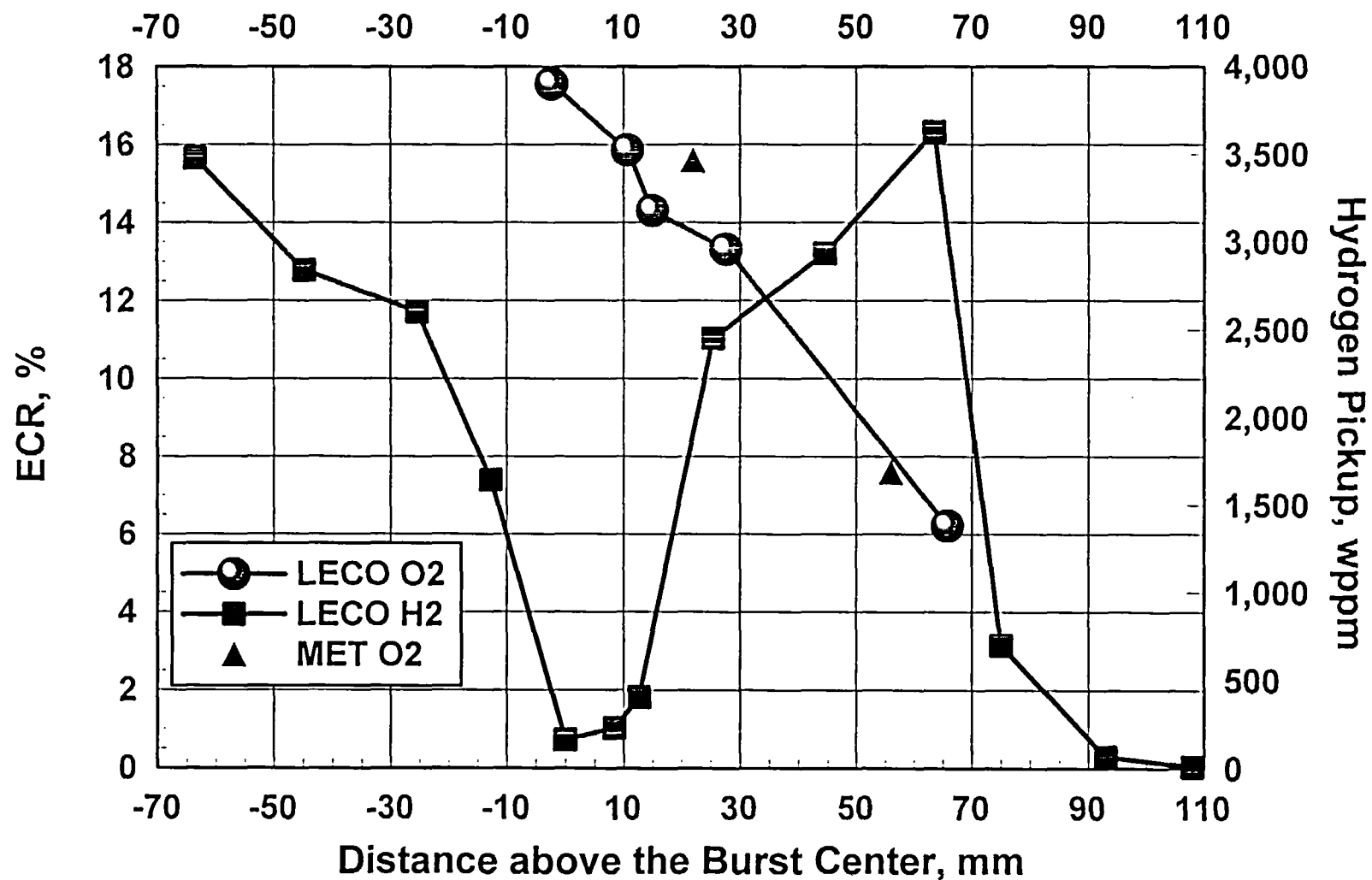


Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



LOCA Integral Test Results for Zry-2: 1200°C for 5 Min.



Pioneering
Science and
Technology

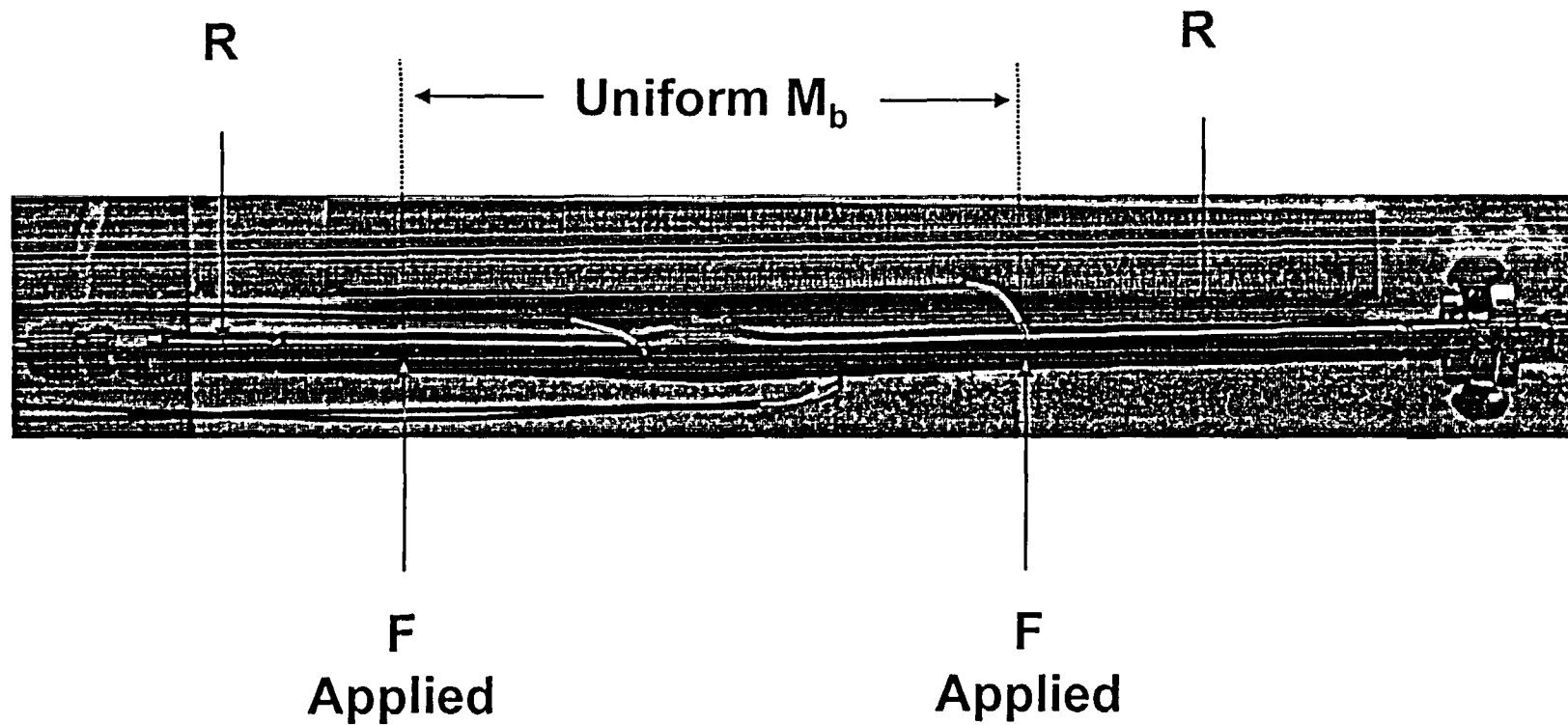
Nuclear
Regulatory
Commission



Four-Point-Bend Demonstration Results

- **OCL#11 “Sibling” Samples**
 - Samples were “rejects” because of T-history oscillations
 - ECR and H distributions are “nominally” those of OCL#11
- **1st 4-Point-Bend Demo (June 16, 2003 – OCL#7)**
 - 267 mm of zirconia pellets (each 25-mm long) left inside cladding
 - Uniform bending moment applied along high ECR and H regions
 - Nominal axial tensile stress aligned with burst opening
 - Sample “snapped” cleanly across high-ECR/thin-wall burst region
- **2nd 4-Point-Bend Demo (July 16, 2003 – OCL#5-1)**
 - Zirconia pellets removed from sample
 - Burst region under nominal axial compression (180° sample rotation)
 - Axial cracks initiated at burst opening ends; extended to high H region
 - Sample failed across high H & O region, ≈ 17 mm from burst center

4-Point-Bend Demonstration Burst Area under Tension

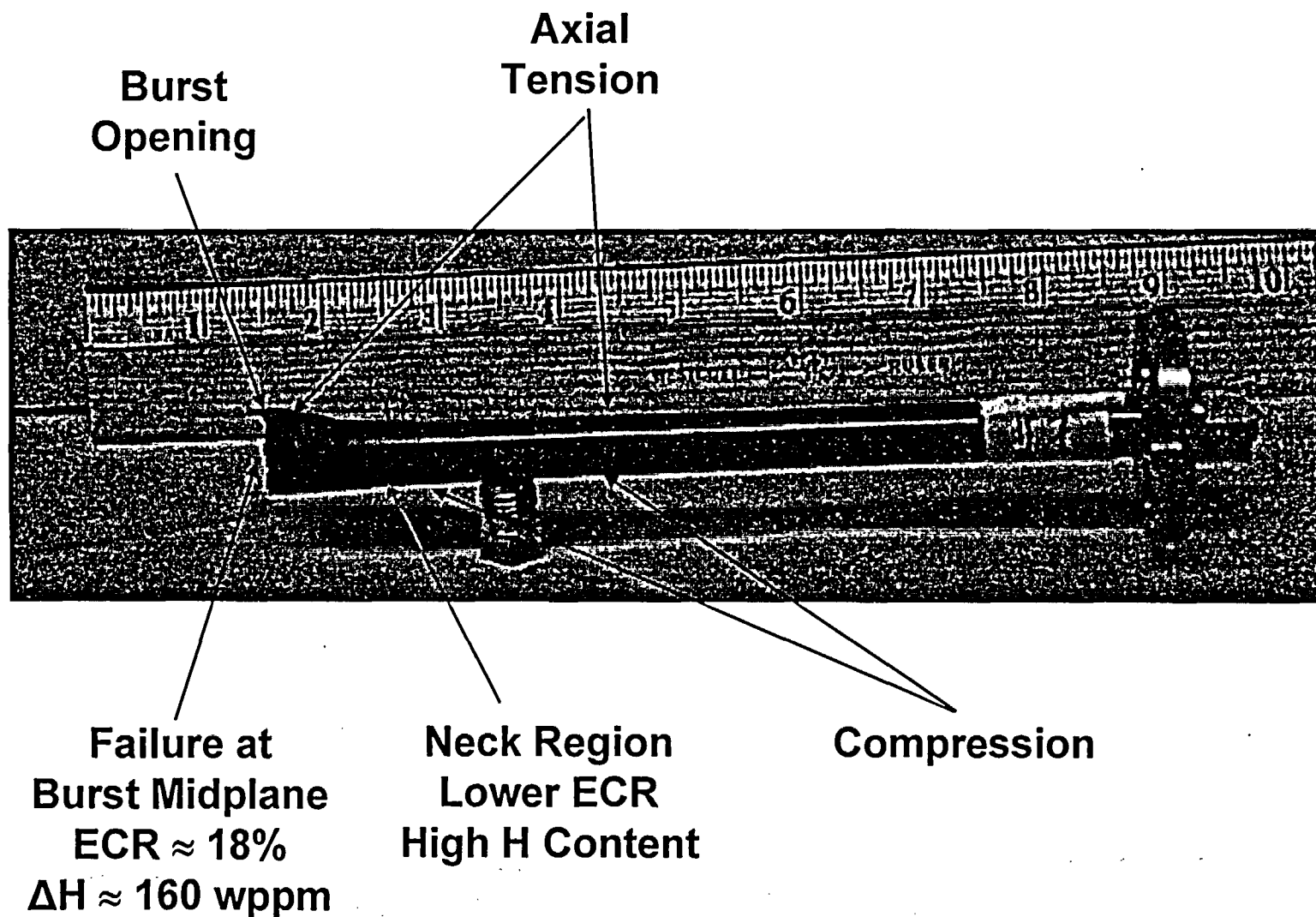


Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



June 16, 2003 4-Point-Bend Demo Results (OCL#7)

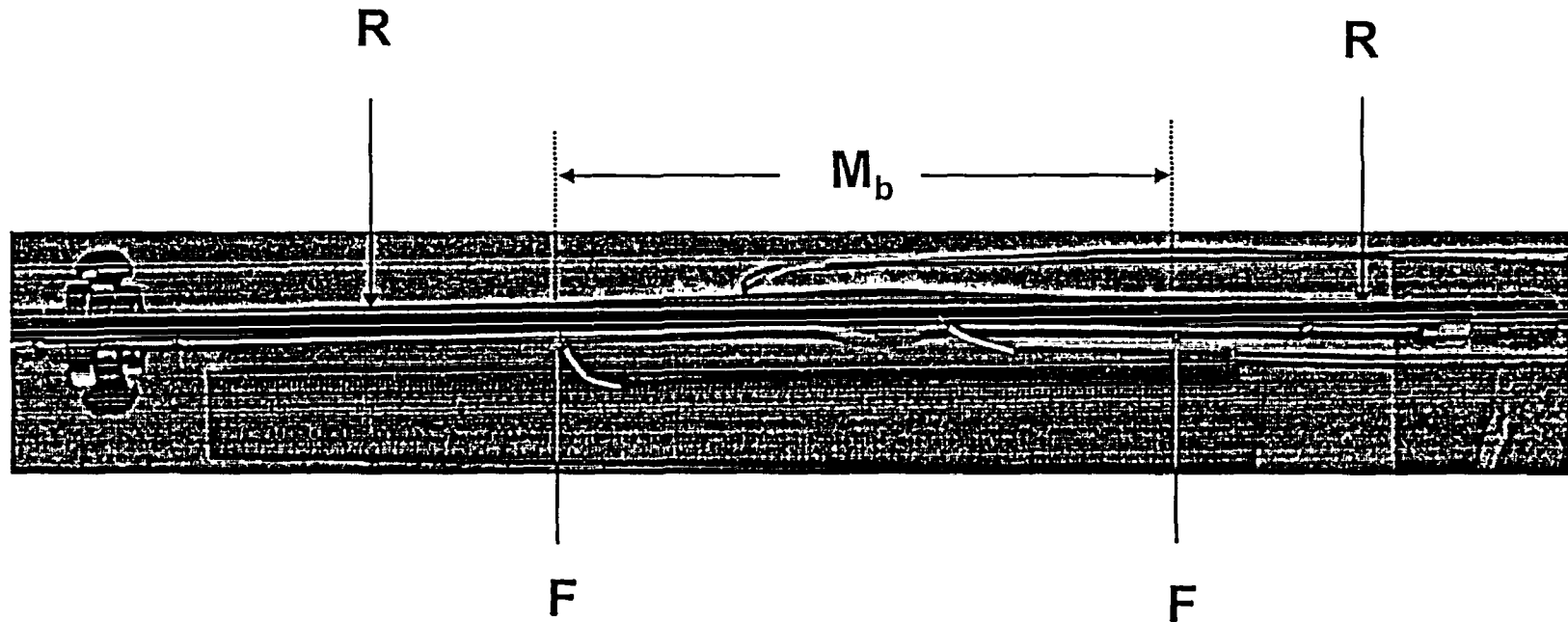


Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



4-Point-Bend Demonstration Burst Area under Compression

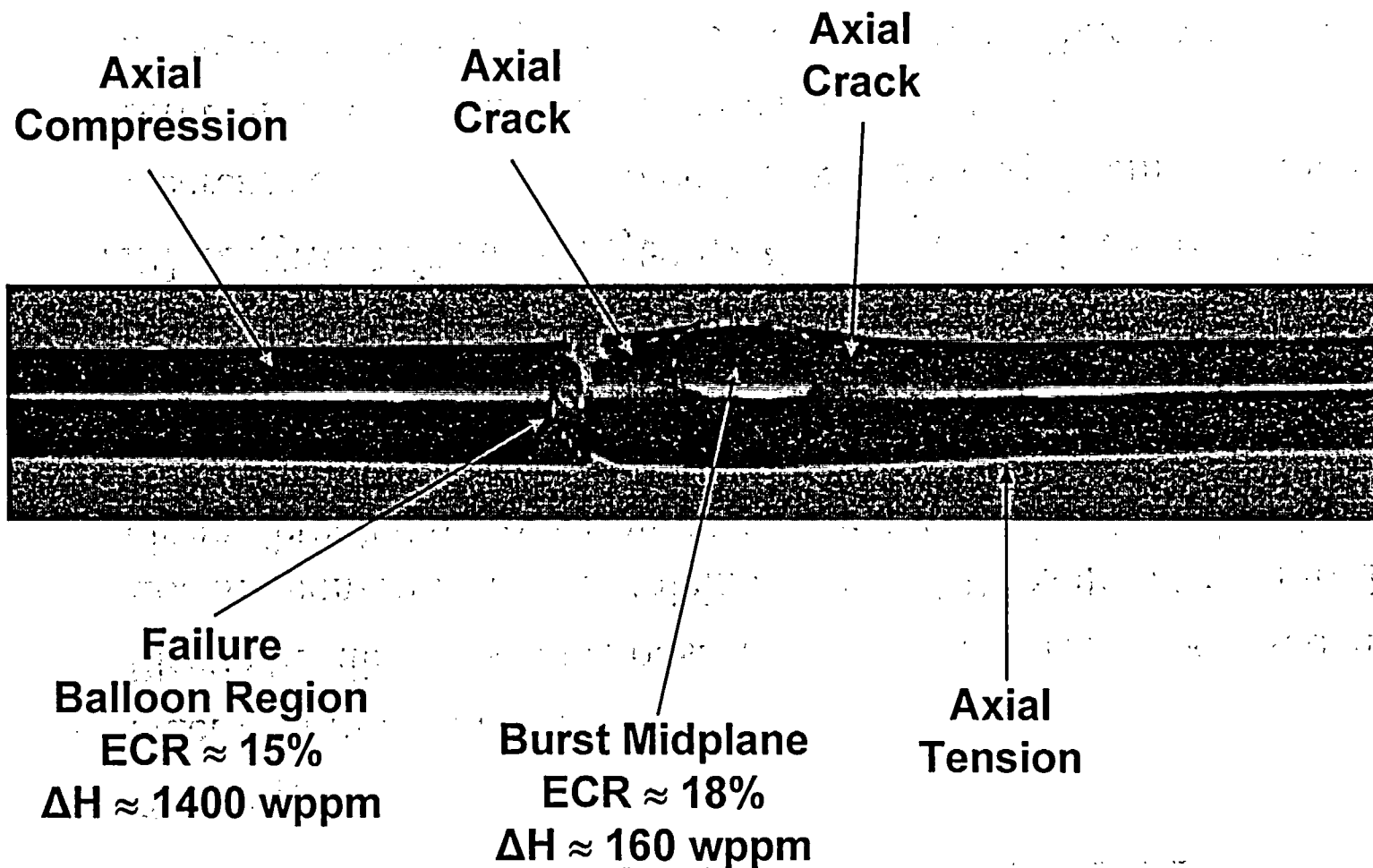


Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



July 16, 2003 4-Point-Bend Demo Results (OCL#5-1)



Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



Observations

- **Burst Region**

- Ductile at time of burst;
Plastic bending of sample observed due to jet force (3-point-bending)
- Locally non-uniform wall thickness and ECR result in brittle-to-ductile circumferential regions from burst opening to 180° from burst
- Bending moment (M_b) vs. deflection (δ) curve may suggest brittle behavior of structure when burst region is subjected to axial tension

- **Axial Regions from Edges of Burst to Balloon Necks**

- Decrease of ductility due to both O & secondary-H embrittlement
- Structural failure may occur in this area as $ECR \downarrow$ and $T \downarrow$
- Structural failure may also occur in this region if burst region is subjected to nominally compressive axial bending stresses
- Burst-to-neck region behaves in a brittle manner under impact loading



Plans for Additional Bend-Test-Ductility Work

- **Conduct Six New Out-of-Cell LOCA Integral Tests**
 - Five LOCA Integral Tests at 1204°C with hold times of:
 - 0 s (3% CP-calculated ECR for 0.5-mm wall)
 - 60 s (9% calculated ECR), 120 s (13% calculated ECR)
 - 180 s (16% calculated ECR), 240 s (18% calculated ECR)
 - 300 s (20% calculated ECR)
- **Perform Instron 4-Point Bend Tests**
 - Remove zirconia pellets orient sample with burst under tension
 - Determine failure location and mode by visual inspection
 - Determine “ductility” from bending-moment vs. deflection curve
 - Compare Instron “ductility” with direct observations of failure surfaces

Future LOCA-Relevant Work

- **Advanced-Alloy Post-Quench Ductility**
 - Oxidize-and-quench 1200°C and 1260°C samples (Zry-4, ZIRLO, M5)
 - Conduct ring-compression tests; H measurements & met for 20%ECR
 - Conduct LOCA Integral Tests with advanced-alloy cladding samples
- **In-Cell LOCA Integral Tests with High-Burnup Samples**
 - Conduct Limerick BWR tests (5 min. at 1204°C) with quench – ASAP
 - Initiate Robinson PWR oxidation and LOCA tests – Fall 2003
 - Develop simple in-cell 4-point-bend test benchmarked to out-of-cell Instron tests; perform bend test on fueled post-quench samples
 - Perform ring compression tests on defueled samples from beyond the ballooned region; use tabletop Instron in beta-gamma cell
- **Continue Companion Out-of-cell LOCA Integral Tests**





United States Nuclear Regulatory Commission

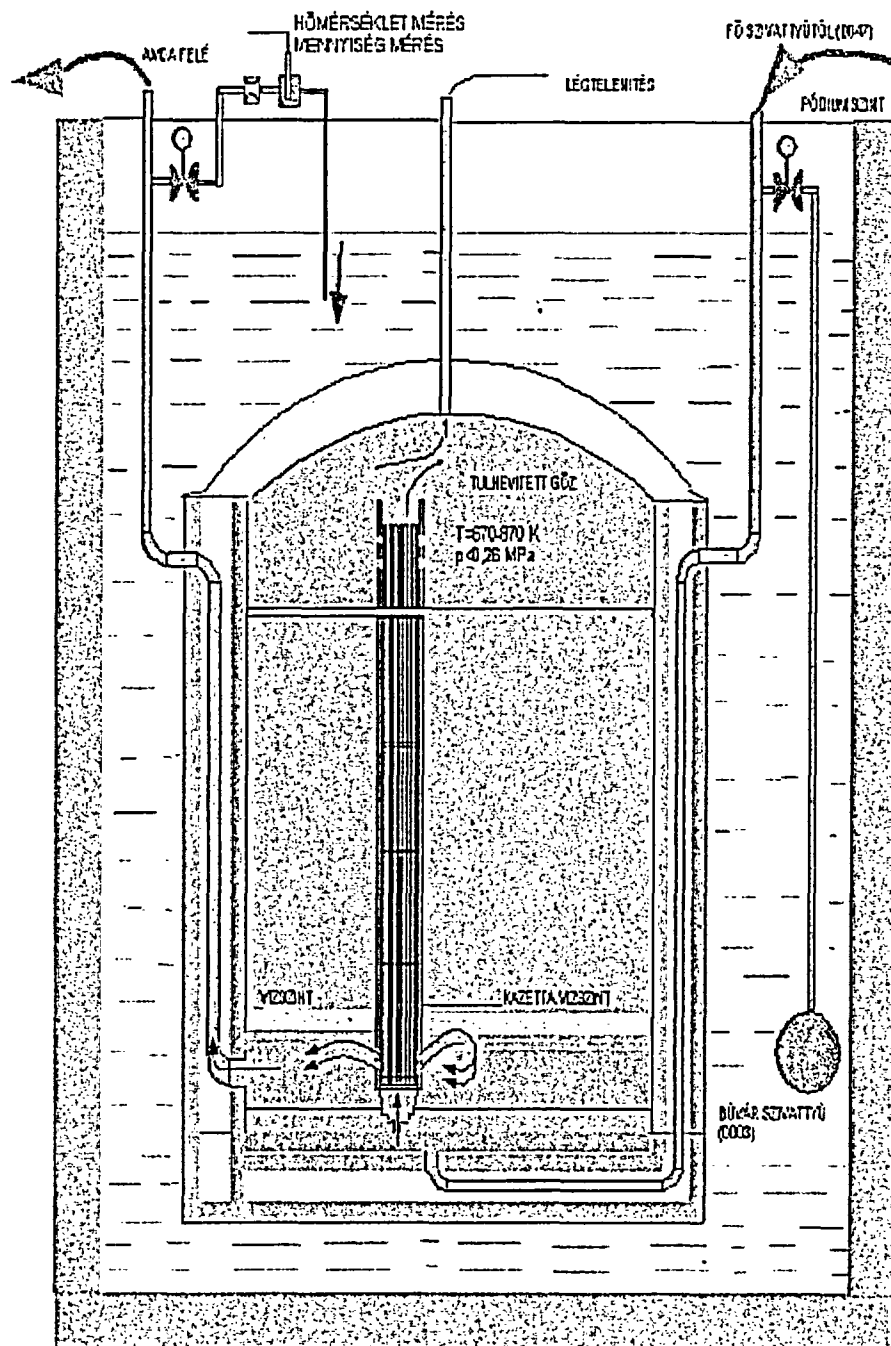
FUEL DAMAGE ACCIDENT IN CLEANING TANK AT PAKS NPP

Ralph Meyer
Office of Nuclear Regulatory Research

ACRS Subcommittee
September 29, 2003

PAKS FUEL CLEANING EVENTS

- Crud buildup (magnetite) on the fuel from prior cleaning of steam generator tubes
- 5 batches cleaned successfully with oxalic acid prior to April 10, 2003
- 6th batch cleaning was completed, but the fuel was left in cleaning tank overnight (April 10-11, 2003) with a small circulation pump running
- Overheating of the fuel occurred from insufficient circulation in the tank
- Noble gas activity was detected in the ventilation stack and at other locations within the plant

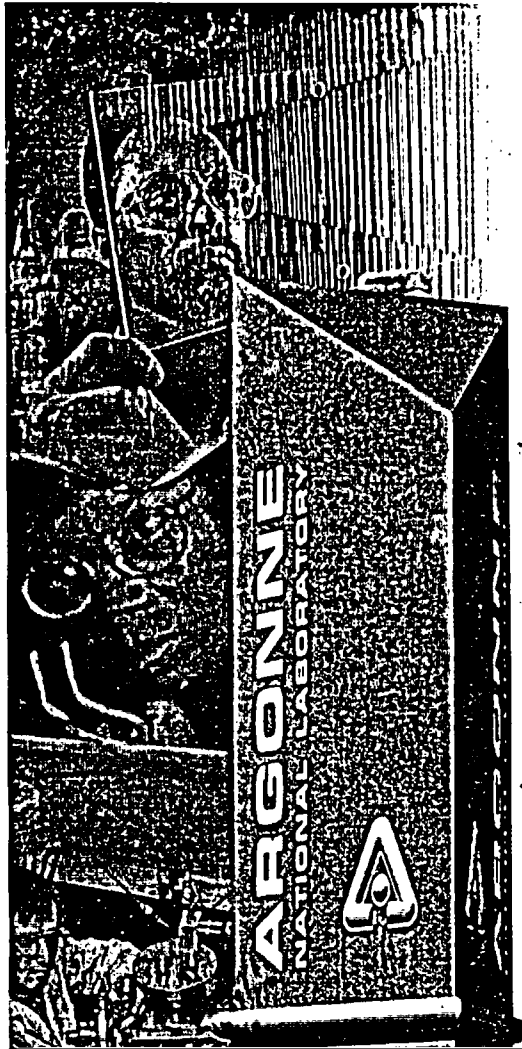


EXTENT OF FUEL DAMAGE

- Steam bubble at top of tank resulted in high cladding temperatures, oxidation, and hydrogen production
- All 30 fuel assemblies were badly damaged
- Release of ~20% of the gap activity suggests that fuel temperatures probably reached 1000°C, but did not reach 2000°C.
- Some fuel assembly shrouds are broken and have missing pieces
- Short ruptured balloons and long non-ruptured balloons can be seen
- Broken pieces of fuel rods and pellets can be seen
- Large portions of many shrouded fuel assemblies appear intact

POSSIBLE FUEL EXAMINATION

- CSNI initiative to form an international cooperative program to examine the fuel
- Initial meeting in Budapest on August 22, 2003, to discuss the possibility
- Participants from U.S., France, Germany, Russia, and Hungary
- TVEL (with Bochvar, Kurchatov, and RIAR) had just been awarded recovery contract
- Agreement in principle by all parties to cooperate
- Next step is a written proposal from CSNI in late October



ANL Dry Cask Storage Program

*M.C. Billone, R.S. Daum and H.C. Tsai
Energy Technology Division*

*ACRS Meeting
NRC Headquarters*

Summary of Dry Cask Storage Tasks

- **Dry Cask Storage License Renewal (≤ 45 GWd/MTU)**

- ANL work documented in NUREG/CR-6831 (September 2003)
- Surry PWR fuel rods at 36 GWd/MTU (dry-cask stored for 15 years)
- Profilometry (12), fission-gas analysis (4), destructive exams (3)
- Thermal creep (360-400°C) and axial tensile tests (RT-400°C)
- Radial reorientation and axial redistribution of hydrides
- Post-storage, post-creep bending tests; impact tests???

- **High-Burnup SNF Behavior Issues**

- H.B. Robinson PWR rods at 67 GWd/MTU
- Fuel actinide and fission-product concentrations; burnup analysis
- Thermal creep (360-400°C) and axial tensile tests (RT-400°C)
- Annealing and reorientation-redistribution of hydrides
- Effects of annealing and hydride reorientation on mech. Properties
- Post-storage, post-creep bending tests; impact tests???



PWR Fuel Rods at ANL for Dry Cask Storage Program

Reactor (Design)	Burnup GWd/MTU	^{235}U wt.%	Gd_2O_3 wt.%	Clad.	React. EOL	Dry- Stored
Robinson 15×15 PWR	67 (3)	2.90	0	Zry-4	1995	No
	63 (1)	3.85	0	Zry-4	1995	No
	47 (1)	1.95	10	Zry-4	1995	No
TMI-1 15×15 PWR	49 (1.5)	4.00	0	Zry-4 Low-Sn	1997	No
Surry 15×15 PWR	36	3.11	0	Zry-4	1881	15 y



Cladding Irradiation Parameters for Correlations

Reactor (Design)	Burnup GWd/MTU	Clad.	Fast Fluence 10^{25} n/m^2	Oxide μm	H wppm
Robinson 15×15 PWR	67	Zry-4	14	≤ 110	≤ 800
TMI-1 15×15 PWR	49	Zry-4 Low-Sn	9	≤ 30	≤ 170
Surry 15×15 PWR	36	Zry-4	7	≤ 40	≤ 300

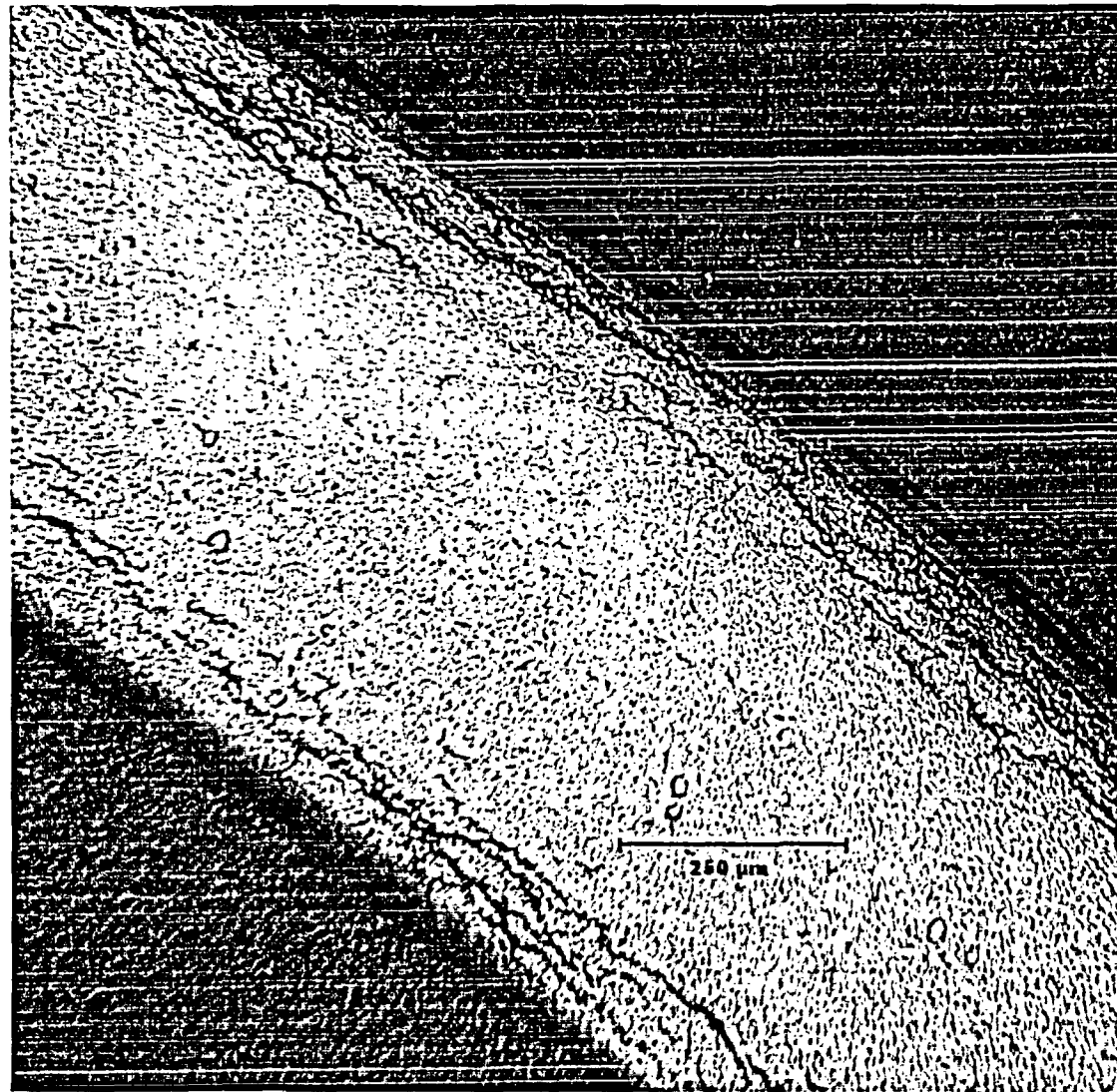


Surry PWR Cladding Characterization

Rod ID	Midplane	+0.5 m	+1.0 m	+1.5 m	Plenum
H9					
OD Oxide, μm	24	33	40	TBD	TBD
wppm H	250	300	250	TBD	TBD
G6					
OD Oxide, μm	22	26	---	---	---
wppm H	---	---	---	---	---
H7					
OD Oxide, μm	TBD	---	---	---	---
wppm H	TBD	---	---	---	---
Isotopics	TBD	---	---	---	---



Surry Post-Storage Hydride Distribution



Thermal Creep of Post-Storage Surry Cladding

Surry Summary Results

Sample	Temp. (°C)	Stress (MPa)	At End of Test			Sample Disposition
			Hours	Avg. ϵ	Intact	
C3	360	220	3305	0.22	Yes	DE ⁽¹⁾
C6	380	190	2348	0.35	Yes	DE ⁽¹⁾
C8	380	220	2180	1.10	Yes	Bend Test
C9	400	190	1873	1.03	Yes	--
		250	693 ⁽²⁾	5.83	Yes	Bend Test
2-C9	400	160	286 ⁽³⁾	0.22	Yes	tbd

(1) DE: Destructive examination, for hydride orientation determination. For this, the final shutdown was done with sample pressurized.

