

Official Transcript of Proceedings

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: Wednesday, July 27, 2005

SISP REVIEW COMPLETED

Work Order No.: NRC-525

Pages 1-336

ORIGINAL

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

DISCLAIMER

UNITED STATES NUCLEAR REGULATORY COMMISSION'S
ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

July 27, 2005

The contents of this transcript of the proceeding of the United States Nuclear Regulatory Commission Advisory Committee on Reactor Safeguards, taken on July 27, 2005, as reported herein, is a record of the discussions recorded at the meeting held on the above date.

This transcript has not been reviewed, corrected and edited and it may contain inaccuracies.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25

UNITED STATES OF AMERICA

NUCLEAR REGULATORY COMMISSION

+ + + + +

ADVISORY COMMITTEE ON REACTOR SAFEGUARDS (ACRS)

+ + + + +

SUBCOMMITTEE ON REACTOR FUELS

+ + + + +

WEDNESDAY,

JULY 27, 2005

+ + + + +

ROCKVILLE, MARYLAND

+ + + + +

The subcommittee met at the Nuclear Regulatory Commission, Two White Flint North, Room T-2B3, 11545 Rockville Pike, at 8:30 a.m., Dana A. Powers, Chairman, presiding.

COMMITTEE MEMBERS:

DANA A. POWERS, Chairman

RICHARD S. DENNING, Member

THOMAS S. KRESS, Member

WILLIAM J. SHACK, Member

ACRS/ACNW STAFF:

RALPH CARUSO, Designated Federal Official

NEAL R. GROSS

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

1 PANELISTS:

2 MIKE BILLONE, Argonne National Laboratory

3 BERT M. DUNN, Advisory Engineer, Framatome ANP

4 JEAN-PAUL MARDON, EPRI

5 ROBERT MONTGOMERY, EPRI

6 ODELLI OZER, Fuel Reliability Program, EPRI

7 NRC STAFF:

8 FAROUK ELTAWILA, RES/DSARE

9 RALPH MEYER, RES

10 HAROLD SCOTT

11

12

13

14

15

16

17

18

19

20

21

22

23

24

25

A-G-E-N-D-A

Technical Basis for Revision of the Embrittlement

Criteria in 10 C.F.R. 50.46

Introduction

Chairman Dana Powers 4

Opening Remarks

Dr. Farouk Eltawila 6

Technical Basis for Revision of Embrittlement Criteria
in 10 C.F.R. 50.46

Dr. Ralph Meyer 13

ANL LOCA-relevant Research Results

Dr. Mike Billone 16

Overview of Industry Concerns

Mr. Odelli Ozer 182

Recent Data from CEA Experiments

Mr. Jean-Paul Mardon 199

Evaluation of Experimental Results

Mr. Robert Montgomery 241

Framatome Perspective

Mr. Bert Dunn 281

Staff Response to Industry Comments

Dr. Ralph Meyer 309

Adjourn

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

8:30 a.m.

CHAIRMAN POWERS: The meeting will come to order. This is a meeting of the Advisory Committee on Reactor Safeguards Subcommittee on Reactor Fuels. I'm Dana Powers, chairman of the subcommittee. Subcommittee members in attendance are Dr. Tom Kress, who I'll note is the member with the longest tenure on the ACRS, Rich Denning, who I'll note is the member with the shortest tenure on the ACRS, and Bill Shack, who is the vice chairman of the ACRS.

MEMBER DENNING: Did you say he's the --

CHAIRMAN POWERS: No, he's on the left wing, as you well know. The purpose of the meeting today is to discuss the results of activities in the Office of Research related to the development of revised LOCA criteria for reactor fuel. Tomorrow we will hear about the behavior of reactor fuel during reactivity-initiated accidents. The subcommittee will hold discussions with representatives of the NRC staff and with the 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 participating 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 June 29, 2005. For those of you that
6 regularly review the Federal Register, you will know
7 that a transcript of the meeting is being kept and
8 will be made available as stated in the Federal
9 Register notice. It is requested that speakers first
10 identify themselves and speak with sufficient clarity
11 and volume so they can be readily heard. We have
12 received requests from one member of the public, Mr.
13 Shadis of the New England Coalition for time to make
14 oral statements. And Mr. Shadis, if you will be kind
15 enough to look at the agenda and let me know when it
16 would be appropriate for you to speak we will make the
17 arrangements to give you time then.

18 Do members of the subcommittee have any
19 opening comments they would like to make?

20 MEMBER SHACK: Yes, Mr. Chairman. I'd
21 like to note that I have a conflict of interest today
22 since some of the work that's being discussed is being
23 performed at Argonne National Laboratory.

24 CHAIRMAN POWERS: And the subcommittee
25 will then be utilizing you as a resource for

NEAL R. GROSS

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

1 clarification, but not for generation of opinions and
2 tentative actions. Right? Yes. Feel free to join in
3 for the technical discussions. Historically meetings
4 of the Reactor Fuel Subcommittee have been highly
5 technical in nature.

6 With no other comments to be made, I'll
7 turn to our first speaker who is Mr. Farouk Eltawila
8 of the Office of Nuclear Regulatory Research.

9 MR. ELTAWILA: Good morning and thank you
10 Mr. Chairman. As you know, for several years we have
11 been investigating the effect of burnup on fuel
12 behavior during pulse related directivity and shaft
13 accident, and loss of coolant accident. This has been
14 done according to a program plan that has been
15 endorsed by NRR, and was most recently updated in
16 August 2003.

17 In September 2003, we met with this
18 subcommittee, a new member here, Dr. Denning, and
19 updated the provided -- described the detail, how we
20 are going to address the regulatory criteria for
21 reactivity insertion accident and loss of coolant
22 accidents. A few months later the ACRS in its report,
23 NUREG-0365 I believe, wrote a very favorable comment
24 about the research, and we appreciate the feedback
25 that we got from you on that.

NEAL R. GROSS

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

1 In the staff requirement memorandum, and
2 that's the mechanism that the Commission interact with
3 the staff, dated March 31, 2003, the Commission
4 approved the staff recommendation to proceed with
5 modification to 10 C.F.R. 50.46 to provide for more
6 performance-based approach to meeting ECCS acceptance
7 criteria. Our research is complete enough now to
8 initiate this modification, so we asked for this
9 meeting today to get early ACRS input in this
10 progress. This modification is intended to
11 accommodate the effect of high-burnup on fuel cladding
12 behavior, and to generate a rule to apply to all
13 zirconium alloy cladding. As you know, the rule right
14 now is written for zirconium, and ZIRLO, and M5 is not
15 specified in the rule, and we have to apply every time
16 for a licensing amendment or exemption.

17 At the present time exemption from the
18 regulatory is needed for the M5. We are working on a
19 tight schedule now to try to rectify this situation.
20 And the current schedule called for publication of an
21 advance notice of proposed rulemaking in early January
22 of next year. Therefore we would like to get a letter
23 from the ACRS after the full committee meeting in
24 September so those comments can be factored into the
25 internal discussion before we issue the rulemaking.

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: Dr. Eltawila, is the
2 schedule such that you need the letter in September?
3 October would not do?

4 MR. ELTAWILA: The technical basis on the
5 operating plants is supposed to be provided to NRR at
6 the end of September. But, you know, getting a letter
7 in September or October will not cause any problem
8 because we are planning to, you know, just preparing
9 for the rulemaking and things like that will take all
10 the way up to January or something.

11 CHAIRMAN POWERS: I mean, I guess the
12 situation is if we're going to write you a letter that
13 says it looks good, then you can get it in September
14 or October. If we have any substantive comments on it
15 you'd like to get it in September.

16 MR. ELTAWILA: Definitely September. You
17 are going to hear a different story from the industry,
18 I can assure you that. So I'm giving you a heads-up,
19 you know, because we received a letter from
20 Westinghouse indicating that they would like to see a
21 delay in the rulemaking, and we are planning to
22 respond to that letter. Not Westinghouse, the
23 chairman of the program just happens to be from
24 Westinghouse.

25 Also last year we prepared a research

NEAL R. GROSS

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

1 information letter, and we forward to NRR to provide
2 the technical basis for reactivity insertion accident.
3 NRR used that, and based on that evaluated an EPRI
4 supplemental on proposed criteria for the reactivity
5 insertion accident. And EPRI is planning to make a
6 presentation on that issue today.

7 CHAIRMAN POWERS: On the general thrust,
8 I mean, the general strategy without speaking to the
9 specifics of the letter, this evolution of a fairly
10 detailed scientific research into a research
11 information letter that then goes into the regulatory
12 process strikes me as an area that RES should be proud
13 of, and that the Commission should be aware of that
14 progression. Do you share that view? We might want
15 to think about commenting on that history in some
16 report to the Commission, just so they're aware how
17 this program has progressed.

18 MR. ELTAWILA: I think we'd appreciate
19 that, definitely.

20 CHAIRMAN POWERS: We might.

21 MR. ELTAWILA: It would be very good for
22 the Commission --

23 CHAIRMAN POWERS: I'd work with you a
24 little bit to try to put that together as distinct
25 from the September issue, just so we understand how

NEAL R. GROSS

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

1 these things go. Because as you are aware, in a
2 couple of reports that the ACRS has prepared on
3 research, one of which was written just when you
4 started your RIA work, and one about three-fourths of
5 the way through. They were fairly complementary on
6 the planning and whatnot, and it would be nice to
7 round that out, just to say, well, and here's what the
8 product was that came out.

9 MR. ELTAWILA: In fact, some of the
10 comments that the ACRS committee made on the
11 reactivity insertion accident in the NUREG report
12 helped us as ammunition that we interacted with RSN
13 about the way the test program should be, and we said
14 if you don't really have a test program that
15 challenging the fuel, and things like that, we will
16 not be able to participate. And we used the report as
17 a weapon. So that was very good.

18 CHAIRMAN POWERS: Well, our intention is
19 not to write things that are weapons, but I think it
20 might be useful for the subcommittee to consider
21 drafting a letter that just ties that up. Because as
22 you recall, I think it was four years ago that we
23 wrote in our research report when this work was just
24 being undertaken. And we subsequently wrote a report
25 that Dr. Eltawila mentioned in which we suggested some

NEAL R. GROSS

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

1 course corrections. And then to say, okay, here's
2 what came out of it would be useful, I think,
3 especially since the Commission now has two members
4 that did not track that history.

5 MR. ELTAWILA: And actually you have two
6 new Commissioners who will appreciate this kind of
7 mention. Just, that takes me to my final comments.
8 As you know, this research program is a cooperative
9 research program, and we work very closely with EPRI
10 and Westinghouse, Framatome. They have provided us
11 with the fuel, and provide good comments on the
12 research program. We also have international
13 cooperation with RSN as I mentioned. We have
14 cooperation with Russia, and Halden, and JAERI of
15 course in Japan. And the information is flowing
16 freely among this organization, but because, as you
17 are aware, that we have to interpret our results
18 independently from the industry, you will see some
19 difference in interpretation. The way we interpret
20 our results, the same results actually, the same
21 experimental data, is being interpreted differently by
22 NRC versus the industry. And we hope by the end of
23 these couple of days we will try to shed some light
24 about these differences, and if they are a big problem
25 or something that we can deal with. That's all the

NEAL R. GROSS

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

1 opening remarks that I have. I would like to see if
2 you have any questions before I turn it to Dr. Meyer
3 to open the meeting.

4 CHAIRMAN POWERS: I'm sure we'll have a
5 lot of questions. I'd like to work with your staff in
6 trying to put together a little history on this RIA,
7 especially the ability to do things jointly with the
8 industry and with international cooperation, yet
9 retaining this independence of interpretation. My own
10 feeling of course is independent interpretations, and
11 differences of opinion in interpretations is a healthy
12 sign for the field. I think that that's not a
13 detraction. It may create challenges for our friends
14 in NRR, but it is -- in the scientific basis, this is
15 a healthy thing. And I think it's an area that the
16 Commission needs to know about.

17 Now we move on to --

18 MR. ELTAWILA: I agree with you. I
19 believe definitely at the end of the day our rule, our
20 regulation, the result of that research will be much
21 more stronger once we reach the understanding of the
22 other point.

23 CHAIRMAN POWERS: That's right.

24 MR. ELTAWILA: So I don't -- I agree with
25 you. We are not thinking about it as a detraction or

NEAL R. GROSS

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

1 anything like that. So, Ralph?

2 DR. MEYER: Well, this is really a special
3 moment for me because we're bringing to completion two
4 large projects that I've been working on for about 10
5 years. And of course there will be some follow-on
6 work in each of the areas, but we're now going to try
7 and make use of the major results from these programs.
8 I'm especially proud of the LOCA work that is being
9 done at Argonne National Laboratory. In 1995, while
10 most of the fuel world's attention was still focused
11 on reactivity accidents after the test in France and
12 Japan that we all know about, I initiated the project
13 at Argonne to look at the fuel damage criteria used
14 for LOCA analysis. Others soon realized that possible
15 deficiencies in the LOCA criteria were more important
16 than those in the RIA criteria because of the greater
17 risk significance of a loss of coolant accident.