(2) Incremental hours

(3) On-going



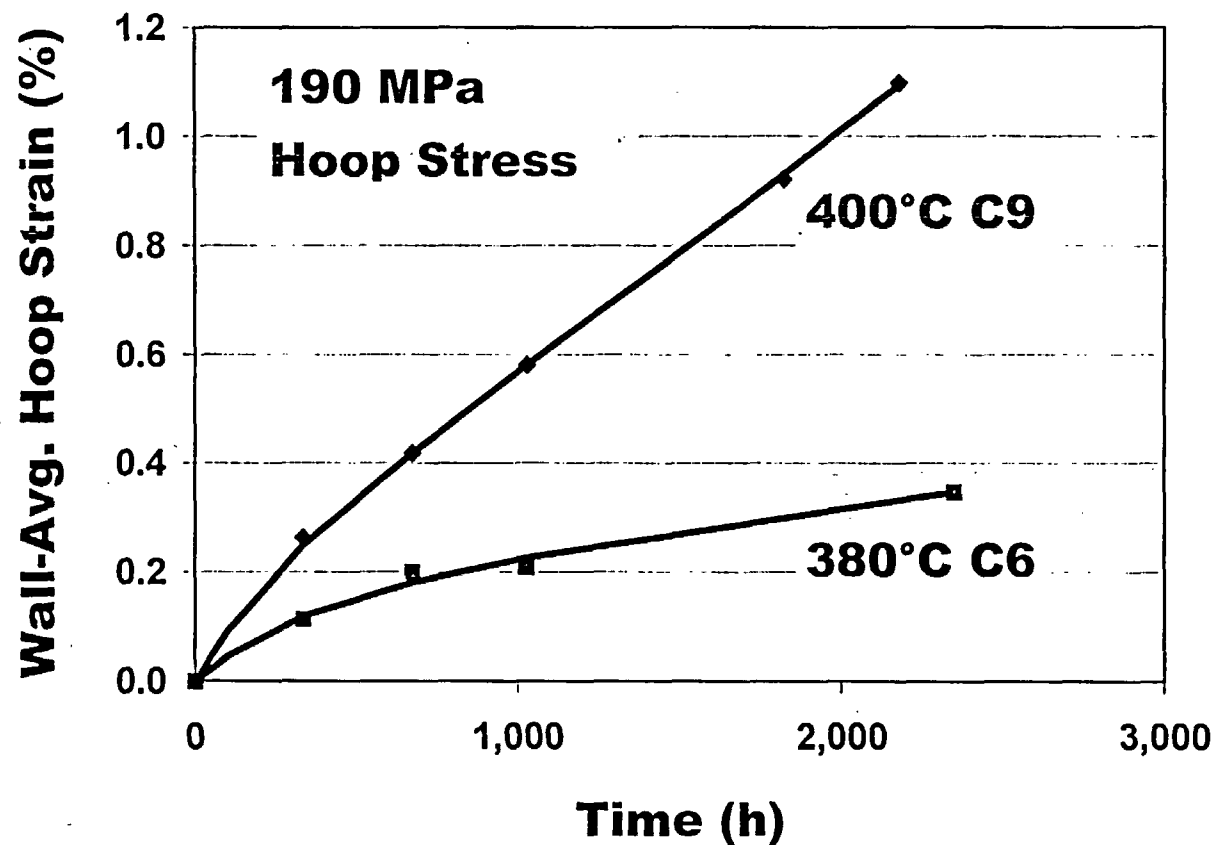
Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



Thermal Creep of Post-Storage Surry Cladding

- Temperature Dependency



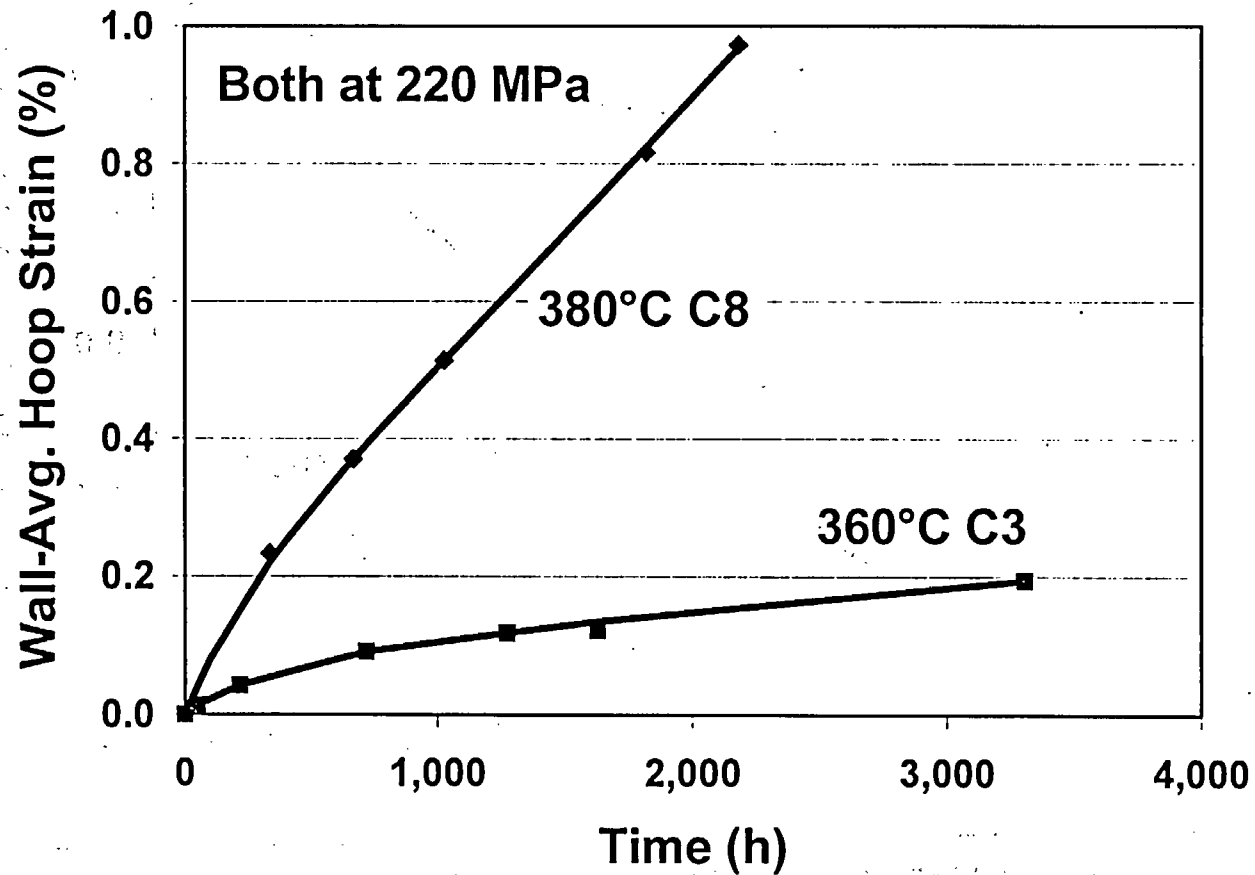
Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



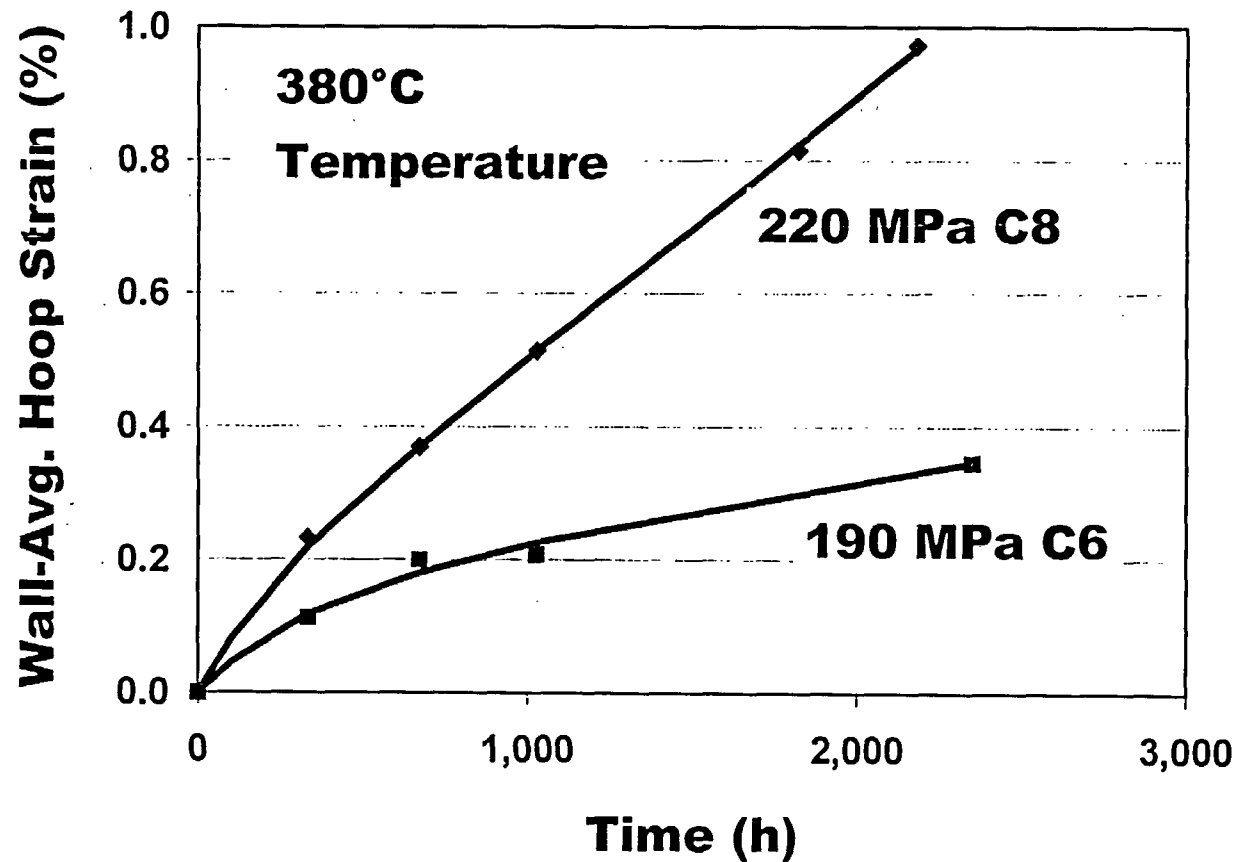
Thermal Creep of Post-Storage Surry Cladding

- Temperature Dependency



Thermal Creep of Post-Storage Surry Cladding

- Stress Dependency at 380°C



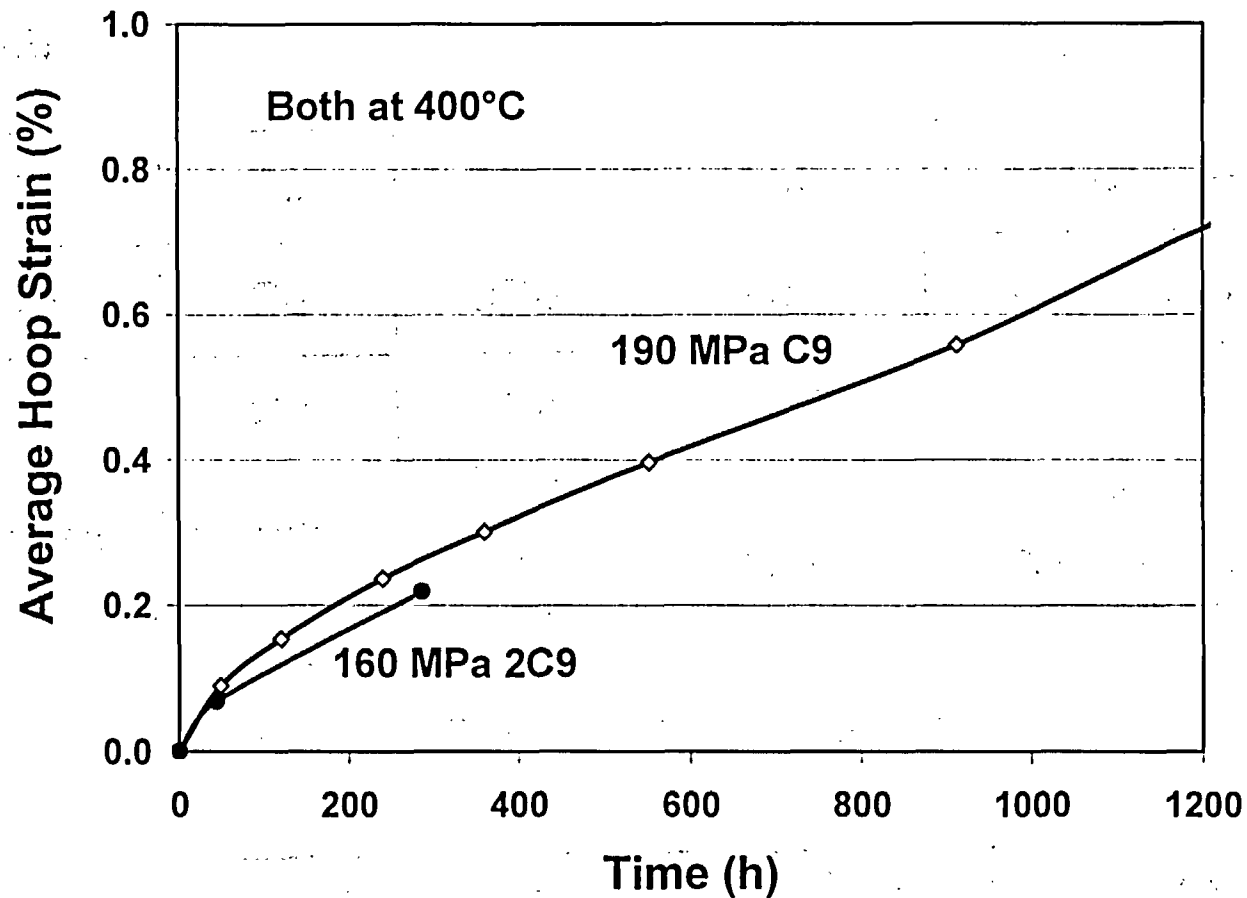
Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



Thermal Creep of Post-Storage Surry Cladding

- Stress Dependency at 400°C



Thermal Creep of Post-Storage Surry Cladding

Secondary Creep Rates

Rod ID	Sample	Temp. (°C)	Stress (MPa)	SS $\Delta\epsilon/\Delta t^{(1)}$ (%/h)
H9	C3	360	220	$\approx 1.6 \times 10^{-5}$
H9	C6	380	190	$\approx 8.6 \times 10^{-5}$
H9	C8	380	220	$\approx 4.6 \times 10^{-4}$
H9	C9	400	190	$\approx 4.9 \times 10^{-4}$
			250	$\approx 4.9 \times 10^{-3}$