18 The industry then joined us in the Argonne
19 program, and within a couple of years, as Farouk will
20 underscore, we were spending big bucks on real
21 experimental research. The laboratory also pitched in
22 with refurbishing of some aging equipment. We soon
23 had a world-class research program that had taken the
24 lead on the safety testing. Spending big bucks in the
25 21st century is relative, though, and this program is

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 nothing like the big LOCA research programs that we
2 had in the late '70s and early '80s. We have only got
3 about 10 people, some part-time, working at one
4 laboratory and a 40-year-old hot cell. Nevertheless,
5 under the first-class leadership of Mike Billone we're
6 getting really high quality results, but we're not
7 able to pursue all avenues and answer all questions in
8 this modest program. And we're not going to keep
9 asking for more money to extend the program year after
10 year in pursuit of more answers when we have enough to
11 make good decisions now.

12 Here's what to expect. You'll find this
13 to be true in today's presentation and in tomorrow's.
14 The number of data points that we have is smaller than
15 you'd like. You can ask some questions that we won't
16 be able to answer. And you'll see us trying to do
17 best estimate work, but sometimes having to make a
18 choice between assumptions, and if one assumption
19 looks conservative and one looks non-conservative
20 we'll choose the conservative one. In the end, our
21 result might be a little conservative, but our
22 conclusions are sound, and I don't think you can do
23 better with the available data.

24 Now, I'd like to talk about our LOCA work,
25 and after two very brief background slides I'll give

NEAL R. GROSS

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

1 you the bottom line, and then proceed to fill in the
2 blanks. Okay. So, the criteria we're going to talk
3 about are called embrittlement criteria, and they came
4 about in this way. We start with the requirement to
5 maintain coolable geometry, which is embedded in our
6 general design criteria. And then, after a lengthy
7 hearing in the early 1970s the Commission concluded --
8 I'm going to need a pointer, Theron, sometime -- the
9 Commission concluded that if you step down from the
10 general requirement of maintaining coolability to
11 keeping fuel pellets inside the cladding, and to do
12 that, not letting the cladding fragment, and on down
13 the logic chain you end up with putting limits on
14 oxidation and temperature.

15 CHAIRMAN POWERS: When I look at this, I
16 mean the coolability seems very plausible, keeping the
17 fuel pellets inside the cladding seems a plausible
18 criterion. Don't let the cladding fragment, break
19 into several pieces seems. This next step, to go from
20 there to retain some ductility in the cladding. It
21 seems plausible. What I wonder is do we have anywhere
22 information that says, gee, when I re-flood hot cores
23 I get fragmentation when I have this much ductility,
24 and don't get fragmentation when I have another amount
25 of ductility. I mean, do we know what re-flooding of

NEAL R. GROSS

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

1 cores do and loss of ductility?

2 DR. MEYER: Well, yes we do, not from re-
3 flooding whole cores, but from doing tests on
4 individual and multiple fuel rods where we in fact re-
5 flood the test apparatus and produce quenching
6 conditions that are very similar to what we expect
7 during the LOCA. Now, your -- okay, ask it again.

8 CHAIRMAN POWERS: Where do I go to find
9 these experiments?

10 DR. MEYER: The experiments?

11 CHAIRMAN POWERS: Yes.

12 DR. MEYER: Well, Mike will talk about
13 some of them today, and historically the original
14 experiments that were -- there were some done by not
15 Hobson, but who were some of the? Mike, help me here.
16 The early quench tests. I don't think Hobson did
17 quench tests, did he?

18 DR. BILLONE: Not of -- I'm sorry, Mike
19 Billone. I was going to address the question a little
20 differently, Dana. There's no complete analysis done
21 of a degraded core that would include every possible
22 load mechanism. There are experiments that were done
23 in the '70s and in the early '80s in which sometimes
24 non-irradiated material was ballooned, and burst, and
25 quenched. And very limited work would have been done

NEAL R. GROSS

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

1 with lightly irradiated rods. So we don't have -- in
2 my opinion, and Ralph can disagree, we don't have a
3 classical stress analysis of a degraded core during
4 quench. So there's a multiple number of possible
5 loads. The idea about cladding retains some ductility
6 historically was because there was some skepticism on
7 the Commission's part that you could quantify what
8 those loads were for a degraded core.

9 DR. MEYER: There were quench tests prior
10 to the hearings in 1972. And they were discussed.
11 There have been a lot more in the late '70s and early
12 '80s. And we've done some ourselves recently. And
13 this is a major point. And going from this step to
14 this step is one that is of interest to the industry
15 right now. But this is a historic fact, that the
16 Commission debated this, that the parties debated it
17 at the hearing. And the Commission then, based on the
18 findings of the hearing went in this direction. And
19 they expressed their skepticism at being able to
20 analyze the loads and strength responses to the LOCAs
21 because they didn't know what loads would arise. And
22 so they backed down to the position that they said --
23 where they said just give us some ductility, any
24 ductility, and that will be okay. And in fact, I
25 think it's true in all of the quench tests that are

NEAL R. GROSS

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

1 done, if the material has ductility it survives the
2 quench. In fact, all of the specimens that -- well,
3 maybe that's not true. Maybe you slow-cool some
4 specimens. But we test specimens -- the matter of
5 ductility is post-quench ductility. So you've
6 survived the event and have something else left. And
7 just simply the historical origin of the oxidation and
8 temperature limit.

9 CHAIRMAN POWERS: Here's where I get a
10 little bit confused. If we go back to the title of
11 your slide where you say we're going to revise
12 criterion, we're not looking back at something that's
13 now 30 years old. And quite frankly, a lot of water
14 has gone over the technical dam in 30- 35 years. On
15 the other hand, I am aware of experiments conducted in
16 Germany with boron carbide control rods in which the
17 quenching process did not progress in a classic quench
18 and freeze process, but rather resulted in a rather
19 exothermic excursion in the facility, and did
20 significant damage even to the facility. So this
21 step, it seems to me that don't let the cladding
22 fragment, and going then to ductility seems to be a
23 step that needs some attention, at least to establish
24 the basis for going on through the ductility step.

25 DR. MEYER: Well, I guess I want to

NEAL R. GROSS

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

1 respond two ways. First of all, we did not attempt to
2 start from scratch, and start up at this line, and re-
3 derive LOCA criteria. We attempted to stay down here
4 and find a minimum change in the regulations that
5 would account for the effects of burnup, and the
6 effects of alloys that have been introduced to achieve
7 the burnups. And that's where we're going with this
8 presentation. But on the other hand, I have to say
9 that there's been an awful lot of testing with
10 quenching. The Japanese are doing a lot right now.
11 And the retention of post-quench ductility always is
12 sufficient to make sure that the fuel rod survives the
13 quench process. It doesn't shatter. It doesn't
14 oxidize rapidly during the quench process or anything
15 like that. It's already in the steam. It's already
16 oxidizing at the higher temperature.

17 CHAIRMAN POWERS: Can you explain Quench
18 8 then?

19 DR. MEYER: Hm?

20 CHAIRMAN POWERS: Can you explain that at
21 Quench Test 8?

22 DR. MEYER: Can I explain?

23 CHAIRMAN POWERS: Quench -- the Number 8
24 test in the quench program.

25 DR. MEYER: This is a severe accident test

NEAL R. GROSS

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

1 that I think is conducted under conditions more severe
2 than we're talking about here because we put limits on
3 temperature and oxidation in order to stay in this
4 rather benign regime.

5 CHAIRMAN POWERS: But I think that raises
6 questions on whether you're in the benign regime
7 universally, doesn't it?

8 DR. MEYER: Well, I think we have ample
9 demonstration that the regime is benign. If we limit
10 the temperatures to about 1200 degrees Centigrade, and
11 limit the oxidation, or as you'll see I'm going to
12 take time at temperature, limit the time at
13 temperature such that you don't embrittle the cladding
14 to the extent that it would be subject to a lot of
15 brittle --

16 CHAIRMAN POWERS: Remind me, what's the
17 minimum eutectic in the boron carbide steel system?

18 DR. MEYER: I'm sorry?

19 CHAIRMAN POWERS: The boron carbide steel
20 system, where's the minimum eutectic in that system?

21 DR. MEYER: In boron carbide? I have no
22 idea.

23 CHAIRMAN POWERS: For some reason, 1100
24 degrees Centigrade sticks in my mind, but I could be
25 wrong about that.

NEAL R. GROSS

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

1 DR. MEYER: So you're thinking of control
2 rods now?

3 DR. BILLONE: That's preferable, yes.

4 CHAIRMAN POWERS: Say that again, please?

5 DR. BILLONE: I was -- Farouk was going to
6 speak. I was going to ask you if you wanted an
7 example of when cladding does fragment, or are we past
8 that point. And how it's related.

9 CHAIRMAN POWERS: That would be
10 interesting.

11 DR. BILLONE: Okay. Generally, if I go
12 back to the experiments of Hee Chung in the early
13 '80s, what he found is that for any single rod test,
14 or portion of a rod, it's very easy to survive quench
15 if there are no other loads, until you get to very
16 high oxidation levels. But if you oxidized at 1260
17 degrees C, which is above the limit, in let's say 17
18 percent ECR, you not only totally embrittle the
19 material, and whether a brittle material fragments or
20 has a clear break depends on the loading, but he
21 subjected his loading to a pendulum impact test.
22 Those samples did shatter. So generally in any
23 experiment you do something else beyond just the
24 quench. Either you're restraining it axially to put
25 axial loads, or you literally after the experiment run

NEAL R. GROSS

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

1 a series of mechanical tests, whether they be impact
2 tests or not. But you generally -- you lose ductility
3 first, then you go farther than that, and then you
4 fragment.

5 So, it's sort of like being a little
6 conservative. You want the material to be forgiving,
7 and able to withstand --

8 CHAIRMAN POWERS: Yes, I think my
9 understanding of the point that Dr. Meyer was making
10 was that if he's got ductility at room temperature
11 after the quench, he certainly had ductility at the
12 higher temperature, and that therefore he has some
13 conservatives in here. What I'm asking is do we know
14 that this is really the right criterion in light of
15 things like quench tests. I mean, these are tests
16 that have taken place since this era of the '70s when
17 this general strategy was developed. I'm just asking.
18 I mean, it may be fine. I'm just asking if you're
19 looking at it.

20 DR. MEYER: Well, we haven't looked at the
21 severe accident test.

22 CHAIRMAN POWERS: Well, I mean theirs are
23 not what I would call very severe accidents. They are
24 -- I mean, they definitely don't melt fuel. They may
25 melt control rods. But that's because there's a deep

NEAL R. GROSS

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

1 eutectic in the boron carbide steel system, and I
2 quite frankly don't remember where it is. And like I
3 said, 1100 degrees sticks in my mind, but that could
4 be off by 200 - 300 degrees. I simply don't remember.

5 DR. BILLONE: I'm sorry.

6 DR. MEYER: Should I go on?

7 CHAIRMAN POWERS: Yes, please.

8 DR. MEYER: Okay. So, this is the -- I'm
9 going to call it the procedure that we believe is
10 currently being followed. Some of it is in the
11 regulation. Some of it is interpretation. The first
12 part is in the regulation. The embrittlement criteria
13 are in the regulation. They're in subparagraphs
14 (b) (1) and (b) (2) of 50.46. There's a well known peak
15 cladding temperature limit of 2200 degrees Fahrenheit,
16 1204 Centigrade. And there's a maximum cladding
17 oxidation limit of 17 percent calculated on the basis
18 of the total oxygen absorbed, and related to the
19 thickness of the cladding with wall thinning taken
20 into account if you're running this calculation for a
21 region inside of the balloon. I'll show you what the
22 balloon looks like in a little bit.

23 In Appendix K of Part 50 of the
24 regulations you have ECCS models that are -- some
25 required, some others acceptable, and in that it's

NEAL R. GROSS

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

1 prescribed that two-sided oxidation be calculated
2 within 1.5 inches of the location of the burst. In
3 addition to that, in 1998 we issued an information
4 notice with subsequent clarification by letter saying
5 that total oxidation, which are the words that appear
6 in the regulation, is interpreted by NRC to include
7 both the pre-accident oxidation or corrosion, and the
8 oxidation that takes place during the transient. So
9 that's where we are right now. And what we want to do
10 is see what needs to be done to that in order to
11 accommodate burnup, and alloy effects.

12 Now, this is the bottom line, so I'm going
13 to give you the bottom line now and then try and go
14 back and explain how I got there. So if you can maybe
15 save your questions till we talk about them. So at
16 Argonne, we have data being obtained right now on
17 unirradiated and high-burnup cladding to give us the
18 technical basis. We've developed some -- what I think
19 of as minimal modifications, trying not to totally
20 revise the logic and conclusions of this hearing, but
21 to modify the criteria in a way that would be least
22 disruptive to existing licensing models and
23 calculations. The criteria would be different from
24 the current criteria inasmuch as it would not involve
25 a fixed oxidation limit of 17 percent, but rather a

NEAL R. GROSS

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

1 limit to be determined for each planning alloy, and we
2 have determined that limit for all of the cladding
3 alloys that are currently in use. And we'll mention
4 those to you. Because the rule as it's written would
5 require testing on each particular alloy. It's
6 performance-based, and the criteria therefore would
7 apply to all zirconium-based alloys, because you're
8 going to test each one of them. For modern Zircaloy,
9 and I'll make a distinction a little later between
10 modern Zircaloy and old Zircaloy, and ZIRLO, and M5
11 cladding, which are the current types in operating
12 reactors now, these limits would turn out to be 17
13 percent minus the corrosion thickness, that's the
14 current practice. A limit on the time spent at high
15 temperatures of 45 minutes from rupture to quench,
16 which is -- the analyses that we're familiar with are
17 all well below this, so it's not a problem, but I'll
18 show you why such a limit is necessary. All
19 calculations done with the Cathcart-Pawel correlation.
20 If the compliance calculations have been done with the
21 Baker-Just correlation that's no problem, it would be
22 conservative in this application. But you're going to
23 see that we're going to use this Cathcart-Pawel
24 correlation as what I refer to as a time scale rather
25 than anything else. And I'll explain that as we get

NEAL R. GROSS

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

1 going.