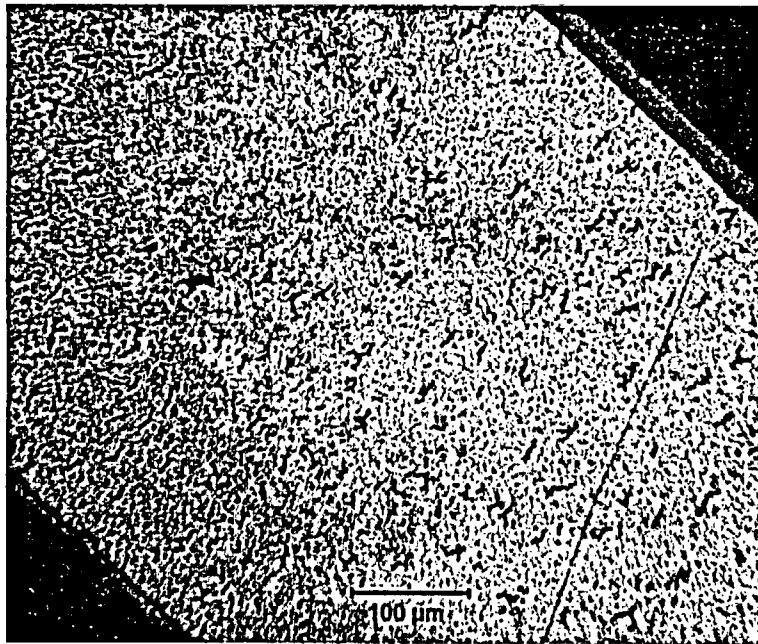
Pioneering
Science and
Technology

Nuclear
Regulatory
Commission

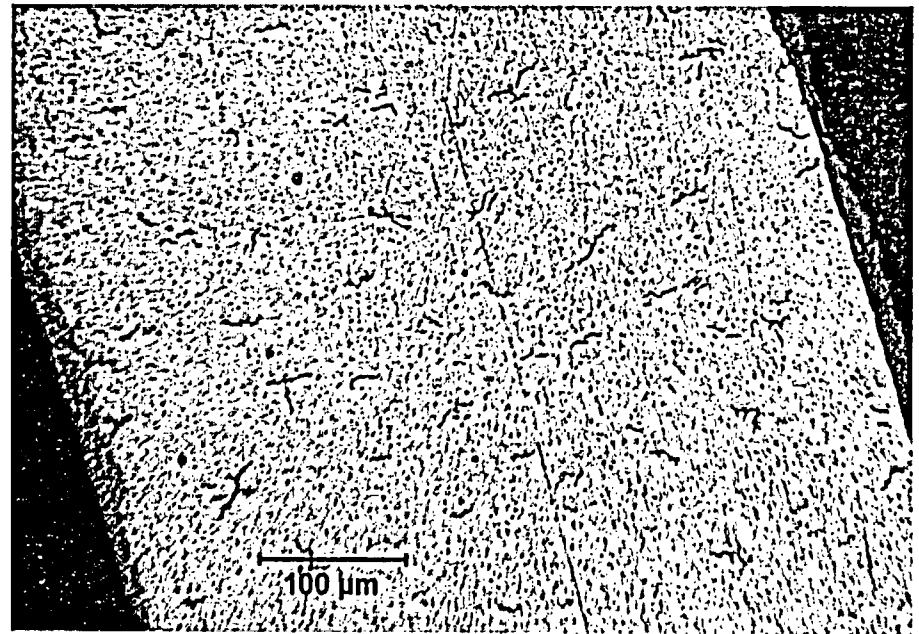


Surry Post-Creep Hydride Reorientation

- Two creep samples survived cooling with under pressure:
C3 (360°C, 220 MPa, 0.22%) and C6 (380°C, 190 MPa, 0.35%)



Posttest C3



Posttest C6



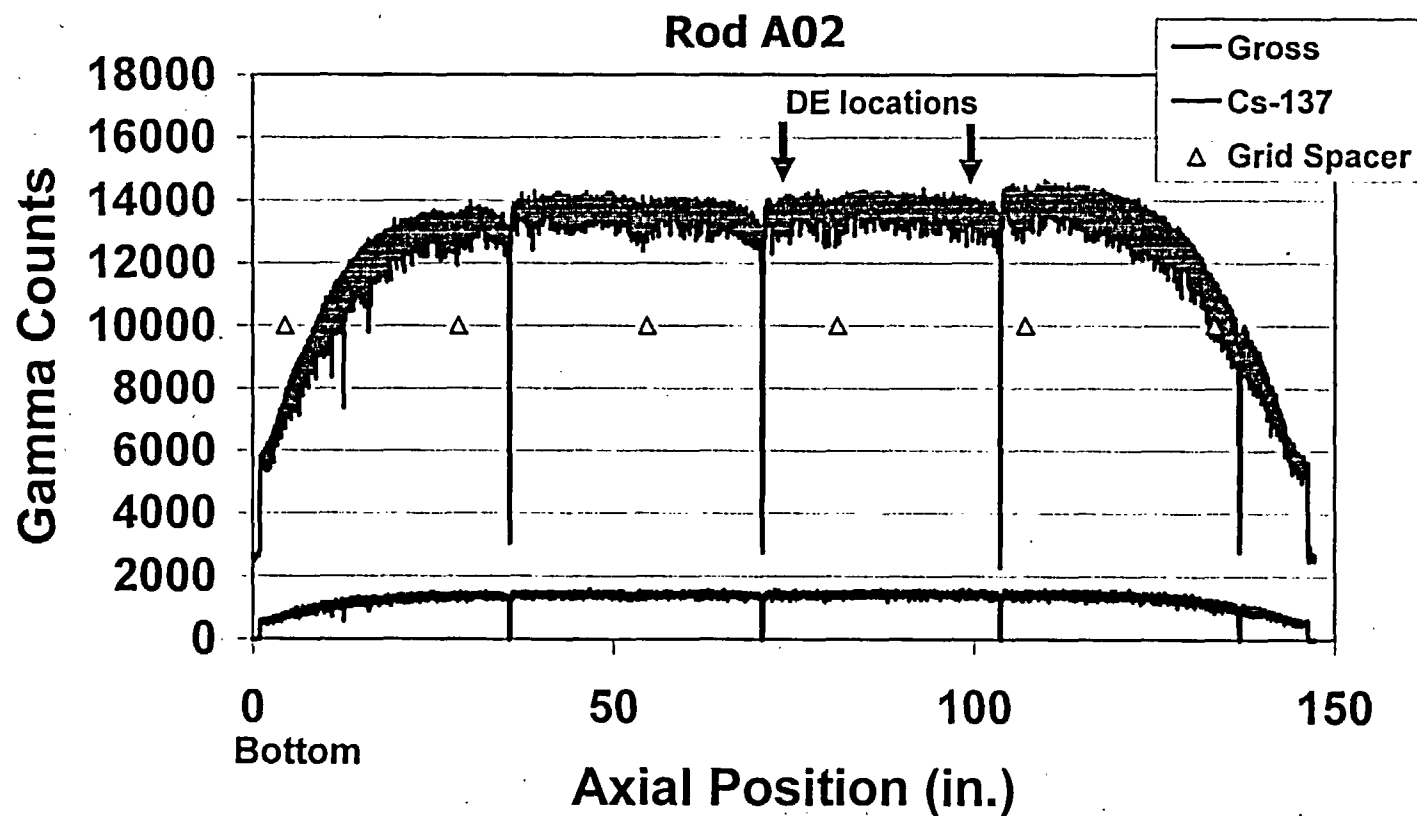
Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



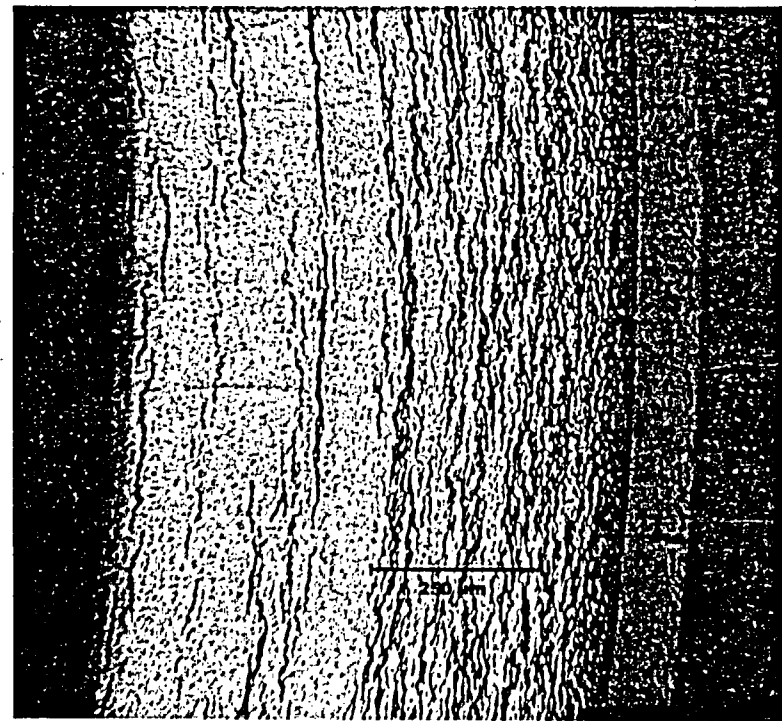
H. B. Robinson Characterization

- Axial Gamma Profile and Location of Samples for Destructive Examinations (DE)



H. B. Robinson Characterization (cont'd)

- **Cladding Corrosion and hydrogen uptake in Rod A02**
 - **OD oxide thickness:**
 $\approx 70 \mu\text{m}$ at axial midplane
 $\approx 100 \mu\text{m}$ at 27 in. above
 - **Hydrogen uptake: $\approx 20\%$**
 ≈ 580 wppm at midplane
 ≈ 750 wppm at 27 in. above
 - **Hydrides:**
circumferentially oriented

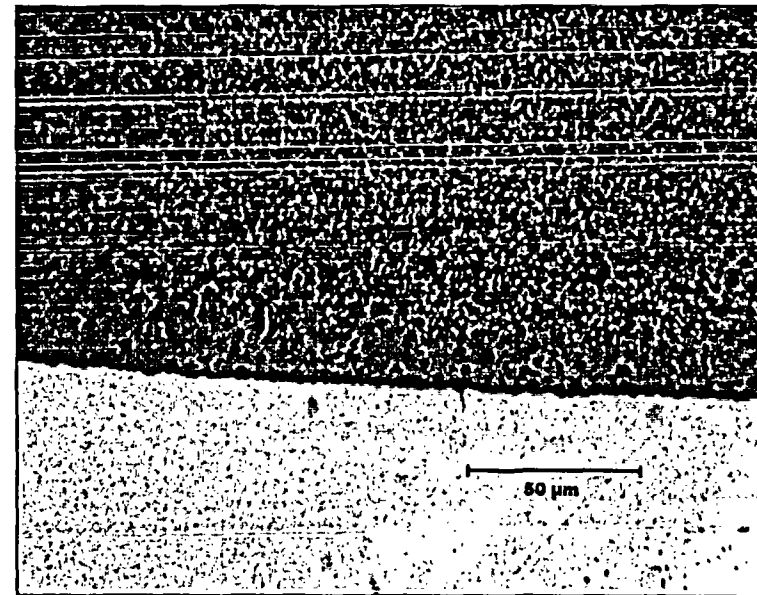


HBR Rod A02 27 in. above axial midplane

H. B. Robinson Characterization (cont'd)

- **Tight fuel-cladding bond**

- Porous fuel rim region
- Fission-product deposit in the fuel-cladding "gap"
- Minimal cladding ID corrosion



27 in. above axial midplane



Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



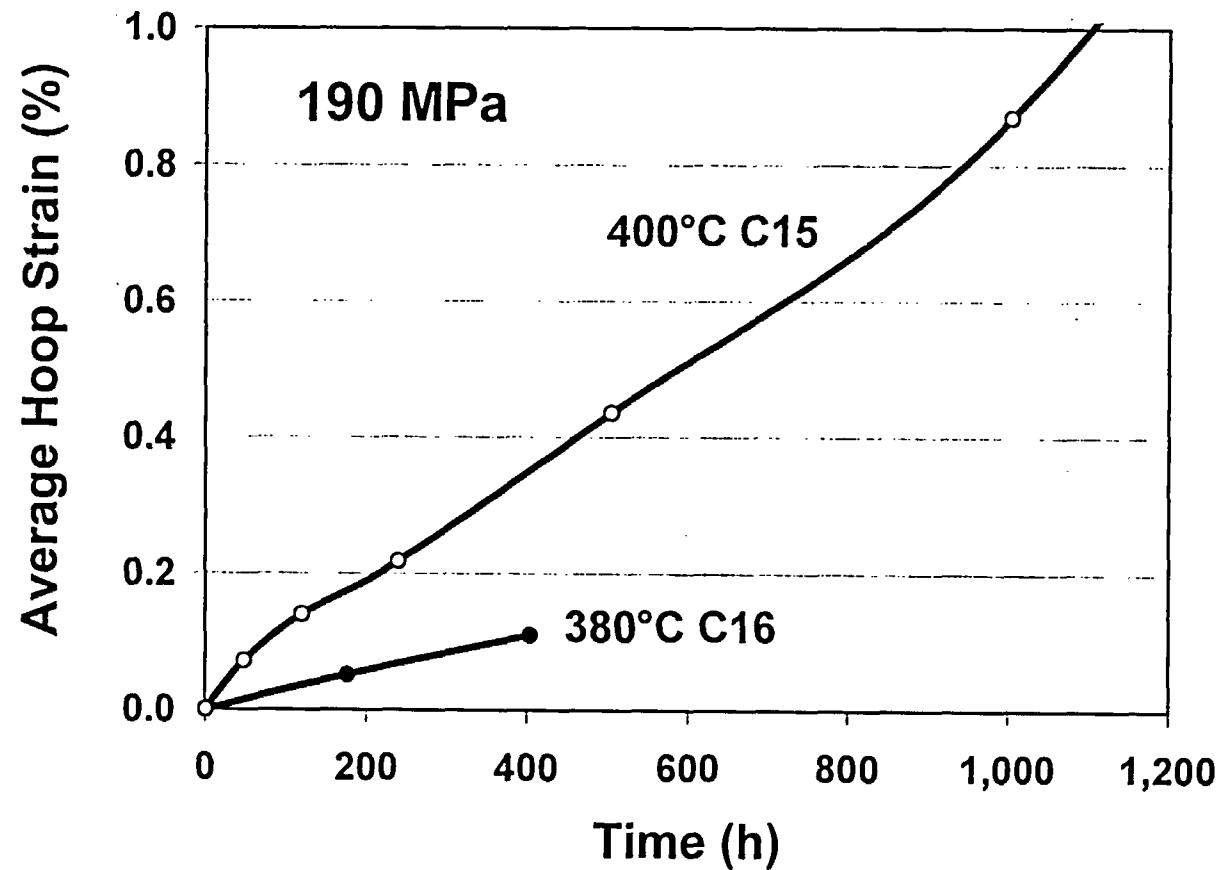
Thermal Creep Tests – H. B. Robinson

Robinson Test Matrix (6/03)

		Stress (MPa)				
		100	160	190	220	250
Temp. (°C)	420		1			
	400		1	C14 C15	1	
	380		1	C16	C17	
	360			1	1	
	320					

Thermal Creep Tests – H. B. Robinson

- Temperature Dependency: 380°C vs. 400°C



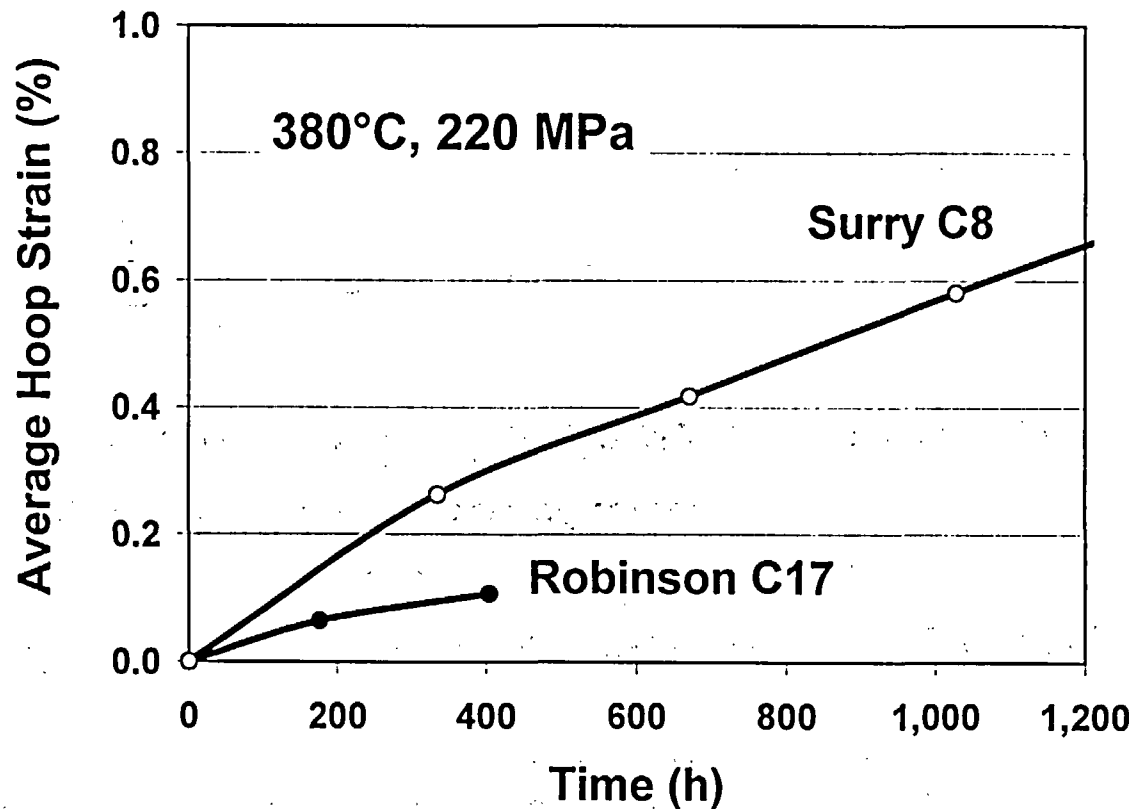
Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



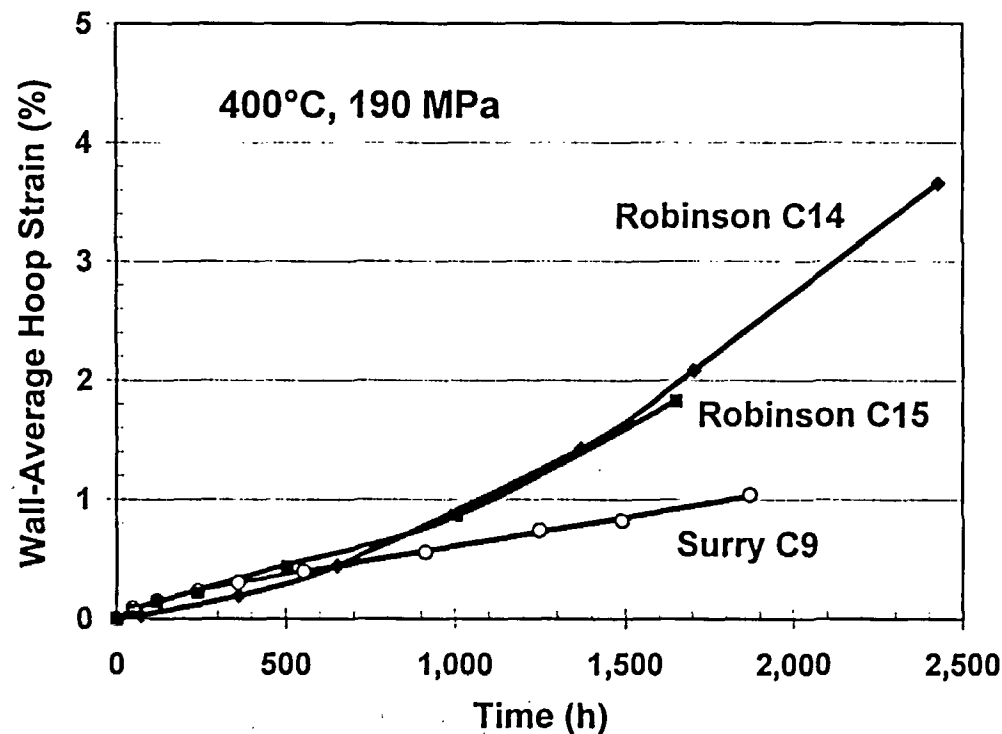
Thermal Creep Tests – H. B. Robinson

- Creep rate of H. B. Robinson appears to be smaller than that of Surry at the lower temperature of 380°C.



Thermal Creep Tests – H. B. Robinson

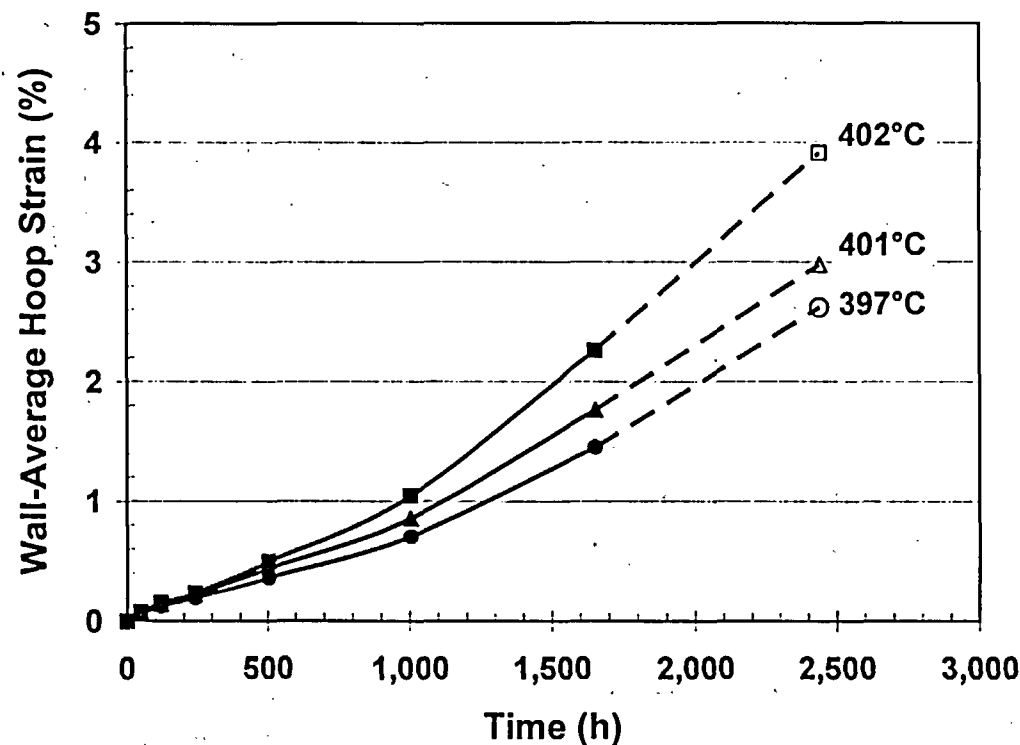
- At 400°C, secondary creep rate of H. B. Robinson appears to be comparable to that of Surry at the onset of test. Rate appears to be greater afterwards.
- C14 was terminated after 2450 h at 3.6% (5.4% peak) ϵ_{θ} .



Temperature Sensitivity of C15 Deformation

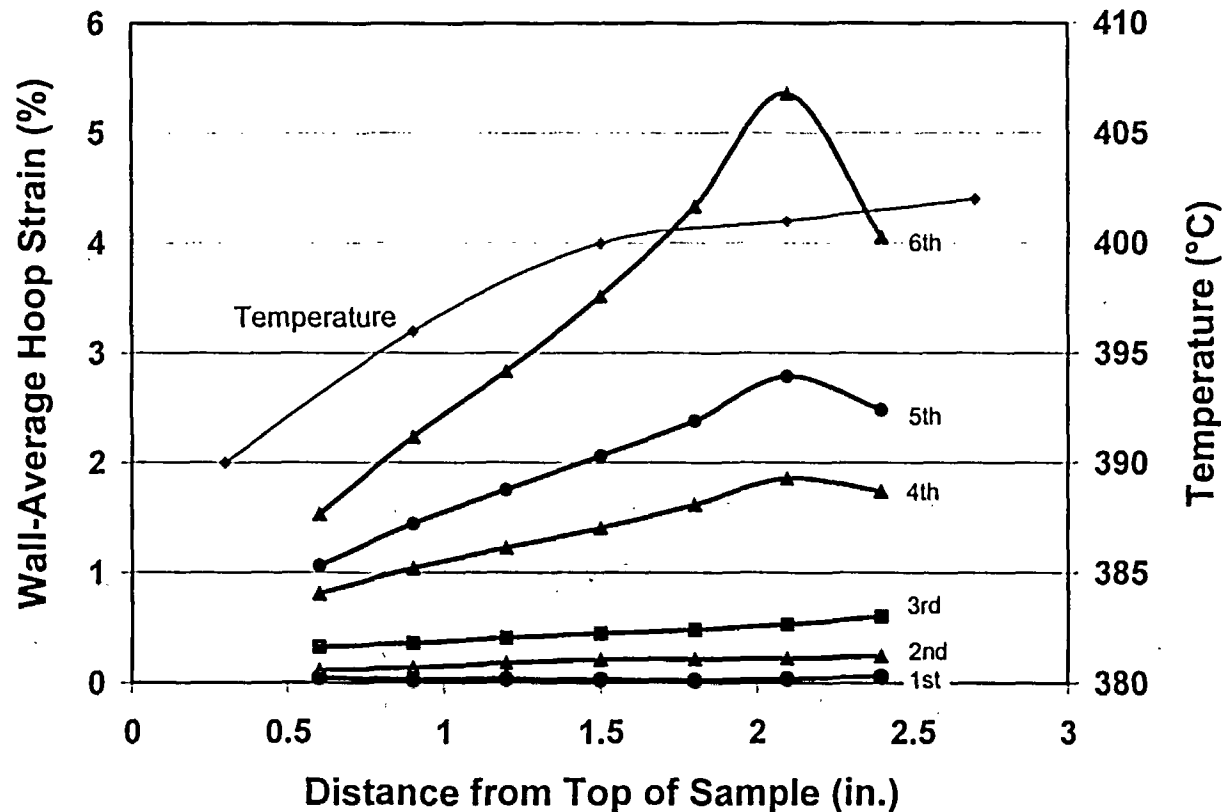
- Based on detailed analysis of C15 data at midplane and ± 15 mm, deformation temperature sensitivity at $\approx 400^\circ\text{C}$ is extremely high (annealing??)

Thermal Creep - H. B. Robinson Test C15



Temperature Sensitivity of C14 Deformation

Axial Variation of H. B. Robinson Hoop Strain
Sample C14, 400°C and 190 MPa



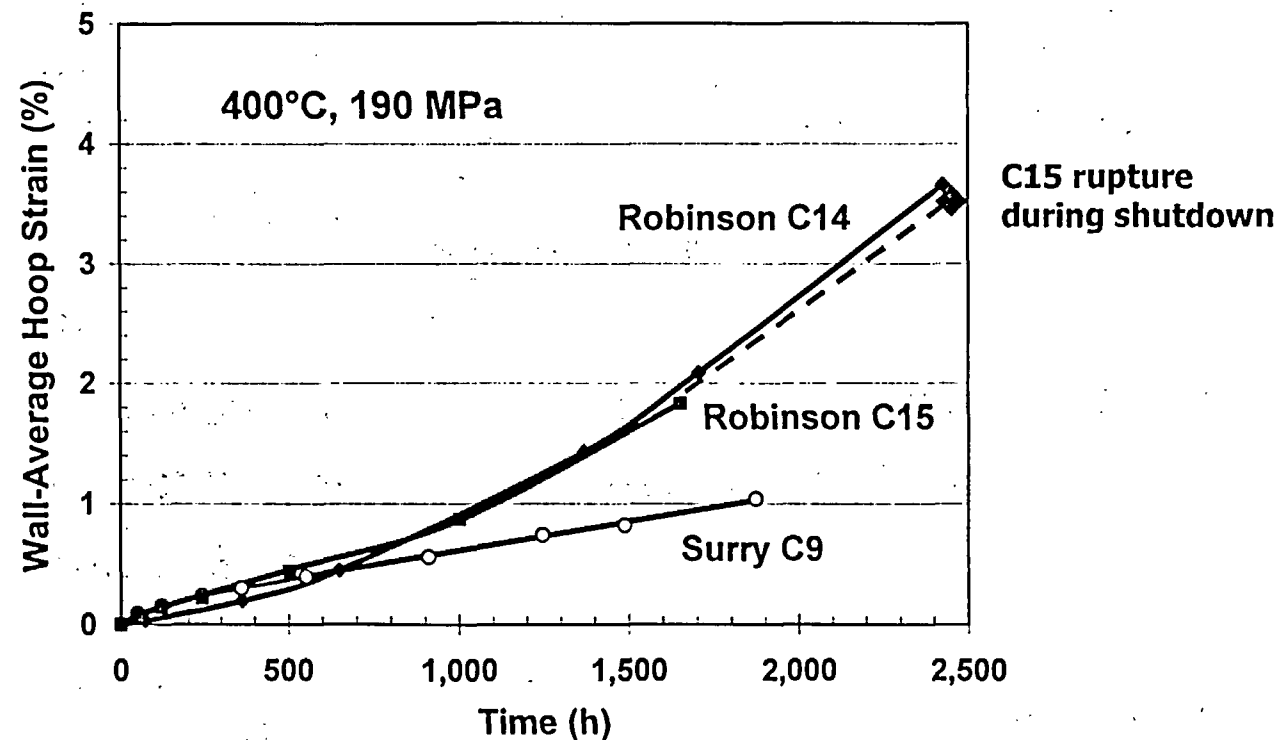
Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



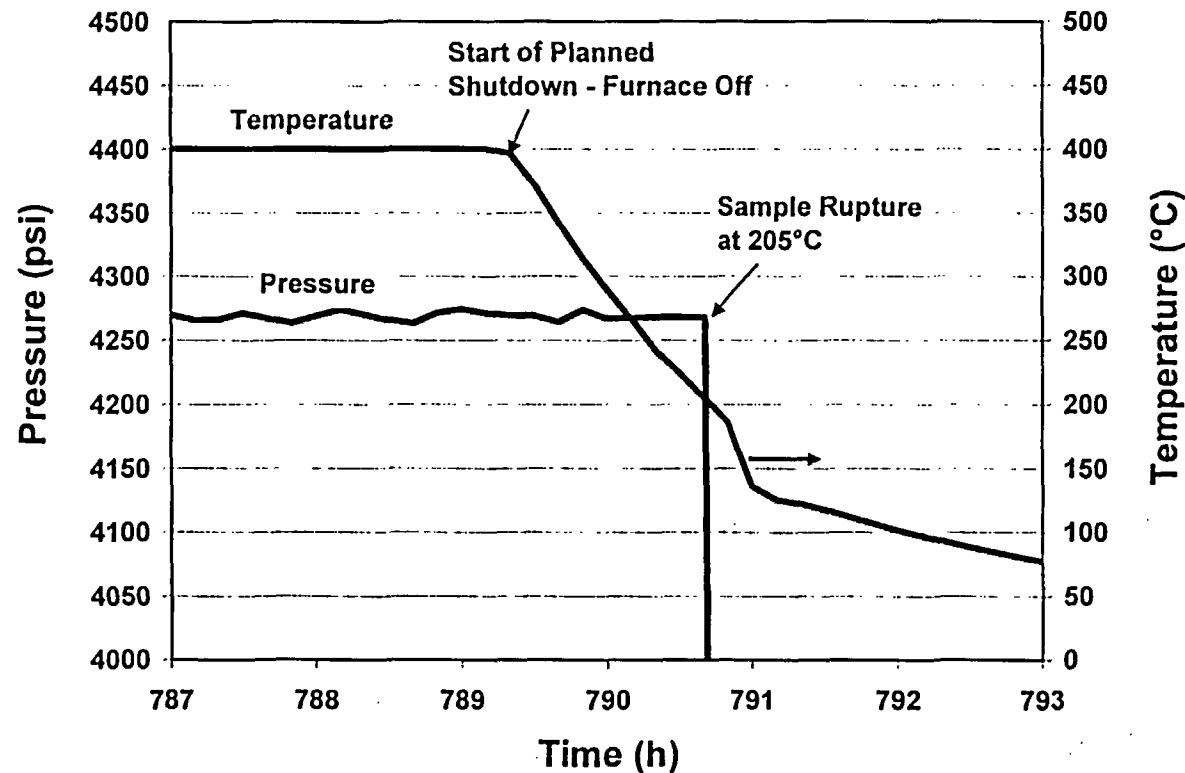
Thermal Creep Tests – H. B. Robinson

- C15 developed a rupture during the final shutdown, which involved cooling from 400°C under full pressure to yield hydride reorientation data. Maximum hoop stress was ≈ 205 MPa



Thermal Creep Tests – H. B. Robinson

- Shutdown history of C15
 - Sample intact at the end of 400°C run after 2440 h
 - Rupture occurred when temperature decreased to 205°C.



Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



Thermal Creep Tests – H. B. Robinson

- **Status of C15**

- **Rupture caused substantial contamination of the beta-gamma hot cell in spite of the following provisions:**
 - **Sample defueled (HNO_3 dissolution) and filled with Zr pellets**
 - **In-line pin hole in pressurization system to restrict gas flow**
 - **Solenoid valve to shut off pressure**
 - **Down-stream HEPA filter.**
- **Condition of the sample cannot be readily determined until the cell is cleaned up (Fall 2003).**
 - **End-plug weld failure or rupture due to hydride reorientation are two possible causes.**
 - **If latter, extensive examination will be conducted to characterize the hydride effects.**

Thermal Creep Tests – Robinson & Surry

• Status of Creep Tests in Bldg. 212 IML

*

- Cell #4 is too contaminated to salvage low-value equipment
- Need to retrieve Robinson C15 (failed) and C17 (intact), Surry 2C9 (intact) and Surry C6 (untested)
- Need to view test chamber to ensure no bulging due to C15 pressure pulse

• Status of Creep Tests in Bldg. 200 K2 Cell

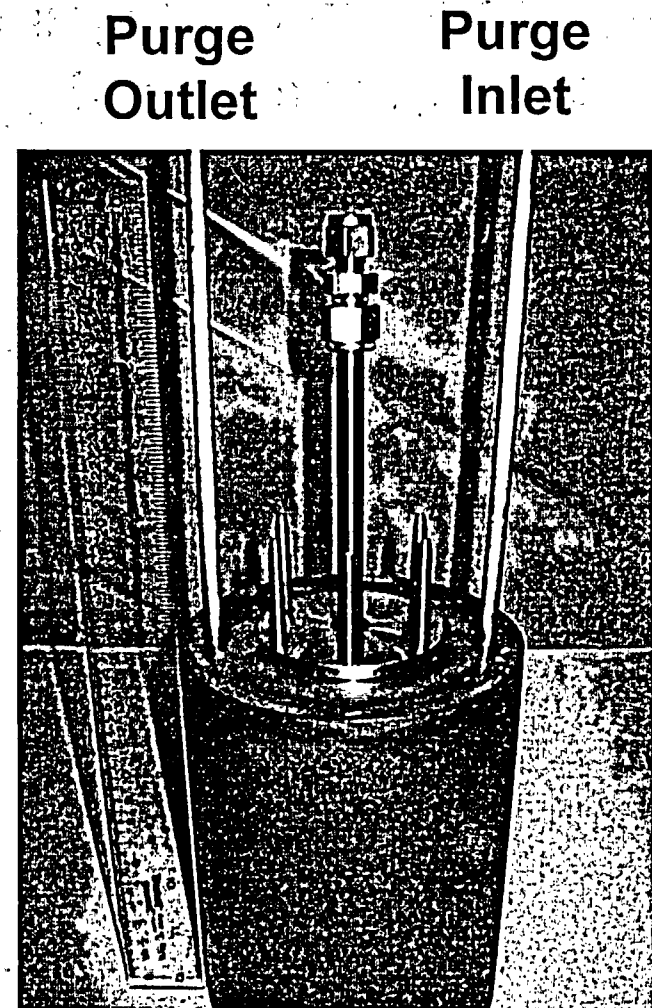
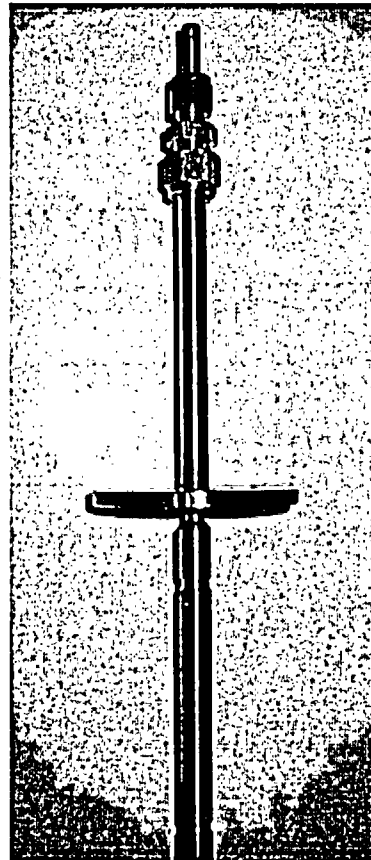
- System identical to IML system (designed for pin-hole leak)
- Redesign required for large pressure pulse (no problem)
- Test chamber redesign depends on IML examination



Test Chamber for Thermal Creep Tests

- **Test Chamber**

- Inert-gas purged to preclude sample oxidation during test



Pioneering
Science and
Technology

Nuclear
Regulatory
Commission

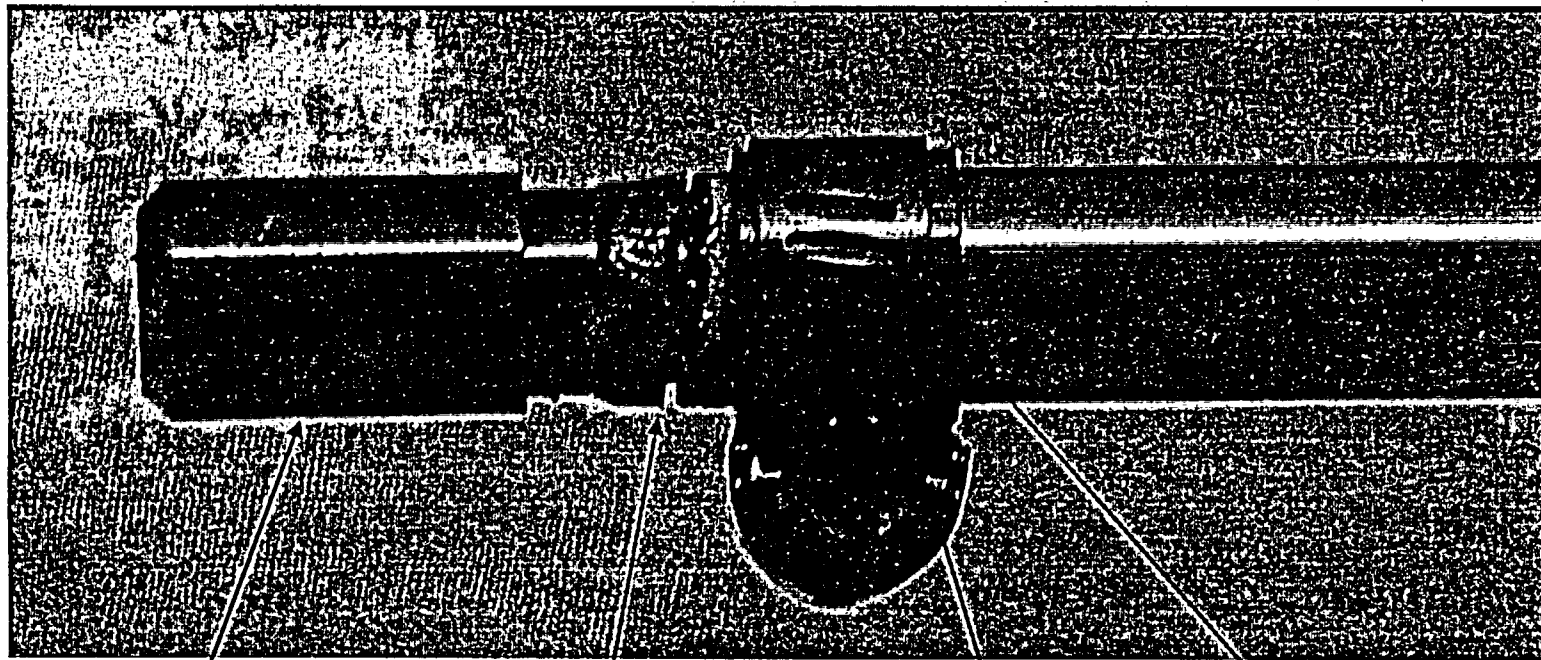


Footnote on H.B. Robinson C16 Failure

- Accumulated $\approx 0.1\%$ strain after ≈ 400 h (380°C , 190 MPa)
- Pressure (≈ 4270 psig) maintained during 236-h run
- Sample was shut down using normal procedures: depressurization followed by cooling to room temperature
- During inspection and profilometry, a crack was observed at the bottom of the sample between the welded end-cap and the hose clamp (used to restrain deformation in the partially annealed weld-affected zone)
- Flaw (see photograph) most likely occurred during shutdown
- Sample C15 (400°C , 190 MPa) held pressure for 2440 h with $>3\%$ hoop strain and failed during cooling under full pressure



Location and Morphology of C16 Failure



Bottom
End-cap

Weld &
Weld-affected
Zone Failure

Steel
Hose Clamp

Zr-702
Split Ring



Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



Annealing, Hydride Reorientation and Hydride Redistribution for H.B. Robinson Cladding

- **Isothermal Annealing of Robinson Cladding (≈ 600 wppm H)**
 - 420 - 500°C; 2 - 72 h
 - Post-annealing microhardness and hydride morphology determinations
- **Hydride Reorientation and Redistribution of Post-Creep Robinson Cladding (≈ 650 wppm H)**
 - Sample C15 was cooled (400°C \rightarrow RT) at full pressure
 - Stress (≈ 200 MPa) well above 100-MPa threshold for reorientation of circumferential-to-radial hydrides
 - Examination delayed: failure & cell contamination
 - Future plans call for closed pressurized tubes in AGHCF (90-150 MPa at 400°C; decreasing stress with cooling)



Robinson Cladding Annealing Tests

- **During vacuum drying, cladding temperature may have been raised to $>400^{\circ}\text{C}$ for hours to days. What effect does this have on mechanical properties & hydrogen distribution? Note: ISG-11 Rev. 2 (August 2002) limits $T \leq 400^{\circ}\text{C}$**
 - **Figure of merit: cladding microhardness (correlates with yield strength for ductile materials)**
 - **Test samples: short segments of defueled cladding from Rod A02 center (≈ 600 wppm H, 1.4×10^{25} n/cm²)**
 - **Corollary objective: study hydride redistribution under stress-free conditions**



Robinson Cladding Annealing Tests

- Annealing Test Matrix**

	2 h	10 h	20 h	48 h	72 h
420°C			C6		C7
450°C	C8	C9			
500°C	C10			C11	



Pioneering
Science and
Technology

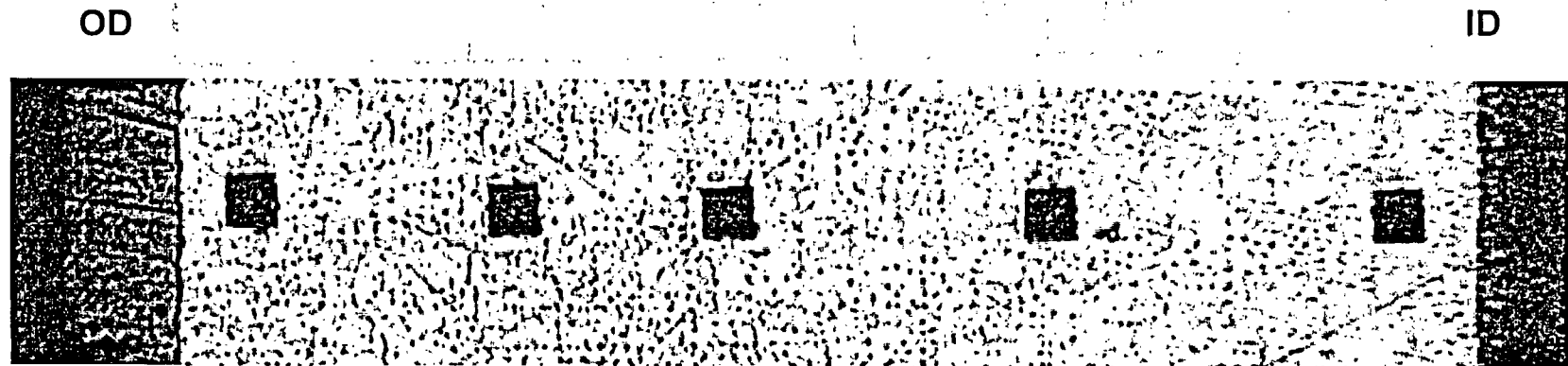
Nuclear
Regulatory
Commission



Robinson Cladding Annealing Tests

- **Microhardness Determination**

- Apply a known load with a diamond tip, measure the size of the indentation, and correlate it to Vicker's hardness



Robinson Cladding Annealing Tests

- **Microhardness Determination**

- For nonirradiated sibling: $H_o = 203$
- For as-irradiated sibling: $H_i = 252$

Microhardness after annealing tests

	2 h	10 h	20 h	48 h	72 h
420°C			226		215
450°C	224	217			
500°C	218			206	



Robinson Cladding Annealing Tests

$$\text{Recovery} = \left[1 - \frac{H - H_o}{H_i - H_o} \right]$$

% Radiation Hardening Recovery

	2 h	10 h	20 h	48 h	72 h
420°C			54		75
450°C	58	71			
500°C	69			94	

Results: Given time, significant recovery will occur at $T > \approx 420^\circ\text{C}$.



Robinson Cladding Annealing Tests

- **Hydride Morphology Evolution**

- Strongly governed by hydrogen solubility in Zircaloy

Temperature (°C)	Solubility (wppm)
25	0
200	13
400	200
420	240
450	310
500	460

**Robinson Samples:
600 wppm**

J. J. Kearns



Pioneering
Science and
Technology

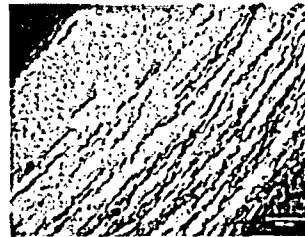
Nuclear
Regulatory
Commission



Robinson Cladding Annealing Tests

- **Hydride Morphology Evolution**

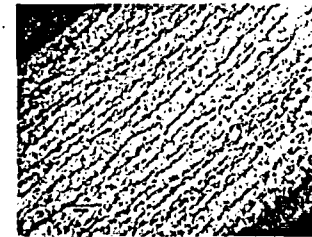
- Distribution homogenized across the thickness in the annealing tests
- No radial reorientation (being stress-free)



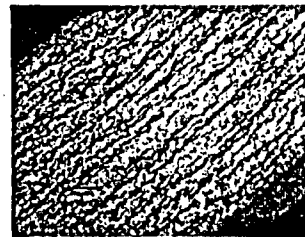
611C2 As-irradiated Control



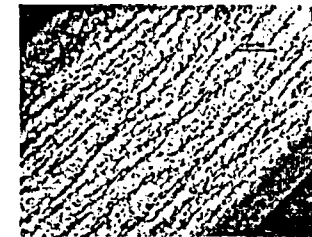
611C6 420°C, 20 h



611C7 420°C, 72 h



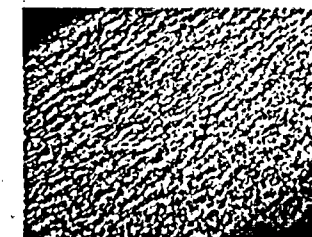
611C8 450°C, 2 h



611C9 450°C, 10 h



611C10 500°C, 2 h



611C11 500°C, 48 h

Hydride Morphology

H. B. Robinson
Cladding Annealing
Test Samples



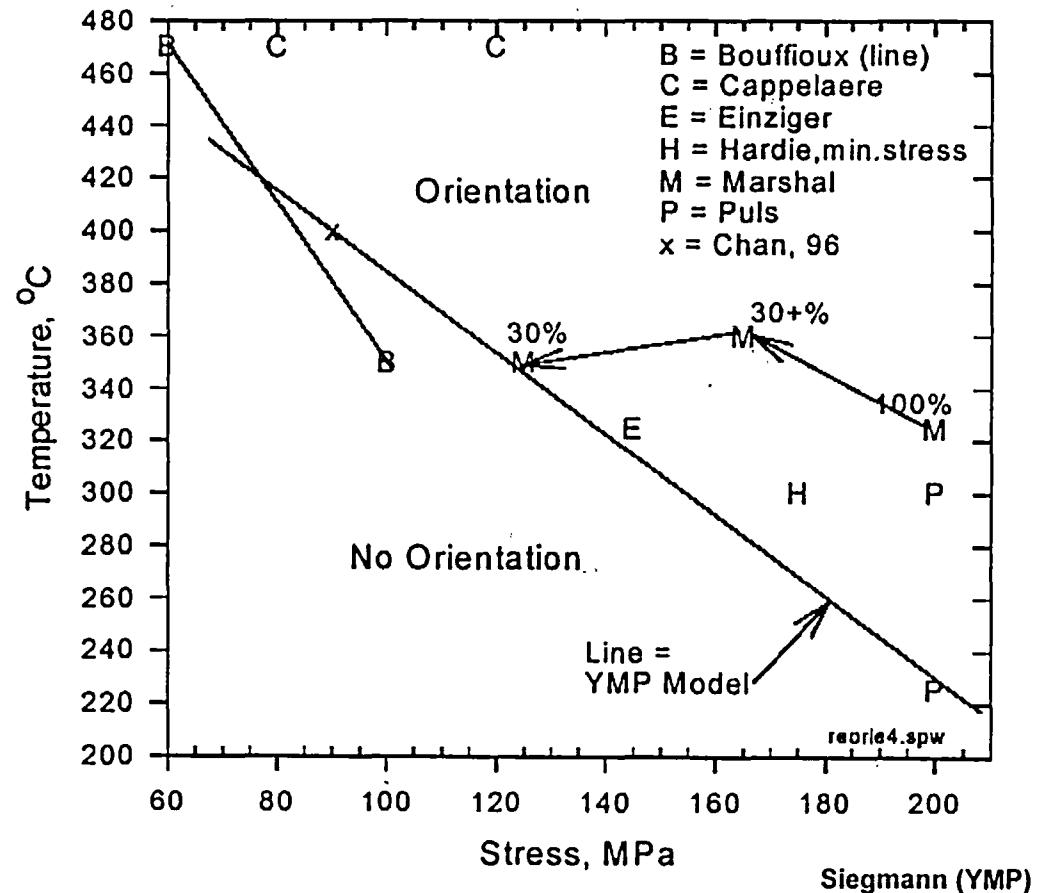
Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