2 MEMBER KRESS: Are the first two sub-
3 bullets under there redundant?

4 DR. MEYER: No.

5 MEMBER KRESS: No?

6 DR. MEYER: They're not redundant. I'll
7 tell you why. At the lower temperature, say 1000
8 degrees Centigrade, which is a very relevant
9 temperature for small break LOCA, where you might sit
10 there for a long time. You cannot get 17 percent
11 oxidation at 1000 degrees before -- in some alloys,
12 before you start getting breakup of the oxide, and
13 high hydrogen absorption, and rapid loss of ductility.
14 And so you need a time limit. So it's got to be less
15 than both of those. In light of all this, we don't
16 expect any re-analysis, and I hope to be able to show
17 you that we haven't raised any safety concerns about
18 the operating plants, because although they might not
19 -- the licensing analysis might not have been done
20 exactly this way, I think we can see that in fact if
21 one had looked at these things they would have fit
22 these criteria.

23 MEMBER KRESS: On the third bullet,
24 Cathcart-Pawel gives you an amount of oxidation and
25 energy release, but it doesn't tell you what

NEAL R. GROSS

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

1 temperature.

2 DR. MEYER: It doesn't tell you what?

3 MEMBER KRESS: What temperature you're
4 running at. It says 45 minutes from rupture to
5 quench. Isn't that related to the temperature you're
6 going to have? Isn't that related to what kind of
7 LOCA you have?

8 DR. MEYER: It's related to the behavior
9 of the cladding, regardless of what kind of LOCA you
10 have. If you hold the cladding at a fairly low
11 temperature, like 1000 degrees is kind of the prime
12 temperature for looking at this because at lower
13 temperatures the oxidation is slower.

14 MEMBER KRESS: That's sort of a limiting,
15 though, value.

16 DR. MEYER: I'm going to show you some
17 pictures, and you're going to see what happens here.
18 But if you -- you simply can't get to 17 percent with
19 some of these alloys before the oxide starts breaking
20 up. And so we put this other limit on there. And you
21 see --

22 CHAIRMAN POWERS: There seem to be a
23 couple of assumptions here. One is that you
24 anticipate all future alloys will continue to be a
25 zirconium base. Is that correct?

NEAL R. GROSS

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

1 DR. MEYER: All future alloys will what?

2 CHAIRMAN POWERS: All future cladding
3 alloys will be zirconium based.

4 DR. MEYER: The staff requirements
5 memorandum has specifically instructed us to write
6 this for zirconium-based alloys. So the rule would
7 say zirconium-based alloys. So if you had something
8 other than zirconium-based alloys, then you'd have to
9 go figure what criteria you needed for the ECCS.

10 CHAIRMAN POWERS: The other assumption
11 that seems to be inherent here is that you come up to
12 a temperature and kind of hold.

13 DR. MEYER: Yes.

14 CHAIRMAN POWERS: Is that what happens --

15 DR. MEYER: No.

16 CHAIRMAN POWERS: -- to fuel rods in a
17 real accident?

18 DR. MEYER: We're well aware of your
19 concern about the ragged temperature histories that
20 could be experienced. We can address those. You will
21 see that as with most diffusion-related experiments,
22 that in order to determine the correlations, you need
23 to do a set of isothermal tests. And then you put it
24 together in such a way that you can reproduce the ones
25 with varying temperature conditions.

NEAL R. GROSS

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

1 CHAIRMAN POWERS: I have to admit I went
2 through your derivation -- not yours, but someone's
3 derivation on that, and that is perplexing.

4 DR. MEYER: It's what?

5 CHAIRMAN POWERS: Perplexing. Certainly
6 not the way that people do it when they analyze things
7 like DTA and TGA types of effects for thermal
8 kinetics.

9 DR. MEYER: Well, let me encourage you to
10 keep this level of question for Mike Billone, and I'll
11 do the best I can when we get to it. I know one of
12 the concerns that you have about spalling oxide during
13 a temperature transient, and I can address that when
14 we get down to it.

15 CHAIRMAN POWERS: Okay. Because I have
16 not seen anybody address that question.

17 DR. MEYER: I'm sorry?

18 CHAIRMAN POWERS: I have not seen anything
19 that addresses that question yet.

20 DR. MEYER: Yes. Well, you know, slides
21 are just slides. They don't have all of the words
22 that are going to flow here. I hope I can do that.
23 Okay, so this is where we're going, and now let's
24 start back at the basics, and see if I can tell the
25 story in a comprehensible way.

NEAL R. GROSS

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

1 So for the uninitiated, which are
2 somewhere behind the table here, loss of coolant
3 accident looks like this to the cladding. The power
4 drops off, and the cladding starts to heat up. You've
5 lost the coolant. Somewhere around 800 degrees
6 ballooning takes place, the cladding gets soft,
7 there's a big pressure differential. It balloons. It
8 pops. That relieves the pressure differential.
9 Coincidentally, at almost exactly the same temperature
10 that this ballooning and rupture process is going on,
11 the cladding -- the Zircaloy, or ZIRLO, or M5, or
12 E110, all of these alloys are going through a phase
13 transformation. At the lower temperatures the crystal
14 structure is a hexagonal close pack, and we refer to
15 that as the alpha phase. At the higher temperature
16 the crystal structure is a body-center cubic, and we
17 refer to that as the beta phase.

18 CHAIRMAN POWERS: What causes the
19 temperature to drop?

20 DR. MEYER: Well, when you get ballooning,
21 you get a thin cooling effect. And so if you're
22 looking in the ballooned region, you would see that
23 kind of. I don't know, there may be something else
24 going on there. It's just typically there's a little
25 blip there. I don't want to dwell on it.

1 CHAIRMAN POWERS: Probably not important.
2 It's probably not an important blip.

3 DR. MEYER: Well, it's where the
4 ballooning and rupture takes place. And this disturbs
5 the thermal hydraulic conditions. And so you do get
6 this kind of a little drop. This curve is not to
7 scale. I simply drew this freehand, and later laid
8 these temperatures in because I needed some
9 calibration on the temperature scale since we're going
10 to be talking about temperatures that are not higher
11 than 1200 degrees Centigrade.

12 Once you get past the ballooning, then the
13 oxidation process picks up. Prior to that, it's
14 extremely slow. Even more important than the
15 oxidation process is the diffusion process. And I
16 hope if I succeed at nothing else during this
17 presentation that I succeed at convincing you that
18 what we're really looking at here is oxygen diffusion
19 into the metal, rather than oxidation on the surface.
20 And we're simply using oxidation on the surface, and
21 it's kinetics equations to give us a time measure.
22 Because what does the deed is getting oxygen from the
23 surface into the metal, and embrittling these ductile
24 metal phases

25 MEMBER KRESS: Well, my question earlier

NEAL R. GROSS

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

1 about this temperature transient being related to the
2 different kinds of LOCAs you may have, related to that
3 because the diffusion of oxygen in a metal is related
4 to this temperature transient, the rate at which it
5 goes in, it seems to me.

6 DR. MEYER: Temperature and time. It's
7 all about temperature and time.

8 MEMBER KRESS: Yes. But I was trying to
9 rationalize how you could put a temperature and time
10 on a number of LOCAs, how you could put a time on a
11 number of LOCAs, because you've come down on just a
12 time.

13 DR. MEYER: Are you referring back now to
14 the 48-minute timeline?

15 MEMBER KRESS: Yes. You've eliminated the
16 temperature.

17 DR. MEYER: Yes. Give me a few minutes.

18 MEMBER KRESS: Okay.

19 DR. MEYER: Give me a few minutes. Okay.
20 So now you oxidize rapidly, and oxygen moves deeply
21 into the metal. The ECCS coolant systems come on, and
22 you cool in a manner something like this. You
23 initially get steam cooling when the water is down
24 low, and then you reach a temperature around 800
25 degrees where it wets and it quenches.

NEAL R. GROSS

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

1 MEMBER KRESS: Is this a small break LOCA,
2 or a large break LOCA?

3 DR. MEYER: Doesn't matter. It doesn't
4 matter. We're talking about materials here. As long
5 as you get temperatures above the 800 region, and you
6 hold them up there for awhile, these processes are
7 going to take place, and I don't think the cladding
8 could care less whether a small pipe did it or a big
9 pipe did it.

10 CHAIRMAN POWERS: Let me ask you a couple
11 of questions that may not be appropriate for this
12 slide, and may be appropriate later, but I'm not sure
13 where to ask them. We did, what, two years ago we had
14 a speaker come to us from France and discuss some
15 experiments he was thinking of doing dealing in his
16 case with large break LOCAs and clad ballooning. And
17 what he discussed in that was the question of not just
18 single rod ballooning, but multiple rod ballooning,
19 and where it occurred, and whether it was all in a
20 plane, or up and down, and whatnot. And he also
21 discussed the fact that as we move up in higher burnup
22 fuel we get more fragmentation, so when the clad
23 balloons up, presumably you get some collapse of the
24 fuel then to the ballooning and things like that? And
25 he had little sketches of that.

NEAL R. GROSS

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

1 DR. MEYER: Yes.

2 CHAIRMAN POWERS: And argued that that
3 changed the heat in the balloon, the decay heat that
4 you had in the balloon region. Is that taken into
5 account when you conceptualize this figure, or talk to
6 me about that stuff.

7 DR. MEYER: Some of it is and some of it
8 isn't. And let me try and make the distinction for
9 you. Multi-rod effects were studied by NRC 25 years
10 ago. We were looking to see if the ballooning process
11 on one rod would affect that on another rod, looking
12 to see if the balloons all lined up in a coplanar
13 manner which would be a worse situation than if they
14 were staggered axially. The tests showed that they
15 were staggered axially. We made licensing decisions
16 on that basis, approved ECCS models on that basis, and
17 so far as I know, there's nothing in the burnup
18 phenomena that would alter that conclusion. And we
19 have not opened up that area to reinvestigation in
20 this program. There was a proposal from IRSN in
21 France to run large tests in the Phebus reactor to
22 revisit that situation, and that proposal is still
23 pending. But we have not raised that as an issue, and
24 I don't see any strong reason at this time to go into
25 the multi-rod question again when the question that

NEAL R. GROSS

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

1 we're pursuing is one of the effect of burnup and the
2 effect of alloys.

3 CHAIRMAN POWERS: I think the more
4 important aspect of high-burnup is actually the
5 fragmentation of the fuel and its collapse into those
6 balloon regions.

7 DR. MEYER: Okay, now that's another part
8 of the question, and that is being included, but it's
9 being included in single rod tests. And these tests
10 are not only being done up at Argonne, but there's
11 also an active program on this at the Halden project,
12 where testing of longer sections under somewhat
13 different conditions are being done with that as the
14 principal objective. And we will bring that
15 information into the seam here. But that kind of
16 information itself does not affect the metallurgical
17 response of the cladding in these particular criteria
18 that we're trying to address here. It would affect
19 ECCS models. It would affect the models that are
20 being used to demonstrate compliance because it alters
21 the heat source in the axial extent. But it wouldn't
22 affect the criteria. It wouldn't affect the
23 conditions under which the cladding would start
24 behaving in a way that we didn't want it to.

25 Okay. Some of these I plan to move

NEAL R. GROSS

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

1 quickly over, and don't mean to do anything but just
2 show you an example. Here is a real fuel rod that's
3 undergone a LOCA simulation. You can see it's swollen
4 in the middle, and it ruptured right there.

5 CHAIRMAN POWERS: And it demonstrates that
6 RES will never get to an SI unit system?

7 (Laughter)

8 DR. MEYER: This is a 40-year-old hot
9 cell, and these --

10 CHAIRMAN POWERS: Oh, I see, 40-year-old
11 hot cells, so our rulers have to be 40 years old too.

12 DR. MEYER: Well, steel tools last
13 forever, right? So I know these steel rules that are
14 laying in the hot cell up there, and you don't want to
15 take that out.

16 MEMBER KRESS: What exactly do you mean by
17 high-burnup here?

18 DR. MEYER: What do we mean by high-
19 burnup. What we mean --

20 MEMBER KRESS: Is it 45, or 60?

21 DR. MEYER: It's very rough, but we mean
22 something above about 40.

23 MEMBER KRESS: Okay.

24 DR. MEYER: At the present time, NRC has
25 a burnup limit of 62 gigawatt days per ton average for

NEAL R. GROSS

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

1 the peak rod. So we tend to test up at that limit.
2 The sections that we test generally are a little above
3 that limit because after all that limit was average
4 for the peak rod, so if we go after some peak rods for
5 specimens, then locally you can find segments that
6 might be a little higher.

7 MEMBER KRESS: Where did you get your
8 fuel? Are these all HB rods?

9 DR. MEYER: This one happens to be a BWR
10 rod from Limerick. We have high-burnup --

11 MEMBER KRESS: Did you pull it out of the
12 pool or what? Pull it out of the spent fuel pool?

13 DR. MEYER: Yes, EPRI did this for us for
14 which we are eternally grateful. It was a big project
15 to get fuel rods out of two plants. We're hoping to
16 repeat this with M5 and ZIRLO clad fuel rods. We do
17 have some small specimens of those that have come via
18 an EPRI program, and we'll mention those later on.

19 Now, I'm going to have to talk about this
20 complicated figure, because we simply can't make any
21 progress unless we deal with some stuff here.

22 CHAIRMAN POWERS: It's not that
23 complicated, is it? It's a cross-section of a piece
24 of oxidized clad.

25 DR. MEYER: I should have expected that

1 from Dana. This simple figure then. So this is a
2 cross-section of a piece of Zircaloy that has gone
3 through a LOCA-like high temperature transient, been
4 brought back to room temperature, sectioned, polished,
5 put on a microscope, and this is what you see. Here
6 is the oxide, this dark gray layer is the oxide that
7 accumulated during the transient. The piece of tubing
8 was fresh.

9 MEMBER KRESS: But first, what do you mean
10 by room temperature ductility equals 6 percent?

11 DR. MEYER: Okay. You go through an
12 oxidation process so we will -- in the testing, we
13 will always -- and we generally try and do these
14 isothermal tests. So we will mention the temperature
15 plateau on which we did the isothermal anneal. And
16 then we bring it down to room temperature.

17 MEMBER KRESS: Okay.

18 DR. MEYER: Sometimes we test at room
19 temperature, but sometimes we test at a higher
20 temperature. In fact, the regulation in 1973 was
21 built on tests that were done at 135 degrees
22 Centigrade. And we are doing that as well sometimes.
23 And Mike will explain why we sometimes do it. I can
24 explain that, but let me try and get on with it here.

25 This one had a very high amount of

NEAL R. GROSS

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

1 ductility left, even when tested at room temperature.
2 It would have had more than that, may have had more
3 than that if tested at 135. 135 degrees is the --
4 what you call it temperature -- help me with the word,
5 Harold. Saturation temperature right after quenching
6 in a loss of coolant accident when you still have some
7 containment pressure to give you a back pressure on
8 the system. And so the ductility in the regulations
9 for the last 32 years had been based on testing at
10 that temperature. Okay. And that's what we're doing
11 now.

12 Okay, so you have the oxide. Now, all of
13 this material was initially in the beta phase after it
14 got up to high temperature. But then oxygen started
15 pouring into the metal at the high temperature. The
16 beta phase, which here is labeled ductile metal, could
17 only hold a small amount of oxygen. And once you got
18 more oxygen in there than it could handle, it would
19 convert back to an alpha phase, even at high
20 temperature. We'd sometimes call it an oxygen-
21 stabilized alpha phase. So here you had two distinct
22 varieties of this oxygen stabilized alpha phase. One
23 is a fairly well defined layer with a very high oxygen
24 content, and then you had these fingers protruding
25 into the ductile beta regions that have oxygen

NEAL R. GROSS

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

1 concentrations higher than the solubility limit of
2 oxygen in the beta phase. You cool it all back down.
3 It's all alpha phase now, but it retains this
4 distinctive appearance of the phases as they existed
5 at high temperature. And as you can see, this one,
6 this dark prior beta phase, is the only one that's
7 ductile. And as that disappears, you're going to lose
8 ductility of the material as a whole. Or, if it's
9 ductility, it's spoiled. And each of those is
10 possible. We can come back if you --

11 CHAIRMAN POWERS: It probably would be
12 useful to inject a phase diagram at this point so that
13 people know that the alpha phase becomes stabilized as
14 oxygen absorbs into the material. And that raises
15 this question. You're going to explore multiple
16 different kinds of alloys with different alloying
17 agents, and try to get something general here. And
18 yet at no point do you discuss the rather well
19 developed rules on how the band structure of the two
20 phases of zirconium metal respond to alloying agents.
21 And that's surprising. Why doesn't that appear in
22 this discussion?

23 DR. MEYER: Well, the reason I didn't do
24 it was because there are differences. Mike will show
25 you some and can talk about them. But the general

NEAL R. GROSS

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

1 character is the same. I will say that this almost
2 looks more like an M5 or a ZIRLO structure where
3 they're very prone to these protrusions into the
4 ductile layer. Sometimes the Zircaloy will have just
5 three distinct layers where you only see a nice
6 uniform prior beta layer in there. But I chose this
7 Zircaloy slide because it exhibits the features that
8 we see in all of the alloys that we've looked at.
9 Now, the temperatures at which the transition takes
10 place are slightly different, and there are
11 variations. But the general character is the same.

12 Now this is the thing that makes the
13 subject so complicated. We're looking for
14 embrittlement, and there's not one cause of
15 embrittlement, but there's several causes of
16 embrittlement. And here's where you have to have that
17 concept of different phase layers. I'm just going to
18 glibly refer to them as layers in mine. Because the
19 beta phase has such a limited oxygen solubility, it
20 keeps -- as you try and put too much oxygen in it, it
21 keeps converting portions of it to this oxygen-
22 stabilized alpha phase. And so the true beta material
23 keeps shrinking. So it gets thinner and thinner.
24 Eventually it gets so thin that the sandwich of
25 several phases just appears to be brittle. And that

NEAL R. GROSS

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

1 point is determined empirically by testing macroscopic
2 pieces of the material.

3 CHAIRMAN POWERS: If we get these
4 intrusions -- When you've got distinct layers, oxide,
5 embrittled metal, ductile metal, you say, gee, all my
6 ductility is in this layer of ductile metal, and it's
7 fine, you can get that down fairly thin and still
8 retain the integrity of the metal structure. But now
9 if you get these intrusions coming in, doesn't that
10 change how you look at these things? Don't you have
11 to worry about something like percolation phenomenon,
12 or something like that?

13 DR. MEYER: Sure, if we were trying to
14 model this mechanistically. But what we do is just a
15 macroscopic empirical test on a piece of material, and
16 use a screening test to determine if it's ductile or
17 brittle. It works very well, and we don't make any
18 attempt to mechanistically model the mechanical
19 behavior of this tangled mixture of phases.

20 CHAIRMAN POWERS: Criteria will come out
21 to be about the same. Remarkable.

22 DR. MEYER: I'm sorry, I can't --

23 CHAIRMAN POWERS: The criteria all come
24 out to be the same, yet if you were looking at a
25 percolation across that, you would expect the amount

1 of oxidation you'd have to get through would be less
2 than if you just had to thin the layer down. But they
3 come out to be about the same. Interesting.

4 DR. MEYER: Let me go on. You can ask
5 those kinds of questions again to Mike, and maybe he
6 can answer them. But you do have situations where the
7 beta layer can get so thin that the macroscopic
8 material appears to be brittle.

9 CHAIRMAN POWERS: Say if we were talking
10 about, I don't know, maybe steam generator tubes, we
11 would be talking about ligaments retaining strength
12 and things like that. And here you're getting up
13 those ligaments because of these protrusions. I mean,
14 it's just interesting.

15 DR. MEYER: Okay. There are also
16 conditions under which the beta layer itself, where
17 you can -- the solubility is increased to the point
18 that you can put so much oxygen in the beta layer that
19 it gets brittle. So you've got to look at that. We
20 have this matter of breakaway oxidation which occurs,
21 and I'll show you examples of that. And when the
22 breakaway oxidation occurs, then you have a rapid
23 absorption of hydrogen. And the hydrogen then quickly
24 induces embrittlement. How that takes place
25 mechanistically you can -- Mike.

NEAL R. GROSS

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

1 CHAIRMAN POWERS: Let's see. You put
2 oxygen in, and it sucks electrons out of the
3 conduction band, so when you put hydrogen in it
4 injects electrons into the conduction band that makes
5 it solute more oxygen?

6 DR. MEYER: Well, the first thing that
7 hydrogen does, and Number 3 and Number 5 may be
8 closely related, but the first thing that hydrogen
9 does when you get hydrogen into the metal is it
10 increases the solubility of oxygen in the beta phase.
11 I don't understand the mechanism for its doing that,
12 but it does that. And when it does that, then the
13 beta phase itself can absorb enough oxygen to become
14 brittle.

15 CHAIRMAN POWERS: Well, bear with me a
16 little bit and assume that it affects on electrons in
17 the metal structure. Alloying agents also affect it.

18 DR. MEYER: I just didn't hear.

19 CHAIRMAN POWERS: Well, if indeed the
20 effect, the hydrogen enhancement of oxygen solubility
21 is due to the electronic structure of the metal, and
22 my point is that alloying agents also affect that
23 electronic structure.

24 DR. MEYER: Yes.

25 CHAIRMAN POWERS: And you could make a

1 more generalized description of this, it seems to me,
2 to cover who knows what alloying agent may come along
3 by focusing on that electronic structure.

4 DR. MEYER: Well, we might be able to if
5 we went that deeply into it. And we haven't done
6 that. It's a modest program. We're looking
7 empirically at the results of these phenomena, and we
8 haven't tried any modeling of the electronic
9 structure, or binding energies, or anything like that.
10 This is simply beyond the scope of the work that we've
11 tackled. We've simply tried to look at what the
12 consequences would be by making practical measurements
13 that we can interpret.

14 We have one other cause of embrittlement
15 that we in fact talked about the last time we were
16 here, and I'll bring it up again, and that's in the
17 balloon itself, where you have a rupture, and you have
18 two-sided oxidation because now steam can get on the
19 inside of the balloon, there's a tendency to trap the
20 hydrogen that's freed from the dissociation of water
21 that participates in this ID oxidation process,
22 because it's not being swept away by steam. And then
23 we find that you get enhanced bands of hydrogen
24 absorption in the cladding above and below the opening
25 of the balloon. And this leads to hydrogen-induced

NEAL R. GROSS

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

1 embrittlement in the balloon. And it also may be
2 related to the oxygen solubility, or it might be
3 something else. I can't tell you. All I know is that
4 the phenomenon exists, we measure it, and we can show
5 it to you in detail in Mike's talk. But we have to
6 look, if we're going to have an effective set of
7 criteria, we've got to look at all of these things to
8 make sure that none of them leads to embrittlement
9 within the bounds of the criteria that we establish.
10 And we're trying to get this all simplified to the
11 point where it can be done in a practical sense in an
12 ECCS calculation where you only have a few parameters
13 available.

14 So, now I'm going to go through these more
15 or less one by one, or a couple at a time, and point
16 out that then and now the 1200 degree temperature
17 limit had to do with the embrittlement of the beta
18 phase in the material. At temperatures above 1200
19 degrees Centigrade, or 2200 degrees Fahrenheit, the
20 solubility limit of the beta phase, which is
21 temperature dependent, it simply goes up. And so the
22 beta phase itself starts becoming brittle at
23 temperatures above 1200 degrees Centigrade. As a
24 practical matter, if you're doing tests at 1000, 1100,
25 1200 degrees, and you get up around 1200 degrees, and

NEAL R. GROSS

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

1 you look at 1170, 1180, at 1200 you see that the
2 ductility is starting to fall off fairly rapidly. And
3 this is why the 2200 degree Fahrenheit limit was put
4 on there in the first place. And we don't have any
5 plans to change that. It's true then, it's true now,
6 and we don't plan to tinker with the 2200 degree
7 Fahrenheit limit.

8 CHAIRMAN POWERS: It's only true for the
9 alloys you looked at. Is there no alloying agent that
10 I could stick in there that would stabilize beta to
11 the point that you could get enough oxygen solubility
12 to embrittle it?

13 DR. MEYER: I don't know. What I can say,
14 though, is we can work within this construct. If we
15 choose 1200 degrees Centigrade, we choose to stick
16 with that as a limit, then we can explore the other
17 parameter that affects the embrittlement, the time at
18 temperature, which is reflected in the oxidation
19 limit, and explore that, and map out ductile and
20 brittle domains. I told you you're going to be able
21 to ask us questions that we couldn't answer.

22 CHAIRMAN POWERS: And I wanted to live up
23 to your expectations, Ralph. That's all I'm trying to
24 do. I didn't want to disappoint you.

25 DR. MEYER: Okay. Now, so we've discussed

NEAL R. GROSS

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

1 most of this. Oxygen diffuses into the metal. The
2 beta layer shrinks. If you limit the time at each
3 temperature, then you can keep the beta layer from
4 shrinking too much and retain an effective ductility
5 of the whole sample.