Hydride Reorientation – Creep Tests

- Radial hydrides, as little as 40 wppm, can significantly degrade cladding's mechanical properties (Marshall)
- Stress, temperature, cool-down rate, microstructure, H content, etc., all play important roles (Einziger)
 - Threshold hoop stress for 400°C is ≈ 100 MPa



Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



Hydride Reorientation – Creep Tests

CEA (Cappelaere et al, ICEM 2001) – 470°C

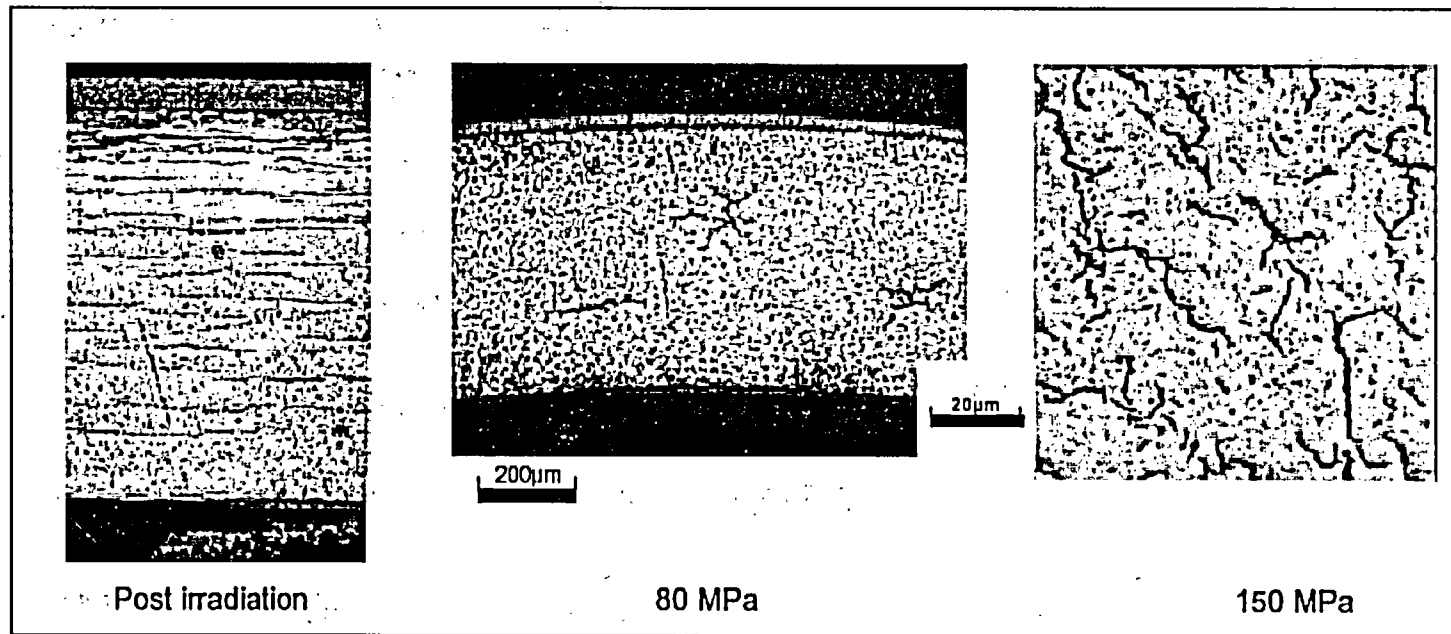


Figure 6 : Impact of creep tests on hydrides morphology, distribution and orientation

Plans for Additional Hydride Reorientation Tests

- **Reorientation during Vacuum Drying**
 - Sealed, pressurized capsules at 400°C and 90-150 MPa
 - Controlled cooling rate; corresponding pressure decrease
 - Technology for laser-welding pressurized capsules in AGHCF supported by DOE-RW
 - Conducting tests in AGHCF circumvents dose-rate issues with specimen transfer to IML and failure-induced contamination issues
- **Reorientation during Dry Cask Storage**
 - Hold samples at 400°C and 90-150 MPa to induce creep
 - Controlled cooling rate under decreasing pressure



Mechanical Properties Testing Plan

Reference: IPS-263-Rev.3 * - denotes specimens from different grid spans

T (°C) \ $\dot{\epsilon}$ (s ⁻¹)	0.1%		100%	
	Zr-2	Zr-4	Zr-2	Zr-4
25	1 3 3	2* 6* 6*	1 2 2	2* 4* 4*
150	1 3 3			
300	1 3 3	2* 5* 5*	2	
400	1 3	2* 6* 3*	1 2	2* 4* 2*
450	3	1 5* 5*		
500	1 3	1 6*	1 2	1 4*
550	1	1		
600	1	1	1	1
650	1	1		
700	1	1	1	1
750	1	1		
800	1	1	1	1

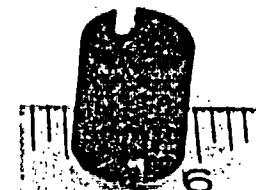
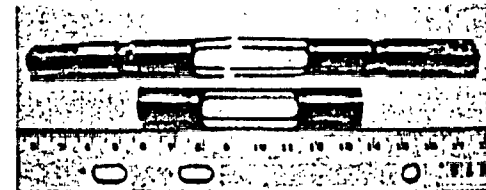
- Uniaxial Axial-Tube

- Uniaxial Ring-stretch

Additional T's between 300-400°C may be tested to determine hydride ductility transition

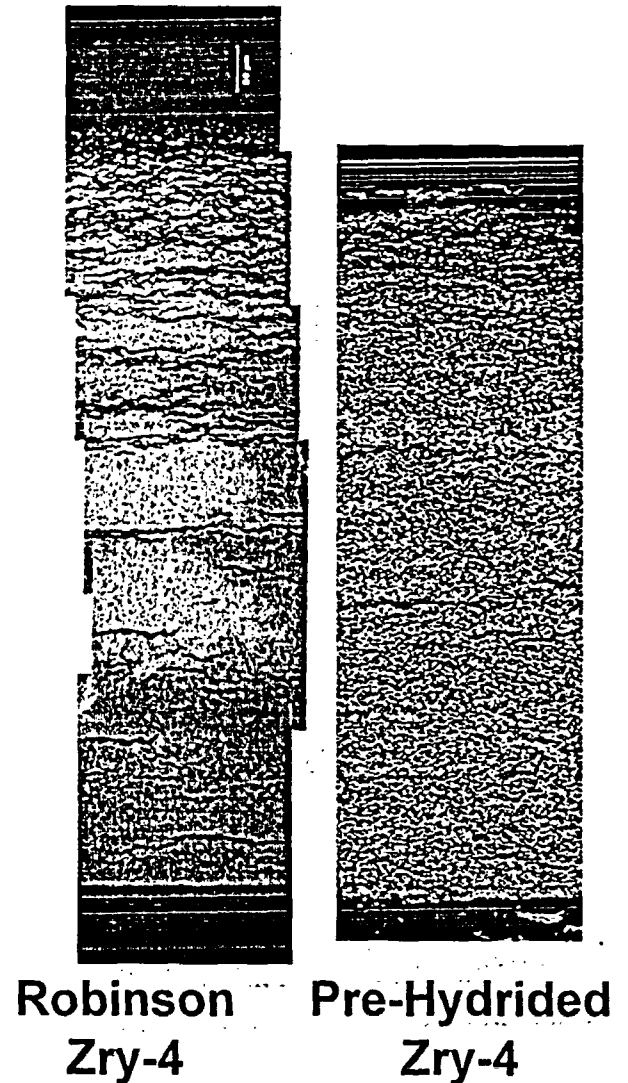
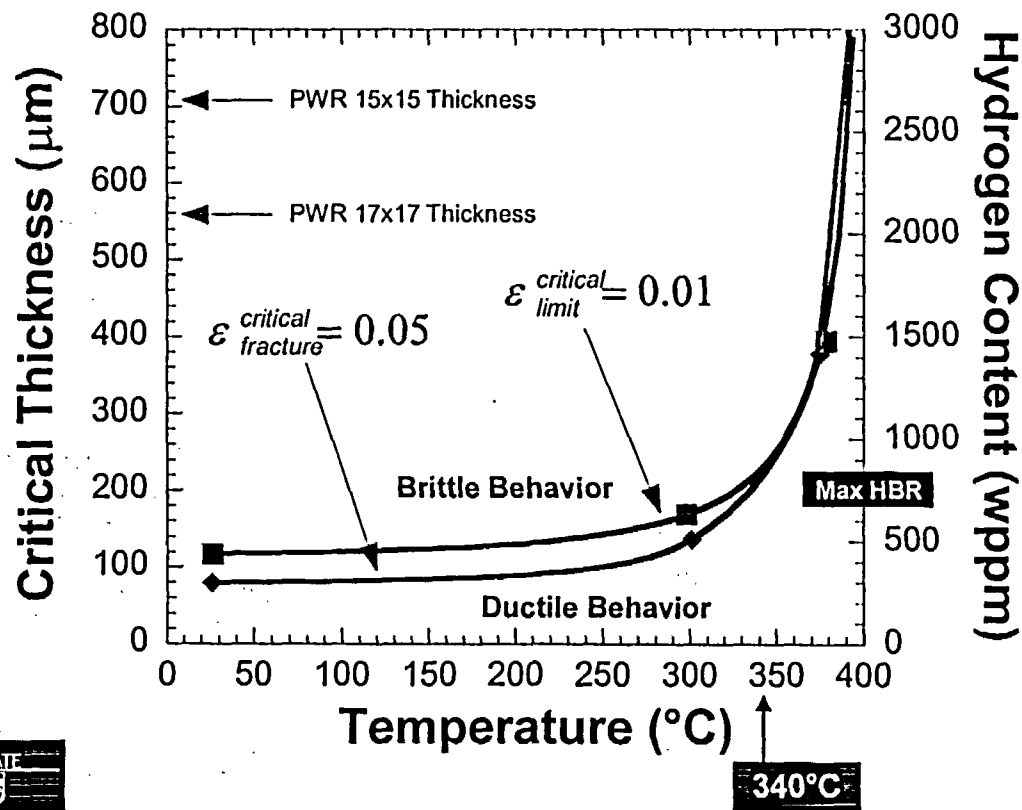
- Plane Strain Ring-stretch

- Biaxial Burst LOCA
 - Constant Pressure 800, 1600 psig (5.52, 11 MPa)
 - Temperature Ramp at 1 and 10°C/sec
 - Determine Rupture Temperature



Critical Strain Results for Pre-hydrided Zry-4

- Determine the influence of localized (layered) hydride precipitation on plane-strain ductility.



Pioneering
Science and
Technology

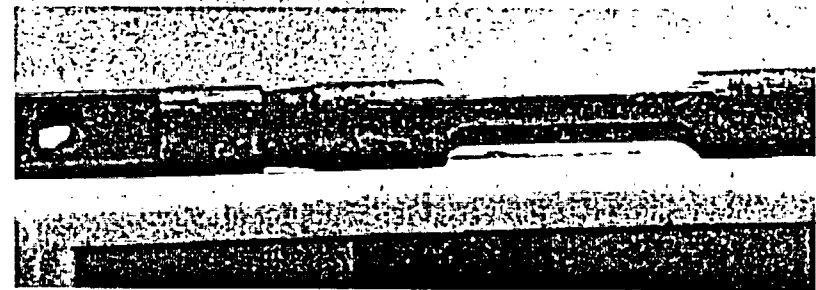
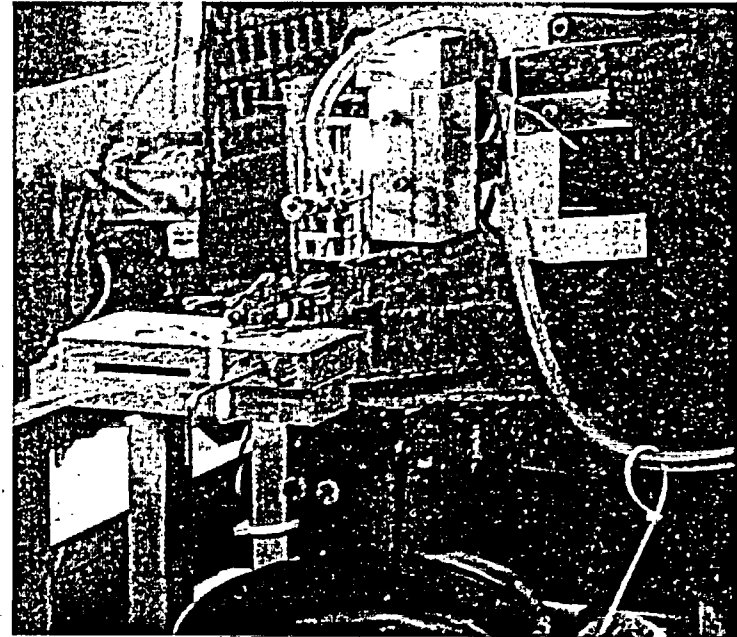
Nuclear
Regulatory
Commission



Irradiated Specimen Preparation

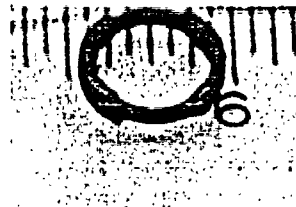
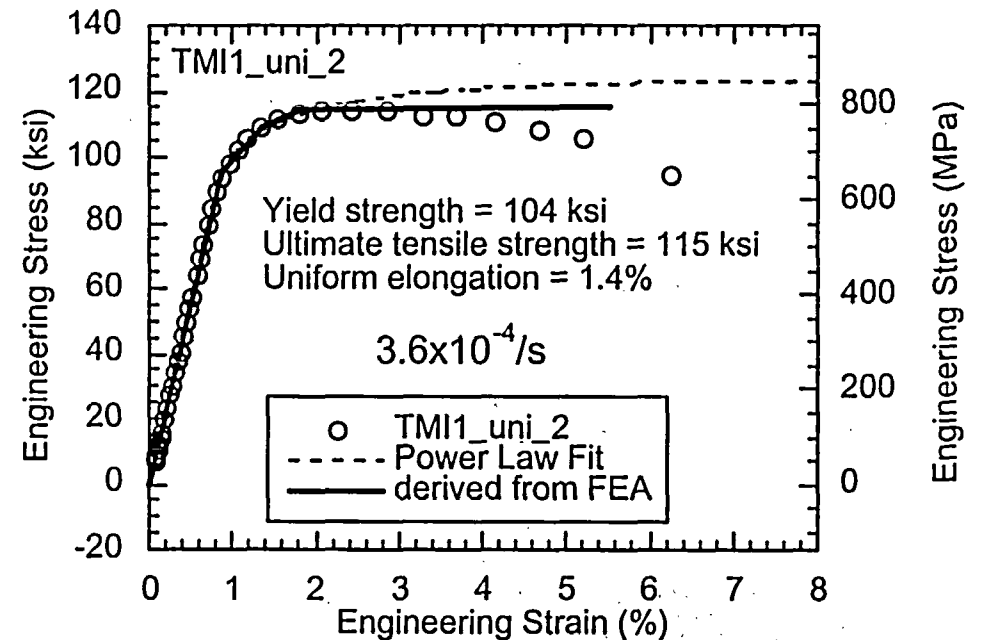
- **Irradiated Specimen Inventory:**
 - 12 RST and 4 Plane-Strain (TMI-1)
 - 7 Axial (5 – Surry and 2 – HBR)

Sectioning	Completed
Defueling	Completed
Oxide Removal	Completed
Endcap Welding	Completed
EDM	Completed
Testing	Re-initiate (October 2003)
Post-test Analysis	To follow