6 Now, I think I'm about to try and make my
7 big point, but the -- I'm going to try and convince
8 you that there's enough oxygen as a source on the
9 surface of these materials that it's really not -- the
10 thinning of the beta layer is not a direct consequence
11 of how much additional oxide you pile up on the
12 surface, but how much time you allow at each
13 temperature. So, we're going to choose the Cathcart-
14 Pawel correlation as our temperature scale. And what
15 this does for us is gives us, you know, if we put a
16 number, 17 percent, which is the old comfortable
17 number, on the Cathcart-Pawel correlation, what this
18 gives us is a time scale for different temperatures,
19 2400 seconds at 1000 degrees, and smaller amounts at
20 11 and 12. So we're going to try and use this and see
21 if it works.

22 And so here is an oxygen concentration
23 diagram from a report by Hee Chung, which I have
24 annotated to show it in the way I'd like to think of
25 it, is that you have an oxygen source sitting on the

NEAL R. GROSS

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

1 side of your metal, and when the temperature is high
2 enough, oxygen diffusion will pump oxygen into the
3 metal itself. Now, on this slide I want to try and
4 digress, and comment on your concern about oxygen
5 spallation during some temperature transient. I think
6 if you chiseled off half of that oxide thickness, it
7 wouldn't make a wit's difference in how much time it
8 took to embrittle the material. And so if you're
9 using an equation which is fixed, like we are. For
10 our time scale we're calculating the time that it
11 takes for oxygen to move in and thin the beta layer.
12 And although that calculation was derived from an
13 oxidation process, we're really not using it for that.
14 And if you lost some of the oxygen source, you would
15 quickly replenish it. And the amount -- the true
16 amount of oxygen that was taken from steam and put
17 onto this system here, that might be different in the
18 region of some spallation, but I don't think it would
19 make any difference on what was going on inside of the
20 metal because it found ample oxygen on the surface,
21 and all we're waiting for here is enough to arrive in
22 the beta phase to alter its properties. And so that's
23 both the point that I want to make about time at
24 temperature rather than oxidation on the surface, and
25 hopefully an answer to your longstanding concern about

NEAL R. GROSS

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

1 the flaking of -- or spallation of oxygen during a
2 temperature transient that might -- a non-uniform
3 temperature transient that might kick off some
4 spalling, some oxide that we would miss by doing tests
5 under uniform heating conditions.

6 CHAIRMAN POWERS: I understand your point.
7 I'll have to think about it for oxygen driving. I
8 think that you've raised a different question now, is
9 do you not now get an enhanced hydrogen uptake in this
10 system?

11 DR. MEYER: What about hydrogen?

12 CHAIRMAN POWERS: If I spall the oxide,
13 don't I get an enhanced hydrogen uptake in this
14 system?

15 DR. MEYER: I don't think so, because I
16 mean we have -- we do a lot of testing with bare
17 cladding, and we don't get enhanced hydrogen. In
18 fact, I don't think we get significant hydrogen uptake
19 during -- help me, Mike -- during the high temperature
20 oxidation. We don't get a lot of hydrogen, do we?

21 DR. BILLONE: No, very little. Maybe 10 -
22 20 ppm of hydrogen. Except for E110.

23 DR. MEYER: Yes, which had the breakaway.

24 DR. BILLONE: Which has a breakaway.

25 DR. MEYER: And when you get to -- and you

1 can get that in any alloy, and I'll show you a figure
2 on that, just one or two more slides down the line
3 here.

4 CHAIRMAN POWERS: I guess what I'm
5 struggling with is what's the difference between
6 breakaway oxidation and spalling the oxide?

7 DR. BILLONE: You have to -- breakaway
8 means the oxide layer is literally breaking up,
9 cracking. And that's followed by device-lamination,
10 where it actually separates from the surface, and then
11 spalling. So those are related, but there are
12 different kinds of oxide layers. So if you're really
13 talking about -- let's call it the corrosion layer,
14 the thing that grows in-reactor. That's what's on the
15 metal as you start the transient. And if you're
16 asking does it matter if some of that flakes off, if
17 that was your question, that's a different question
18 than asking --

19 CHAIRMAN POWERS: Get halfway through this
20 --

21 DR. MEYER: Also, mention the form of the
22 oxide, because the normal form of the oxide that we're
23 working with is a shiny, black tetragonal oxide, and
24 the breakaway stuff is white in color, and I think
25 it's monoclinic.

NEAL R. GROSS

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

1 DR. BILLONE: Right.

2 DR. MEYER: So, when the breakaway
3 phenomenon takes place, other stuff's happening that
4 you don't see in this situation.

5 CHAIRMAN POWERS: That's fine. You get
6 halfway through your story there. And now you go
7 through a sudden drop in temperature. The stuff
8 spalls, it fractures, it looks just like your
9 breakaway stuff. I mean, I defy you to tell the
10 difference if I showed you two specimens.

11 DR. BILLONE: No, no.

12 CHAIRMAN POWERS: I don't defy you. I
13 defy him. Let me be clear on this.

14 DR. BILLONE: If you want help, Ralph,
15 just ask.

16 DR. MEYER: Okay. Point taken. So, the
17 proof of the pudding is in the eating, and so now I've
18 gone back to plotting things in a fairly familiar
19 manner. I've plotted what we call offset strain,
20 where we reckon zero ductility to be at 2 percent.

21 CHAIRMAN POWERS: I'm going to ask you --

22 DR. MEYER: And there's a lot of details
23 here. I'm not going to describe these details. If
24 you want them --

25 CHAIRMAN POWERS: I looked with some

NEAL R. GROSS

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

1 diligence to understand what you mean by offset
2 strain.

3 DR. MEYER: I know exactly what it is, but
4 I'm going to let Mike talk about it. He's going to
5 show you the data.

6 DR. BILLONE: Deviation from plastic
7 strain. Non-linear.

8 CHAIRMAN POWERS: The strain where you
9 deviate from the Hook's law?

10 DR. BILLONE: Yes. You deviate from
11 Hook's law, and it's permanent, meaning you unload,
12 it's still there.

13 CHAIRMAN POWERS: You might want to make
14 sure you define that on your nice -- you have a nice
15 little plot.

16 DR. BILLONE: In my first 10 minutes I'll
17 show it.

18 CHAIRMAN POWERS: And whatnot, because I
19 looked for it, and said I'm not sure what they mean by
20 offset. I know what I mean, which is deviation from
21 Hook's law. And but it's not defined. And you might
22 want to define it.

23 DR. BILLONE: I have it in my
24 presentation, exactly the slide you want.

25 DR. MEYER: Okay. Now, keep in mind this

1 is unirradiated. So we're going to show you some
2 results here for unirradiated cladding, and then we'll
3 get to the irradiated stuff. Unirradiated new
4 Zircaloy, 17 percent line is right here. So all of
5 these retain their ductility for the time it took to
6 get to 17 percent with the Cathcart-Pawel equation.

7 This is ZIRLO. You see the same result.
8 It's got a little more than the Zircaloy, but close.
9 And here is M5. I don't think -- we don't have
10 another data point down here on the M5 I don't
11 believe, but you can see where it's heading, and you
12 can see that for practical purposes, the 17 percent
13 limit, which is the one we're using to date, works for
14 all three of these unirradiated alloys.

15 Now, it doesn't work for everything. And
16 here's an example where it doesn't work. Here's old
17 Zircaloy. It comes down around 13 percent. And back
18 in the '70s and early '80s, when we were using this
19 kind of cladding, we were also using the Baker-Just
20 correlation because it was required by Appendix K, and
21 that requirement wasn't lifted until 1988. And the 17
22 percent calculated by Baker-Just is the same as 13
23 percent calculated by Cathcart-Pawel. So what I'm
24 showing you here is a reproduction, or a confirmation
25 of the early work that Hobson did, and the criteria

NEAL R. GROSS

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

1 that were derived from it. The difference between old
2 Zircaloy and new Zircaloy has largely to do with the
3 surface finish. And you'll see that surface finish
4 can have some pretty dramatic effects. It's one of
5 the two fabrication processes that we've identified as
6 having a fairly strong effect on the behavior of the
7 cladding under these high temperature LOCA conditions.

8 CHAIRMAN POWERS: I looked at that
9 particular note at the bottom, and at first I said, oh
10 yes, I know exactly. Then I thought about it. What
11 you mean is the time required for Baker-Just to get
12 you to 17 percent is the same as the time required for
13 Cathcart-Pawel to get to 13 percent? Is that what you
14 mean?

15 DR. MEYER: That's what I mean.

16 CHAIRMAN POWERS: At some particular
17 temperature, 1200 degrees I guess.

18 DR. MEYER: If I could have thought of
19 those words, I would have put them on this slide.

20 MEMBER DENNING: Ralph, would you go back
21 to the previous slide. There's something I want to
22 question you about.

23 DR. MEYER: Before that?

24 MEMBER DENNING: It was the one on the
25 unirradiated cladding for the ZIRLO and the new Zirc.

1 Those figures.

2 DR. MEYER: The figures for?

3 DR. BILLONE: Go back two more slides.

4 MEMBER DENNING: That's fine.

5 DR. BILLONE: That's ZIRLO.

6 MEMBER DENNING: Now, as we look at the
7 data there, there's not a consistency in terms of as
8 a function of temperature.

9 DR. BILLONE: The test temperatures are
10 different, so make sure Ralph clarifies that.

11 MEMBER DENNING: Yes, the test
12 temperatures are different, okay. But there's not a -
13 -

14 DR. MEYER: Oh, you're looking at that
15 rather than that?

16 MEMBER DENNING: I'm looking at those,
17 right. And then you see that, you know, there's not
18 a pattern where the curve is dropping down with, you
19 know, the curve is lower for the next temperature, and
20 then lower for the next temperature. Is that an
21 indication of the uncertainty in the data there, or is
22 that really something phenomenologically where there's
23 a minimum that one's going through?

24 DR. MEYER: It's an indication of the
25 monoscope of the program. What we did, and we did

NEAL R. GROSS

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

1 this deliberately, when we could run a test at room
2 temperature and get ductility, we did it because it's
3 cheaper to run a test at room temperature than at 135
4 degrees. When we didn't get -- and that was
5 sufficient. So you knew that if you tested at room
6 temperature you got ductility, you would have
7 ductility at 135 degrees. It was only in the cases
8 where the ductility was near zero when tested at room
9 temperature that we switched to the more expensive
10 testing at 135. And we haven't filled out this whole
11 matrix. I mean, there's a lot of testing that goes
12 into getting a curve like this.

13 DR. BILLONE: But to directly answer your
14 question, if that red line were done at room
15 temperature -- it was really done at 135 -- you would
16 see your trend. In other words, you would lose
17 ductility for ZIRLO at about 10 percent, and you would
18 have your trend. But you had two room temperature
19 tests, and one test at 135 degrees C, and that's why
20 you're not seeing what you're looking for.

21 DR. MEYER: In the beginning we thought we
22 could get by with doing room temperature tests.

23 MEMBER DENNING: I see.

24 DR. MEYER: But we had to switch.

25 MEMBER DENNING: I see. On the 1200,

NEAL R. GROSS

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

1 that's -- I understand. Okay.

2 MEMBER KRESS: Each one of those points is
3 a different test.

4 DR. MEYER: Yes. Each point is -- this is
5 a short piece of tubing, a couple of inches long, that
6 was oxidized at 1000 degrees until a time that
7 corresponded to a Cathcart-Pawel prediction of about
8 12 percent ECR.

9 MEMBER KRESS: I was trying to rationalize
10 --

11 DR. MEYER: And then you cut a ring from
12 that, and you --

13 MEMBER KRESS: You subject it to the --

14 DR. MEYER: And you squeezed it.

15 MEMBER KRESS: I was trying to rationalize
16 the blue curve. It's just the data is uncertain,
17 probably. Rather than being smooth.

18 DR. BILLONE: When material is extremely
19 ductile it's very subjective and difficult to
20 determine how ductile. The test is better, easier to
21 interpret the data as you approach embrittlement. So
22 some of that could be judgment, what's your seeing
23 there, judgment in interpretation of a curve that has
24 no sharp load drop indicating a significant crack all
25 the way through the wall.

1 MEMBER DENNING: And if you were to put an
2 uncertainty bound on that from your best judgment,
3 what would they look like, if you put an uncertainty
4 bound or a reproducibility for the same conditions.
5 What would that look like?

6 DR. BILLONE: We've done a lot more
7 testing with the 15 x 15 cladding, because we had a
8 lot more of it. And we got very reproducible results.
9 I think the bigger -- the broader question that could
10 be asked is if you go lab to lab to lab with different
11 testing techniques, do you see the same data trends.
12 And the answer for this -- go the next slide, please -
13 - is for the M5 and the Zirc-4 we have the same data
14 trends for unirradiated cladding as CEA-Framatome-EDF
15 have, using very different testing techniques. And so
16 we don't run a lot of tests with these alloys, but
17 once we get a set, and once we get a pattern for
18 screening tests, we tend to look at what other people
19 have gotten, and are we consistent. And that's how we
20 sort of look at uncertainty.

21 MEMBER KRESS: The line going straight up
22 from the first point on the green one, we do know that
23 point. The 12-minute -- the 13-minute point.