First Irradiated Test – TMI-1 Uniaxial RST

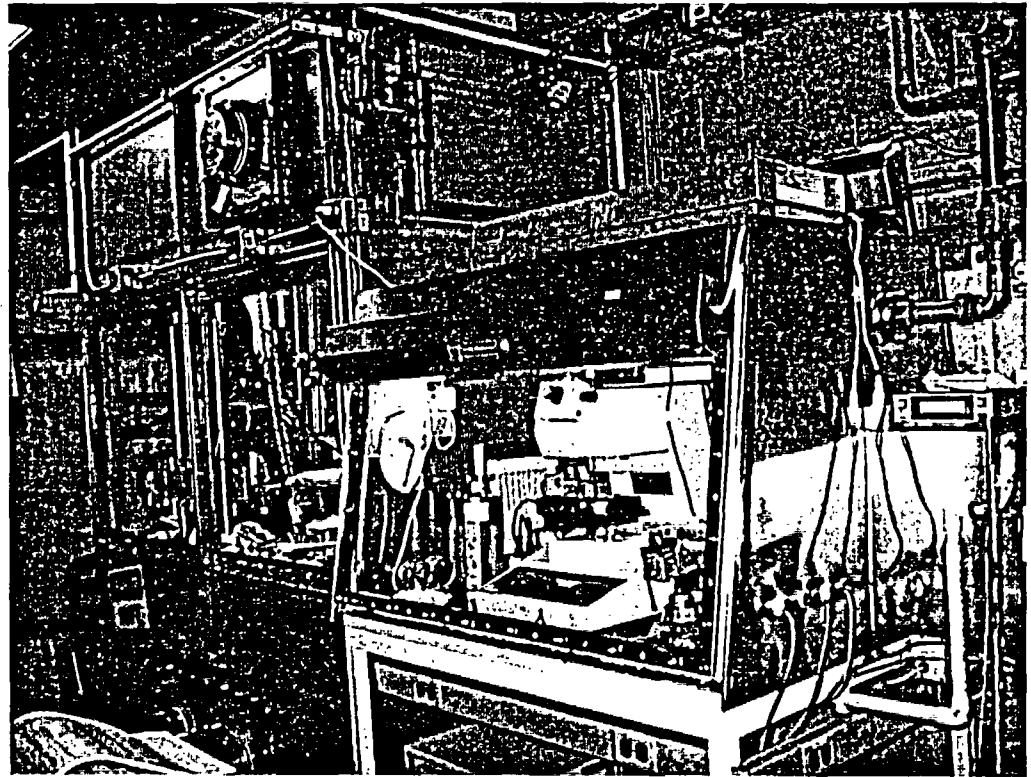
- Successfully completed July 2002
- ALARA assessment
 - Engineering barriers sufficient during test but significant contamination present during disassembly - HOLD POINT
 - Develop better contamination containment
- Recommendation for radiological glovebox system



Testing Facility Upgrades

- **Radiological Glovebox**

- Primary purpose is contamination control
- Conceptual design & operations
- DOE Mandated Reviews
 - Design
 - Experiment Safety
 - ALARA
- Construction
- Validation & Test Initiation
 - Unirrad. Zry-4 (in progress)
 - Irrad. Zry-4 (October 2003)



Pioneering
Science and
Technology

Nuclear
Regulatory
Commission



Summary of Dry Cask Storage Mechanical Tests

- **Thermal Creep Tests**

- Surry: 5 completed, 1 (400°C, 160 MPa) initiated, 1(400°C, 220 MPa)
- Robinson: 2 completed (400°C, 190 MPa)
2 initiated (380°C, 190 MPa & 220 MPa)
6 more tests planned (360-420°C, 160-220 MPa)
- Testing will resume in Fall 2003 after inspection of C15 test chamber

- **Axial Tensile Tests**

- Baseline properties of unirradiated 15×15 Zry-4 at RT- 400°C and 0.1-100%/s (in progress)
- Surry axial tensile tests: 2 at RT, 2 at 400°C, 0.1%/s and 100%/s
- Robinson axial tensile tests: RT-400°C (initiate in October 2003)



Summary of Dry Cask Storage Mechanical Tests (Cont'd)

- **Pre- and Post-Creep 3-Point-Bend Tests at RT**
 - Surry: 2 samples available at 1% and 6% creep strain
 - Robinson: 1 sample available at $\approx 4\%$ creep strain
 - Other samples will be generated at $\approx 1\%$ creep strain
- **Pre- and Post-Creep Impact Tests of Robinson Cladding**
 - ASTM standard tests are really high-strain-rate, 3-point-bend tests of notched bend-bars: guillotine impact (Charpy) or pendulum impact
 - Dynotech Guillotine Impact Tester available for hot-cell use
 - Test results give energy absorbed during crack-growth to failure
 - Fractography of failure surface gives information about brittle, mixed-mode and ductile failures
 - Are such tests meaningful for unflawed pre- and post-creep tubes?
 - How will the data be used?

Dry Cask Storage Status and Plans

- **Isotopic and Burnup Analysis**
 - 1 Limerick BWR location completed to benchmark methods
 - 2 Robinson samples (midplane & +0.7-m) are at ANL-CMT hot cells
 - Data collection and analysis will be completed in Fall 2003
 - Data evaluation to determine if test matrix should be completed (+7)
- **Annealing and Hydrogen Reorientation Studies**
 - Sealed, pressurized tubes with controlled T and cooling rate
 - Option to creep tubes prior to cooling
- **Post-Annealing & H-Reorientation Mechanical Properties**
 - Microhardness (inexpensive) or tensile tests?
 - Static or impact 3-point-bend tests?
- **Need to Prioritize: Time is Limited (Data needed NOW)**

Resources are Limited



Pioneering
Science and
Technology

Nuclear
Regulatory
Commission





Taming the Crud Problem

Arizona Public Service




APS Crud Model

Yovan D. Lukic




Evolving Core Design Philosophy

- Six years ago APS has transitioned to a more efficient core design philosophy
- Transition driven by desire for increased capacity factor and cost reduction pressures
- Shift from traditional checkerboard to Ring-of-Fire/Saturn core designs




Effects of Transition

- Crud/oxide buildup observed
- Crud inhibits heat transfer, increasing clad temperature and oxide layer growth rate
- Crud is also postulated to concentrate lithium leading to potentially increased clad corrosion
- Crud deposition may lead to boron deposition which is a precursor to AOA



Inspection Reveals Presence of Crud

- 1999 PV Unit 2 ninth refueling outage inspection revealed presence of tenacious crud on fuel clad
- Peripheral pins of high duty assemblies predominantly affected



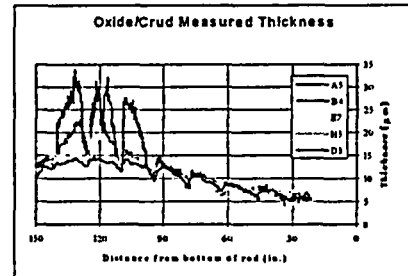
Plan of Action

- Effort was initiated to develop detailed T-H model of selected high duty assemblies
- Objective: establish correlation between localized T-H variables and measured crud thickness
- Correlation could be used as adjunct to lattice redesign to preclude T-H conditions which foster enhanced crud deposition

Crud Model Development

- Visual inspection revealed crud deposits on peripheral rods of assemblies such as P2K410
- P2K410 subsequently taken apart to ECT crud/oxide thickness of selected rods
- Measurements confirmed presence of crud at spans 7 through 9, most predominantly on peripheral rods

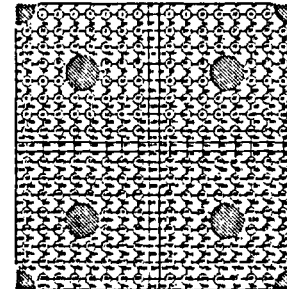
Crud Model Development



Crud Model Development

- A 353 sub-channel, 4 qtr-assembly T-H model was developed
- Axial and radial power distributions were calculated with SIMULATE-3 and entered into VIPRE2 with other required data
- In parallel to T-H development, analyses of ECT data were performed to quantify crud thickness of selected rods at axial locations corresponding to T-H model

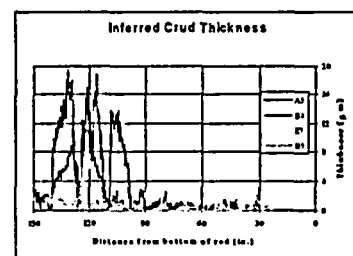
4-Qtr. Assembly T-H Model



Inferred Crud Thickness

- Fuel pin D3 did not show visual evidence of tenacious crud buildup
- As first approximation D3 considered to be affected by oxide only
- Inferred crud thickness for other pins obtained by subtracting pin D3 oxide thickness

Inferred Crud Thickness



Crud Thickness Regression Model

$$D_j(z) = \frac{k \bar{C} D^{F_1}}{D^{F_2}} \sum_{i=0}^{F_1} w_i Q_i(z) D_i(z) \quad 1 \leq j \leq N$$

$D_j(z)$ = crud thickness at end of burnup interval j

\bar{C} = cycle averaged crud concentration

k = crud deposition process efficiency

D = fuel cycle length

D = tenacious crud density

N = number of burnup intervals

w_i = burnup interval weighting coefficient

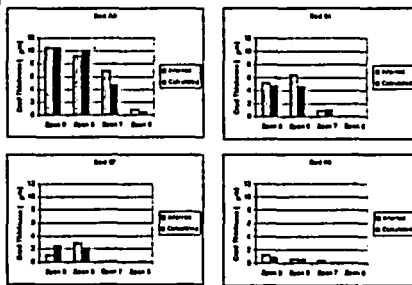
Q_i = burnup interval steaming rate

Q_i = burnup interval correction factor

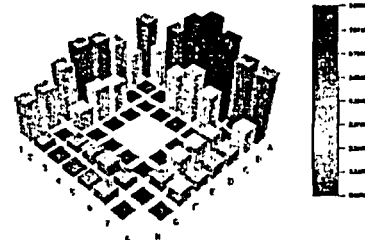
Crud Thickness Regression Model

- APS regression model has 5 parameters
- $\sum w_i = 1$
- Steaming rate traditionally calculated by subtracting convective from total heat flux
- Empirically determined steaming rate provides better results

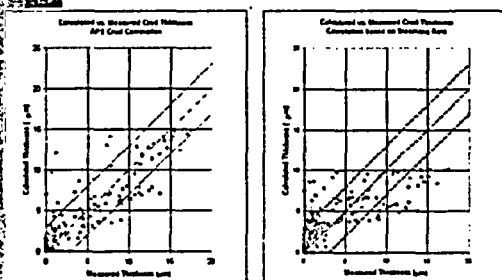
Crud Model Results



Crud Model Results

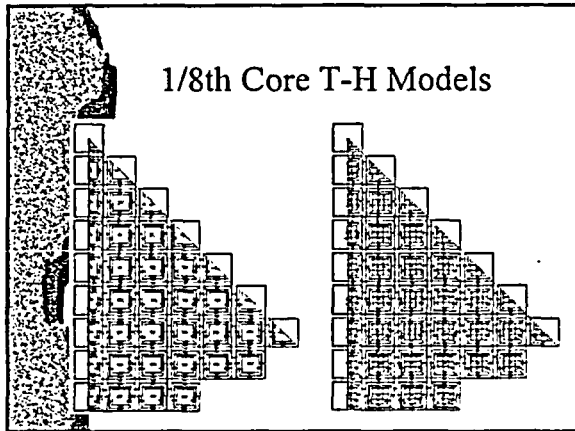


Model Comparison



1/8th Core T-H Model

- Lumped sub-channel model developed to quantify crud deposition on individual assemblies
- First developed 1/8th core model consistent with resolution of traditional lattice
- Second 1/8th core model provides enhanced resolution in assembly interior



1/8th Core T-H Models

A computer program written to read VIPRE2 output data

- Program calculates crud deposited on individual assemblies and on entire core
- Procedure helps us identify which assemblies are subjected to highest crud deposition
- If necessary use 4-Qtr. assembly model for fuel pin resolution level

Crud Model Application Results

- Crud model integrated into core design process
- Crud model used in six reload cycle designs with no AOA or crud induced fuel failures
- Crud model application prevents the cause, eliminates potential for crud induced corrosion and AOA, does not treat the symptoms

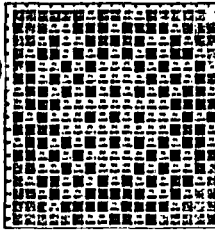
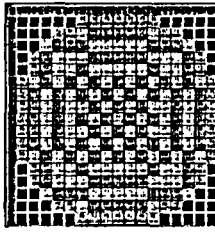
Lattice Redesign

Jeff S. Schmidt

PV Changes Fuel Mgt. Strategy

- Six years ago, Palo Verde switched in-core fuel management strategy
- Transition was driven by desire to increase plant capacity factor while trying to manage fuel costs
- From traditional checkerboard loading to ring type loading

PV Changes Fuel Mgt. Strategy

Checkerboard Loading
Ring Loading

Effect of Fuel Mgt. Strategy

- Refueling outage fuel inspections discover tenacious crud deposits on fuel clad
- Deposits are primarily on peripheral pins of high duty assemblies
- Contributing causes:
 - highest pin powers in low flow assembly locations
 - degrading core T-H conditions due to conservative steam generator tube plugging

Effect of Fuel Mgt. Strategy

- PV current core designs are predominantly limited by crud deposition, not by peaking factors or DNBR
- Crud deposition has led to AOA and fuel failures at some stations
- Integrated Fuel Performance Program created to address crud deposition

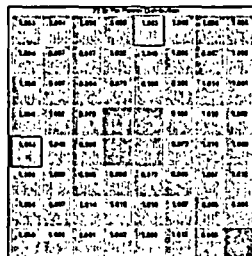
Current Lattice Design

- Two intra-assembly enrichments
- Low enrichment pins surround interior guide tubes and corner peripheral rods
- High enrichment pins make up rest of assembly
- This enrichment placement “pushes” power to high enrichment peripheral rods

Current Lattice Design

- Current lattice design in ring type loading is further compromised as a result of additional required erbium absorber
- Placement of burnable poison within assembly further shifts power to peripheral pins

Current Lattice Design



Pin power Distribution; NW assembly quadrant at BOC

Lattice Redesign

- Goal: avoid plant operational and pin integrity challenges while attempting to reclaim cost efficient ring loading
- Redesign aims to reduce total crud mass deposited; also a more homogeneous crud deposition across all pins in lattice
- Lattice redesign only consists of changes in intra-assembly enrichment and burnable absorber placement

Lattice Redesign

- Redesign effort consists of three phases:
 - Phase I: examine behavior of current lattice in ring type loading
 - Phase II: perform calculations to modify intra-assembly enrichments and poison distribution
 - Phase III: perform parallel core designs, one using the current lattice pattern and the other using the revised lattice pattern

Lattice Redesign

- Two approaches were applied to reduce total crud and to uniformly spread the rest:
 - lower early-cycle peak pin powers
 - improve match between pin powers and sub-channel flow

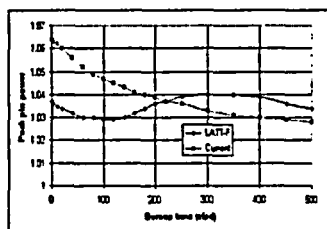
Lattice Redesign

- Steps used to redesign lattice pattern
 - Step 1: select intra-lattice enrichment split
 - Step 2: fine-tune intra-lattice power distribution by moving burnable poison placement
 - Step 3: repeat steps 1 & 2 until converging to a combination where peak power at BOC and MOC are ~ equal
 - Step 4: calculate crud deposition impact
 - Step 5: extend lattice development to a full range of lattice patterns

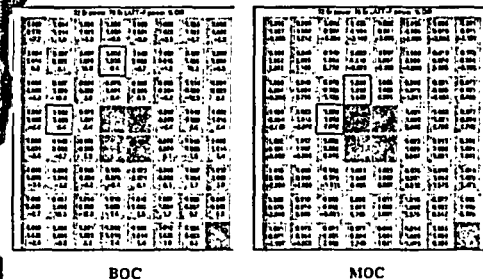
Lattice Redesign

- Completion of step 3 yielded a prospective 2-enrichment lattice redesign
- Lattice evaluation shows significant decrease in crud deposition
- Additional crud reductions were made possible by a 3-enrichment lattice redesign

Lattice Redesign



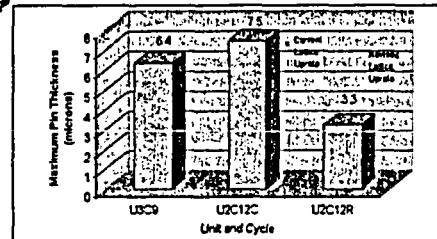
Lattice Redesign



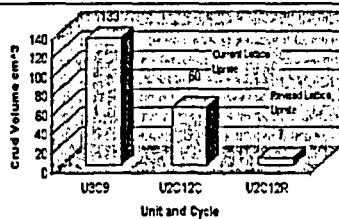
Lattice Redesign

- Phase III U2C12 design comparison
 - Current 2-enrichment lattice (U2C12C)
 - Redesigned 3-enrichment lattice (U2C12R)
- U2C12 core power +3% & $T_{in} +1.5$ °F
- Crud deposition contrasted with U3C9 which had mild, localized AOA

Lattice Redesign



Lattice Redesign



Conclusions

- Redesigned lattice is predicting significant reduction in crud deposition
- Palo Verde has decided to implement redesigned lattice in all future core designs
- Multi-cycle fuel inspections planned for Unit 2 to further validate crud model and lattice redesign