24 DR. MEYER: On the green curve?

25 MEMBER KRESS: Yes.

1 DR. MEYER: That one?

2 MEMBER KRESS: No.

3 DR. MEYER: That one?

4 MEMBER KRESS: The line above that going
5 straight up. How is it derived?

6 DR. MEYER: Oh, there's another point up
7 here.

8 DR. BILLONE: There's two more points, at
9 10 percent and 5 percent and zero. Three more points.

10 MEMBER KRESS: Okay.

11 DR. MEYER: We really didn't want to plot
12 those points because they're -- it's a screening test
13 to try and find out where zero is. And when you've
14 got 20 or 30 percent ductility the test isn't that
15 accurate nor interesting.

16 MEMBER SHACK: I thought you needed your
17 45-minute limit for something like M5 where to get 17
18 percent oxidation at 1000 C, you're running presumably
19 for a fairly longish time. You're doing everything
20 here just with your 17 percent. Where would my 45
21 minutes catch me?

22 DR. BILLONE: Forty-five minutes is, let's
23 see. For this particular curve, if I went -- Ralph,
24 I can't read your legend. What is 1000 degrees C
25 curve?

1 DR. MEYER: The blue.

2 DR. BILLONE: Blue is 1000 degrees? Okay.

3 At approximately 20 percent ECR you're at about 3400
4 seconds, and none of these alloys that you've seen
5 have broken up in our tests. The breakaway oxidation
6 has --

7 MEMBER SHACK: So these --

8 DR. MEYER: The breakaway here is going to
9 be about 5000 seconds.

10 MEMBER SHACK: So for these three alloys,
11 the 45 minutes is --

12 DR. BILLONE: Conservative.

13 DR. MEYER: This is double-sided.

14 DR. BILLONE: Yes, but the 1000 degrees C
15 test was close to an hour, was run for close to an
16 hour. As a matter of fact M5 was run for 4100
17 seconds, which is more than an hour, and in France it
18 was run for 5000 and greater. It's all these alloys,
19 all zirconium-based alloys, the oxide will break up
20 after a certain amount of time, Zirc-4, ZIRLO, M5.
21 It's not a particular M5 issue as far as breakaway
22 oxidation.

23 MEMBER SHACK: Okay, but that would make
24 the 45-minute rule look quite conservative, then, for
25 M5.

NEAL R. GROSS

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

1 DR. BILLONE: And for Zirc-4.

2 MEMBER SHACK: And for Zirc-4.

3 DR. BILLONE: I mean, what do you call
4 quite conservative? One of these alloys starts
5 picking up hydrogen at 3400 seconds, it hasn't shown
6 dramatic --

7 MEMBER SHACK: Well, it just seems that if
8 I did it on my Cathcart-Pawel 17 percent, I'd be
9 conservative enough.

10 DR. BILLONE: Oh, okay, I'm sorry. This
11 is -- Ralph's right. This is two-sided oxidation.
12 The time is relatively short to get to 17 percent. If
13 you did one-sided oxidation you increase the time by
14 a factor of four.

15 MEMBER SHACK: Four. Okay.

16 DR. BILLONE: And that's what we're trying
17 to --

18 MEMBER SHACK: That's where you would find
19 it.

20 DR. BILLONE: I'm sorry, I missed the
21 point.

22 DR. MEYER: Okay, I think you may have
23 seen some of these pictures before. But these are the
24 zirconium-1 niobium alloys, the Russian E110 at the
25 top and the French M5 at the bottom. And you can see

NEAL R. GROSS

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

1 that the E110 has gone south quite early at 290
2 seconds. This is at 1000 degrees Centigrade. It's
3 worse at 1400 seconds. At 2400 seconds M5 is still
4 shiny and hasn't developed any spots on it at all.
5 But very easy to see the difference when you run the
6 test, and of course you could cut a ring and do a
7 mechanical test and you would find the stuff that's
8 brittle, and this is ductile.

9 CHAIRMAN POWERS: And the only differences
10 are texture effects?

11 DR. MEYER: Are what?

12 CHAIRMAN POWERS: Texture effects?

13 DR. MEYER: No. I'm glad you asked the
14 question. I would -- how bad am I on time? I'm
15 supposed to finish in 15 minutes? Or now?

16 CHAIRMAN POWERS: Fifteen minutes.

17 DR. MEYER: I've got 15 minutes. I'll
18 give you the 2-minute version of the E110 story
19 because it's fascinating. At the end of the day we
20 found two fabrication parameters that made the
21 difference between this and this. And neither of them
22 were what you would have expected. One of them is
23 surface finish. You grow a crystal on a substrate,
24 the condition of the substrate matters. And that's
25 true here. The Zirc-4 oxide is a crystal also, and an

NEAL R. GROSS

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

1 ionic one, and it's sensitive to that. So the E110
2 has a very rough surface finish, and the M5 has a very
3 smooth polished surface finish.

4 That's one factor. That's not the whole
5 story. The other one was the one that was equally
6 surprising. And it has to do with the reduction
7 process that's used to go from the Zircon or to the
8 zirconium metal before you even make the ingot. It
9 turns out that the Russians were using an electrolytic
10 process that produced very pure zirconium. And
11 everyone in the west, including the French and the
12 U.S. use a kroll process which doesn't produce such
13 pure zirconium. It has some impurities in it like
14 calcium. Calcium has a valance of three. Niobium has
15 a valance of five. Zirconium has a valance of four.
16 Five and three kind of balance out, and so if you get
17 some impurities from the kroll process into the
18 zirconium, it kind of acts as the antidote to the
19 niobium that you're going to put in, which seems to
20 increase the sensitivity of the process. So if you
21 use sponge zirconium in the fabrication process, you
22 generally get nice behavior. If you use electrolytic
23 or iodide zirconium, you tend to get this. The
24 Russians had some specimens that were made earlier
25 with sponge zirconium. They bought some sponge

NEAL R. GROSS

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

1 zirconium from CEZUS in France and made some E110. It
2 behaved quite nicely. They produced some of their own
3 sponge zirconium and made some E110, and it behaved
4 nicely. But the commercial stuff is made with
5 electrolytic and iodide zirconium and it behaves like
6 that. And who would have guessed that that step and
7 the surface finish would have produced the kind of
8 sensitivity that we see.

9 CHAIRMAN POWERS: Why does calcium have a
10 valance of three?

11 DR. MEYER: Hm?

12 CHAIRMAN POWERS: Why does calcium have a
13 valance of three?

14 DR. MEYER: Doesn't it? In the oxide? I
15 think it does.

16 CHAIRMAN POWERS: I don't think it so. I
17 think it's two. But I can always be proved wrong.

18 DR. BILLONE: Don't look at me for
19 chemistry.

20 CHAIRMAN POWERS: When you say the
21 advantage of looking at the electronic structure of
22 these alloys is tremendous, because --

23 DR. MEYER: I shouldn't have got into that
24 discussion anyway, so we'll have to -- it's something
25 like that. Hee Chung is the proponent of this

NEAL R. GROSS

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

1 hypothesis. The fact is that sponge zirconium and a
2 good surface finish seem to produce cladding that
3 behaves very nicely under high temperature LOCA
4 conditions, and other starting zirconium materials and
5 rough surfaces produce poor behavior.

6 Here is a slide from a recent paper, Jean-
7 Paul Mardon who is here, going to make a presentation
8 I think, is the principal author of this. And it
9 shows for Zircaloy and M5 the breakaway process
10 beginning out here around 5000 seconds. And 45
11 minutes is 2700 seconds. And typical LOCA times are
12 1800. So we've just pegged that number in the middle
13 there. And for these three -- this number is not
14 proposed for any regulation or anything. It's just a
15 number that says for these three alloys, Zircaloy, M5,
16 and ZIRLO, if the length of time is less than 45
17 minutes you're okay, and the typical LOCA times are
18 less than that so I think we're okay.

19 Okay. One other feature -- we talked
20 about this a year and a half ago when we met, and this
21 has to do with the hydrogen absorption in the balloon.
22 So here is a plot with the burst location in the
23 center, and going in both directions you see a
24 symmetric behavior. The blue is the hydrogen
25 concentration and you see it increasing quite

NEAL R. GROSS

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

1 dramatically up to 3000 to 4000 ppm, which is quite
2 high, at distances on the order of 6 or 7 centimeters
3 from the center of the balloon where the rupture is.
4 These produce what I think of as bands of embrittled
5 material in the balloon, even when the 17 percent
6 criteria and the temperature criteria are met,
7 according to a calculation in the balloon. This is
8 not a new observation. This was observed and reported
9 in 1980 by Argonne National Laboratory and by the
10 Japan Atomic Energy Research Institute. So it's an
11 old observation, and we simply recognized it and go on
12 with it.

13 So what we propose to do in the balloon
14 section is basically leave the regulation as it is.
15 We recognize that you won't have ductility everywhere
16 in the balloon. There'll be a couple of local
17 regions. In our previous meeting I referred to them
18 as singularities. Maybe they're a little broader than
19 singularities. But by retaining the current rule
20 where you calculate the oxidation in the balloon
21 region, assuming double-sided oxidation, taking
22 account of the thinning from the ballooning process,
23 all of which is described in the regulation, that what
24 this will do for you is it will protect areas within
25 the balloon that are ductile. And this will mitigate

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 any fracturing behavior that might take place in the
2 balloon, and tend to keep it from shattering. So that
3 if you had fracturing, you are likely to have just
4 clean breaks. And we've seen some of those with
5 material that's gone through this process, and they do
6 tend to be clean breaks. And if they're clean breaks,
7 then the pellets can't get out. You might lose some
8 granulated material, a small amount, but I don't think
9 there's any threat to coolability from that small
10 loss. The rods can't displace an offset enough for
11 much material to go out. In fact, with the order of
12 magnitude of ballooning that we see, the balloon will
13 nearly touch the neighbor rods so that lateral
14 movement of the balloon in this location is going to
15 be restricted anyway.

16 Now, I think I have very little on what is
17 the most important subject for the high-burnup effect,
18 and that is the hydrogen enhanced beta layer
19 embrittlement, the last of the causes that I listed.
20 Now we're talking about hydrogen that comes in during
21 the corrosion process. So during normal operation, at
22 operating temperatures where the cladding is around
23 300 degrees Centigrade, over the lifetime of the fuel
24 if you get 20, 40, 60 microns of corrosion or oxide
25 built up on the surface, you may get 20, or 50, or

NEAL R. GROSS

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

1 200, or 400 ppm hydrogen absorbed into the metal. And
2 it's this hydrogen that is available in the metal to
3 alter the solubility limit of oxygen in the beta phase
4 at high temperature. And so that's what it does. And
5 we therefore have to do something to account for this.
6 And the interim requirement of a few years ago was to
7 say that total oxidation meant pre-accident oxidation
8 plus the transient oxidation.

9 So what we did was look to see if that
10 would work. This is done in a very pragmatic,
11 empirical manner. We take the corrosion layer and
12 convert it to this ECR equivalent cladding reactive
13 percentage, subtract it from the 17 percent, and see
14 if that is an adequate accounting for the hydrogen.
15 Now, there's a phenomenological link here. It's not
16 a mechanistic model, but the logic is there. The more
17 corrosion you have, the more hydrogen you get into the
18 metal. The more hydrogen you get into the metal, the
19 higher the solubility for oxygen in the beta layer and
20 the lower the embrittlement. So it hangs together
21 logically. And in the one series of tests that we've
22 done on high-burnup cladding it seems to work. This
23 is 1200 degrees Centigrade with the post-quench
24 testing at 135 degrees Centigrade. I can't read that.
25 What's that.

1 DR. BILLONE: The red are the data points.

2 DR. MEYER: Oh yes, and these are -- and
3 these are -- yes. The red are the data points --

4 DR. BILLONE: For steam oxidation alone.

5 DR. MEYER: I shouldn't have gotten
6 tangled up on this slide.

7 DR. BILLONE: Your legends are so small.

8 MR. SCOTT: We added the corrosion
9 thickness to the layer --

10 DR. MEYER: There you go. There you go.
11 Thank you Harold. Thank you. So we did the reverse
12 here. We added the corrosion thickness to the test
13 results and compared that with the 17 percent, or the
14 13 percent in this case because it's old Zircaloy. It
15 works. I'm sorry I didn't present this slide in a
16 more elegant manner.

17 In the program plan, and up until very
18 recently, this is all we expected to have on the
19 burnup effect. That is, test results for Zircaloy
20 from high-burnup fuel. Because we did not have on
21 this time scale access to high-burnup ZIRLO and M5
22 runs. So the plan was laid out. It was endorsed by
23 everyone that what we would do was to investigate the
24 effect of alloys on unirradiated specimens, and
25 investigate the effect of radiation on Zircaloy

NEAL R. GROSS

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

1 specimens, assume that the radiation effect played out
2 the same with M5 and ZIRLO. Fortunately we're going
3 to be able to do better. We haven't done it yet, but
4 we will.

5 Here are the data for ZIRLO. There are no
6 points on here because the tests are in progress right
7 now. And M5. We were able to get some small pieces
8 of irradiated M5 and ZIRLO cladding shipped back to us
9 from Studsvik in Sweden, cladding that was over there,
10 the ZIRLO cladding at least, on an EPRI program. And
11 so we have these cladding specimens in the laboratory
12 at this time. They're being moved into position in
13 the hot cell, and we will do this kind of testing on
14 the M5 and the ZIRLO, and the next time that I show
15 these slides I hope that we have data points on here.
16 And I have full confidence that they're going to come
17 in above this line.

18 So, the criteria. The criteria that could
19 be used, and we think are justified by this research
20 would require some input. The applicant, or vendor,
21 or whoever would have to determine an oxidation level
22 in unirradiated cladding at which the ductility
23 disappears. Easy test to do because it's unirradiated
24 material. You don't need a hot cell for that. You'd
25 have to take some additional segments at a lower

NEAL R. GROSS

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

1 temperature and find the time at which breakaway
2 oxidation occurred, and declare a time that would
3 prevent that from happening, and use that as a limit.
4 And then you also have to know what the corrosion
5 thickness is on the cladding of interest. And so you
6 put those all together, and in the LOCA analysis then,
7 in your ECCS calculations, you calculate the cladding
8 oxidation during the LOCA and show that it doesn't
9 exceed that limit that you just found. This one.
10 I'll tell you, that number is 17 percent for the
11 alloys that are being used, but it could be different.
12 And then you show that the calculated time from
13 rupture to quench is less than the time for breakaway
14 oxidation, and you do all of this with Cathcart-Pawel.
15 And that's the proposal.

16 And the conclusions are that we've looked
17 at old Zircaloy, new Zircaloy, M5, ZIRLO. All of them
18 seem to fit. We've determined what the oxidation
19 value is, where ductility is lost. We've determined
20 where the breakaway oxidation process begins. We've
21 put it all together in that manner, and we haven't
22 found any problems. I don't think any re-analysis of
23 operating reactors would be needed. You don't have to
24 change any ECCS models. The criteria would work for
25 small break and large break, the cladding really

NEAL R. GROSS

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

1 doesn't care.

2 The change that we made to add the time
3 limit is especially appropriate for small break, so I
4 would make that estimate. I also think that these
5 criteria would be valid for modest burnup extension
6 because we really didn't see a burnup effect per se.
7 It was a corrosion effect, which is a consequence of
8 the burnup process. And because we have tested
9 specimens with a lot of corrosion on them, I think we
10 probably covered the corrosion range that would be
11 experienced with newer cladding that were taken up
12 there. So my expectation is that you could justify
13 this at higher burnups than the current limit of 62
14 gigawatt days per ton. And I think because these
15 criteria as they would be written in a regulation
16 would be performance-based, they would apply to all
17 zirconium-based alloys. And this would avoid the need
18 for exemptions from the rule for not only the current
19 alloys, M5, but newer alloys such as low tin, ZIRLO,
20 and other alloys that might be coming along.

21 I'm finished. He didn't see this coming.
22 This is Mike Billone who's sitting over here. And I
23 just wanted to mention that Mike recently got a very
24 nice award at the University of Chicago. And here he
25 is with this important body himself, the president of

NEAL R. GROSS

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

1 the university, his important vice president, and the
2 director of Argonne National Laboratory. So I hope
3 you will let me sit down now and congratulate Mike.

4 (Applause)

5 MEMBER SHACK: He even got enough of a
6 bonus he could buy another tie.

7 CHAIRMAN POWERS: Seems to be a tradition
8 of conservation of ties at Argonne. Members have any
9 questions of Dr. Meyer? Dr. Meyer, could you put up
10 your slide in which you showed the layers and argued
11 that spallation made no difference?

12 DR. MEYER: Okay. You've got to read to
13 do this. I thought you just had to look at pictures.
14 Oh, when I do that it's going to put me to the
15 beginning.

16 CHAIRMAN POWERS: This'll do.

17 DR. MEYER: Do what?

18 CHAIRMAN POWERS: This'll do fine. Okay.
19 What I would argue is that if you're at a fixed
20 temperature, you're having a quasi-steady state across
21 each one of those layers, because there's a fixed
22 oxygen potential at each interface, right?

23 DR. MEYER: Yes, probably.

24 CHAIRMAN POWERS: Okay. If I thin one
25 layer, the flux across that layer has to increase.

NEAL R. GROSS

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

1 DR. MEYER: If you thin the layer?

2 CHAIRMAN POWERS: Sure. Cut that layer in
3 half, the flux across it's got to go up. So if I
4 spall off a little of the oxide, the flux across the
5 layer's got to go up because the oxygen potential at
6 each interface is fixed.

7 DR. MEYER: Oh, I don't know.

8 CHAIRMAN POWERS: How else could it be?
9 The oxygen potential --

10 DR. MEYER: If you thin the layer the flux
11 has to go up?

12 CHAIRMAN POWERS: Sure. The oxygen
13 potential at each interface is fixed.

14 DR. BILLONE: But at the instant you take
15 it off, it hasn't changed. The oxygen profile hasn't
16 changed. Then it grows. That's true.

17 CHAIRMAN POWERS: It has to go faster too
18 because the oxygen flux across the layer went up.

19 DR. BILLONE: Then it catches up.

20 CHAIRMAN POWERS: Yes. And that's usually
21 called oxidation, and it's more rapid, and things go
22 faster.

23 DR. BILLONE: That is correct.

24 CHAIRMAN POWERS: Yes.

25 DR. BILLONE: You're correct, and Ralph

NEAL R. GROSS

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

1 may also be correct, that as long as you have enough
2 oxygen at that alpha/beta interface to pump into the
3 beta layer, you're going to embrittle the material,
4 with or without that spallation. You might both be
5 correct.

6 DR. MEYER: Certainly the oxidation rate
7 would speed up.

8 CHAIRMAN POWERS: It has to.

9 DR. MEYER: Oh, I agree with that. But I
10 don't think the rate of diffusion into the metal is
11 going to change much. If anything, it's going to slow
12 down a little, which is the opposite of what you were
13 thinking, I think.

14 CHAIRMAN POWERS: It's going to slow down
15 a little? I would be fascinated to listen to that
16 argument.

17 DR. MEYER: If I took half of the oxygen
18 source off of there, I think --

19 CHAIRMAN POWERS: No, there's no oxygen
20 source going off there. The oxygen source is exactly
21 the same. The oxygen source is steam.

22 DR. MEYER: Not for the metal. Well, for
23 the oxide. I mean, steam, an oxygen atom from the
24 steam is going to stick right out here. It's not
25 going to weasel its way into the metal surface.

NEAL R. GROSS

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

1 Eventually.

2 CHAIRMAN POWERS: The transfer is by ionic
3 diffusion, but.

4 DR. BILLONE: Yes.

5 CHAIRMAN POWERS: Okay. And if I thin
6 that layer, it goes a lot faster.

7 DR. BILLONE: That's correct.

8 DR. MEYER: The reaction process. Yes.
9 But not the diffusion into the metal. If anything
10 that's going to slow down.

11 CHAIRMAN POWERS: I don't understand how
12 it slows down.

13 DR. BILLONE: I don't know, but I need a
14 break.

15 MEMBER SHACK: He's looking at the oxide
16 itself as the source of oxygen.

17 DR. MEYER: Yes.

18 MEMBER SHACK: And then the transport from
19 the corrosion.

20 DR. MEYER: Exactly.

21 MEMBER SHACK: I'm not sure I agree.

22 DR. MEYER: Well.

23 CHAIRMAN POWERS: But spallation screws up
24 his time scale.

25 DR. MEYER: Let me just recite -- I hope

1 I can get this correct -- a statement that Brachet,
2 Jean-Christophe Brachet made at our meeting last time.
3 He pointed out how they put oxygen into the metal when
4 they went to alloy. They went, you know, you put
5 oxygen in the Zircaloy as one of the alloying things.
6 And in the laboratory if you want to do this you
7 oxidize the specimen on the surface, and then you put
8 it in an inert atmosphere, and you heat it up. And
9 the oxygen goes in.

10 CHAIRMAN POWERS: And okay. I'm at a
11 total loss as to what that has to do with what
12 spallation does. It seems to me what spallation does,
13 at the very minimum it screws up your time scale.

14 DR. MEYER: In the case I just described,
15 if you spalled off a piece of the oxygen that had been
16 laid on there before it was put in this inert
17 atmosphere and heated up, you wouldn't get as much
18 oxygen diffusing into the metal, because you had taken
19 away some of the oxygen source.

20 CHAIRMAN POWERS: Your inert atmosphere
21 seems to have nothing to do with the problem at
22 interest here.

23 DR. MEYER: Well, in a way it does. I
24 realize this is not an inert atmosphere, and as soon
25 as you take some away it's going to grow back mighty

1 quick.

2 CHAIRMAN POWERS: And that changes your
3 time scale.

4 DR. MEYER: Doesn't change the time scale
5 if you're using an equation. By the way, we always
6 use this equation as if the material were bare. We
7 don't put a corrosion thickness on this equation when
8 we use it. It's being used as a time scale, not as an
9 accurate predictor of how much oxygen has grown on the
10 surface. We apply the equation as if the metal
11 started out bare, and ---

12 CHAIRMAN POWERS: If it starts out bare
13 you don't have any choice in that matter usually.

14 DR. MEYER: Well, you know, if it started
15 out with 30 microns of corrosion I guess you could
16 start the Cathcart-Pawel equation there.

17 CHAIRMAN POWERS: Yes. How much
18 difference would it make?

19 DR. MEYER: I don't know.

20 CHAIRMAN POWERS: Epsilon.

21 DR. MEYER: Okay.

22 CHAIRMAN POWERS: But if you come along,
23 and you're saying look, I'm looking at the point of
24 oxidation -- maybe not. Maybe it doesn't screw up
25 your time scale. I don't know. Are there any other

NEAL R. GROSS

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

1 questions? Then we will take a break until quarter
2 of. Thank you Dr. Meyer.

3 DR. MEYER: Thank you.

4 (Whereupon, the foregoing matter went off
5 the record at 10:28 a.m. and went back on the record
6 at 10:46 a.m.).

7 CHAIRMAN POWERS: Let's come back into
8 session. If the members will look on Dr. Meyer's
9 viewgraphs, I think it's Viewgraph 28 and 29, it is my
10 understanding that these are the viewgraphs -- maybe
11 it's 27, 28, and 29 -- that these are the viewgraphs
12 that really contain what RES would like to get some
13 sort of feedback from. And so I'll ask you to bear
14 those in mind as we go through the rest of the
15 discussions, and when we get to 7 o'clock, I will
16 probably come around and ask the members if they have
17 any comments pertinent to these three viewgraphs based
18 on what they've heard up till then.

19 MEMBER SHACK: 27's interesting.

20 CHAIRMAN POWERS: It's 28 and 29?
21 Definitely 28 and 29. 27 is blank? If they have any
22 comments on that as well. I mean, that has to do with
23 the proposed testing. Testing going on. And so if
24 you have comments on that I think it would be useful
25 too. Probably there will be at least one or two words

NEAL R. GROSS

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

1 about thermal transience.

2 With that we will turn to the award-
3 winning speaker, Dr. Billone.

4 DR. BILLONE: That's a tough act to
5 follow, you know. I have a rather lengthy
6 presentation. I have to apologize for it. And what
7 I did was this morning I pulled out about 40
8 viewgraphs for my discussion session later. So you
9 have a combined -- if you have the package, it's like
10 108 viewgraphs.

11 MEMBER SHACK: You didn't number them
12 either.

13 DR. BILLONE: No, I numbered them in my
14 presentation this morning. I apologize for that. But
15 before we get into that, I thought it would be a good
16 idea just to tell you what kind of tests we run, and
17 just to tell you what we mean by "ductility".
18 Basically, we run two types of tests on a 25
19 millimeter cladding sample. And this could be as
20 received, pre-hydrided, or it could be high burn-up.
21 We expose it to steam on both sides, the various
22 oxidation levels, and then we cut -- from this piece
23 we cut 8 millimeter rings. This is as fabricated.
24 I'm using 15 x 15 because it's a little bit bigger and
25 easier to see. So the advantage of this kind of test

NEAL R. GROSS

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

1 is when you get to radiated material where the real
2 estate is very precious, you can run a lot of tests
3 with small segments like this, cut rings from them,
4 and bend the rings.

5 Before we do that, let me just, since I
6 want to give you an idea of ductility as we define it,
7 and brittle as we define it, and then what is the
8 difference between a clean brittle failure and
9 fragmentation is the last part of my demonstration,
10 because that's highly dependent on how you load the
11 sample, what the loading rate is on the sample. So
12 basically, if you take the as-fabricated material, and
13 you put it in an Instron, and you squeeze 2
14 millimeters, it springs back about 1 millimeter, and
15 you've got about 1 millimeter permanent displacement.
16 And this is something you can determine from the load
17 displacement curve through the offset strain, or you
18 can simply measure the diameter before the test in the
19 loading direction, diameter after the test, and you
20 measure about a millimeter of permanent plastic
21 strain. So, going from a circular shape to an oval
22 shape before you crack is an indication of ductility
23 in the ring compression tests. If I go all the way,
24 there's no sense even looking at the load displacement
25 curve. You can essentially squeeze the sample flat.

NEAL R. GROSS

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

1 And it means as-fabricated cladding has very, very
2 high ductility.

3 All right, let's oxidize it two-sided to
4 10 percent ECR. It doesn't matter whether you're at
5 Cathcart-Pawel or actually measure at ECR. They're
6 both about the same. And now when I squeeze that
7 ring, I go from a continuous ring to a split ring, a
8 very, very sharp load drop of about 40 - 50 percent.
9 We stop the test. We take the sample out. We have to
10 look at it under a microscope. You get a crack that
11 is so thin and tight that you need a microscope to see
12 it. That's what we're calling failure in our
13 screening test, is when you go from a continuous ring
14 to a through-wall crack along the whole length of the
15 sample. So this, again, it's too small for you to
16 see, it started out circular, it ends up about
17 circular. You get essentially no plastic deformation.

18 CHAIRMAN POWERS: Excuse me, Mike. If you
19 lay it down somewhere, the cameraman can show it to
20 everybody.

21 DR. BILLONE: Oh, I'm sorry. Okay, let me
22 contrast those two pieces. I'm sorry. Anyway, it's
23 a very simple concept. It's a very simple test to
24 run. And the ring compression test, as much as you
25 may malign it, is used for brittle materials,

1 composite materials, because you don't need to cut or
2 machine gate sections, and you don't need to grip.
3 You just simply load it between two flat plates.

4 I showed you the results of doing a room
5 temperature test after 10 percent oxidation of 1,200
6 degrees C. If you run the test at 100 degrees C,
7 surprisingly, and it's hard to see, you do get a
8 little ductility. You do get a little bit of ovality
9 in the sample. And if you run the test at 135 degrees
10 C, you might be able to see, you get considerable
11 ovality. You've got very high ductility.

12 All right. So those are basically our
13 ring compression tests. We run those, as I say, on a
14 lot of materials. You can do them very fast. The
15 two-sided oxidation's very reliable. It's very easy
16 to determine weight gain by simply measuring the
17 sample before and after. Now, there's a different
18 kind of test that we run for what we call our LOCA
19 integral specimens. And those specimens are about 300
20 millimeters long, 12 feet to those of us in the old
21 units. And for the high burn-up stuff, they're
22 essentially filled with cladding. They're welded end
23 caps with a pressure tube coming down at the top. So,
24 think of our LOCA integral test as pre-pressurizing
25 the inside of this material, which is basically filled

NEAL R. GROSS

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

1 with fuel, ramping and steam at 5 degrees C per
2 second, and we'll show that, and holding at 1,200
3 degrees C for various amounts of time. Slow cooling,
4 3 degrees C per second, and then quenching at 800
5 degrees C.

6 So, what happens if I do that for non-
7 irradiated cladding, because I can't really bring
8 Robinson cladding in here and hold it in my hands. We
9 take that material, and Ralph showed you actually what
10 happens in the more extreme case, if you go all the
11 way to 20 percent ECR in the burst region, he showed
12 you the oxygen profile, and he showed you the hydrogen
13 profile, and that sample is extremely brittle in the
14 balloon region. It's a sample that two years ago I
15 took in my hands, and I did a four-point bend test for
16 one of our technical advisory groups, and I got a very
17 clean break across the burst region. What I would
18 like to show you today is, again, if you took the as-
19 fabricated cladding, and you did a four-point bend
20 test like this, it has extreme ductility, and it has
21 a bending moment of over 2 kiloNewtons per meter.
22 It's not the failure bending moment, but it's capable
23 of not breaking at a very high bending moment, and
24 it's capable of much more deflection than this, we
25 just happened to stop the test at this point. So this

NEAL R. GROSS

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

1 I think they can see without the camera. This is what
2 we mean by ductility. It's a permanent change in
3 shape of the material after the test is over.

4 All right. That's not very interesting.
5 The question really I want to address is I already
6 know that our samples that we let stay at 1,200
7 degrees C for five minutes, that's an ECR of about 20
8 percent Cathcart-Pawel, about 20 percent Baker-Just.
9 They were very brittle at room temperature in the
10 balloon region. So we finally got more sophisticated
11 than my hands, which are not calibrated, so we
12 developed the four-point bend apparatus, the fixtures,
13 and it's now done in an Instron where the -- if you
14 think of it, this is upside down compared to the
15 Instron, my thumbs are moving at a prescribed
16 displacement rate, and are recording the load. So you
17 end up with a load versus displacement at where my
18 thumbs are. Now, what happens for the LOCA integral
19 samples, if I now cut back the time from five minutes
20 to two minutes at the high temperature, because you're
21 picking up all this oxidation on your ramp up, and
22 some on your ramp down, the ECR only goes down from 20
23 percent to 14 percent. So what I'm going to show you
24 is what happens when I do a four-point bend test on a
25 14 percent ECR sample in the balloon region. And what

NEAL R. GROSS

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

1 happens is essentially what happened two years ago.
2 You get a very, very clean break across the weakest
3 part of the material, which is the burst region of the
4 material. So this happened, if you look at the load
5 displacement curve, this failed in the elastic regime,
6 indicating at room temperature it's brittle. I would
7 like to know very soon whether or not you get the same
8 hydrogen peak. And it's a little expensive between
9 Thursday and now to cut a bunch of little samples, and
10 meticulously measure oxygen concentration and hydrogen
11 concentration. So we'll save this sample, and we're
12 just going to tap it with a hammer, because what I
13 found a couple of years ago is if you start tapping
14 with a hammer, you can pretty much map out the
15 hydrogen profile. And it also illustrates that the
16 idea of fragmentation, you can have a brittle material
17 that behaved this way in a bending test. The brittle
18 material would also behave that way if I pulled on it,
19 the tension test. They're both axial type loading.
20 If you whack it with a hammer, that's when the brittle
21 material may fragment, or may not fragment.

22 So the idea of fragmentation, and also you
23 all have the experience of taking a hot plate that's
24 a little too hot and putting it under cold water, and
25 what I've seen is pie-shaped cracks instantaneously

NEAL R. GROSS

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

1 forming, with a loud burst of sound. So you can
2 fragment things with thermal shock. And if you take
3 the combination of thermal shock, and a little bit of
4 impact, a little bit of pulling, it's possible to
5 fragment if you have extreme and brittle material.
6 But fragmentation is not a material property
7 necessarily. It has to be in conjunction with loads.
8 So to the extent you either know or don't know your
9 LOCA loads you can deal with fragmentation. And
10 that's why we're assuming you don't know all the loads
11 in the degraded core, we're backing off from
12 fragmentation to just simply brittle behavior, to
13 trying to avoid brittle behavior. So let's hold this
14 sample.

15 Now, there must be some time or test
16 conditions in which you finish this test and have
17 ductility at room temperature. So we went to the
18 extreme of only holding at 1,200 degrees C for one
19 second. The ECR is 8 percent because we're ramping in
20 steam at 5 degrees C per second, picking up oxidation.
21 We hold for one second, slow cool to 800, and then
22 quench. And it's kind of interesting when you subject
23 it to the four-point bend test, because the sample's
24 still intact. In the elastic regime, you get a very
25 sharp load drop of about 80 percent, which is the

NEAL R. GROSS

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

1 burst region failing, and part of the circumference
2 failing. After that, you get a very low load drop,
3 because the back of this burst region -- and remember
4 this is thin wall. It gets thicker as you go 180
5 degrees. The back of that region is relatively
6 ductile. And because I want to do the same hammer
7 test on this, we'll complete the test. This was the
8 limitation of our Instron machine. We couldn't bend
9 it any farther. And you don't really have to. You
10 would call this sample -- as a structure, you would
11 call this sample ductile. So if I complete the
12 process, which wasn't too hard, I now have another
13 sample which was oxidized much less, may have a lot
14 less hydrogen in it, and that will lead me to my next
15 step.

16 But before I whack these samples, and by
17 the way, these two I'm bringing home for analysis so
18 I'm going to put these away so I don't get a little
19 bit happy with the hammer. Does anyone have any
20 question on the two basic tests we run? We run a
21 four-point bend test on the LOCA integral sample
22 because it's highly non-uniform, and oxygen
23 concentration, the axial direction, a diameter burst
24 or non-burst, and in hydrogen. And what the four-
25 point bend test does is it gives a uniform bending

NEAL R. GROSS

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

1 moment between my thumbs. So you're not biasing any
2 region of non-uniformity. And it fails where it's
3 basically the weakest. All right. The idea here --

4 MR. ELTAWILA: Mr. Chairman, can I ask a
5 question please?

6 DR. BILLONE: Yes.

7 CHAIRMAN POWERS: Sure.

8 MR. ELTAWILA: Why you're oxidizing the
9 inside of the tube?

10 DR. BILLONE: Because from experimental
11 point of view, we're talking about -- I'm sorry. Are
12 you talking about these small ones?

13 MR. ELTAWILA: I think, yes. You were
14 talking about the large for all your tests that you
15 have to oxidize the tube from the inside and the
16 outside, pre-oxidizing the tube.

17 DR. BILLONE: Well, the answer --

18 MR. ELTAWILA: So why the inside?

19 DR. BILLONE: Because based on worldwide
20 experience, some of which was shared to us as late as
21 May 11, there's all kinds of problems in doing the
22 one-sided oxidation test, particularly of short
23 samples on the radiated samples. You get very
24 reliable experimental results, and you can determine
25 weight gain very reliably by doing the two-sided test.

NEAL R. GROSS

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

1 You have good temperature control, and you have good
2 control of the oxidation. If there's hydrogen in the
3 sample, you don't risk losing the hydrogen to the
4 inner surface of the material.

5 MR. ELTAWILA: Would that affect the
6 mechanical properties of the cladding?

7 DR. BILLONE: No, because as I'll show in
8 my presentation, CEA for non-irradiated materials, CEA
9 meaning CEA, EDF, Framatome. I'm just going to
10 simplify it and call it CEA. They do one-sided
11 oxidation tests on the same materials that we're
12 using. We do two-sided. And our test results as far
13 as ring compression agree extremely well for the
14 material that's not pre-hydrided. So it doesn't seem
15 to make a difference from that point of view. So we
16 do it because we get much more reliable results, we
17 have much better temperature control. The two-sided
18 oxidation naturally occurs with the ballooning and
19 bursts.

20 MR. ELTAWILA: But only in the balloon
21 region.

22 DR. BILLONE: Only in the balloon region.
23 Having just lost track of my samples -- well, you know
24 what, this is more interesting. Because it's more
25 interesting not to know which sample is which. All

NEAL R. GROSS

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

1 right. What I'd like to do is, again, my experience
2 is light tapping in the region that's highly
3 embrittled and thin. Highly embrittled with hydrogen
4 and oxygen tends to cause fragmentation. As I move
5 out of that regime, and I won't do it I hope. You can
6 pound as hard as you want, the material's so tough
7 that you can't even get a crack to grow in the
8 material. Hopefully I will not do that.

9 So let's take one of these samples. And
10 let me take the other sample. Okay. I now know which
11 sample is which. This is the sample that was held for
12 one second. You essentially had very little hydrogen
13 embrittlement outside the balloon region. This is the
14 sample that was held for two minutes. And if I
15 pounded a little bit harder, what would happen is I
16 would continue to fragment. So the issue of
17 fragmentation, I know the material is brittle in that
18 regime, I know it would snap cleanly in a bend test,
19 it would snap cleanly and not disperse fuel in an
20 axial test. But there are other loads that could
21 cause a brittle material to fragment, and that's one
22 thing we're backing away from.

23 That's all I really intended to do, is to
24 say that, as Ralph showed, you've got oxygen and
25 hydrogen embrittlement, and there's various ways you

NEAL R. GROSS

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

1 could test for that. The simplest I can demonstrate
2 to you is just tap with a hammer, increase the tapping
3 of the hammer, and eventually as I get out here,
4 outside the balloon and burst region -- I've done it
5 in my office when OSHA has not been around -- you can
6 bang it you know from up here as hard as you can, and
7 the material is really, really tough. So that ends
8 the demonstration part. And I hope I've demonstrated
9 everything I'm about to present to you in this. So
10 thank you for that.

11 We're going to switch off of the camera.
12 Okay, thank you. This has the 108 slides numbered,
13 but I'm going to try to skip to the ones I'm going to
14 use for discussion. It takes a little while to load
15 because it's huge. All right, what one step do I have
16 to do to get it on the screen? Oh, you did it for me.
17 Thank you. Before I start, I'd like to acknowledge
18 Dr. Yong Yan, the principal investigator for this
19 work, Tanya Burtseva who does the very detailed oxygen
20 and hydrogen analysis, along with the ring compression
21 tests. Hee Chung is our senior technical advisor.
22 He's now retired, but as Ralph knows, he's very
23 accessible for last minute questions before big
24 meetings. Okay.

25 All right. Let me try to explain the

1 purpose of our work, although from Ralph's
2 presentation it should be clear, but to generate steam
3 oxidation kinetics and post-quench ductility data for
4 cladding. And as I mentioned, we deal with as-
5 fabricated cladding alloys. There are the four that
6 are in our program. Pre-hydrided cladding alloys, and
7 so far we've just pre-hydrided Zirc-4. You'll see
8 some excellent data, or read excellent data done by
9 CEA-EDF-Framatome, and please just let me say CEA,
10 that the lab has done. M5 and Zirc-4. The Argonne
11 work, we've concentrated only on pre-hydrided Zirc-4
12 because we have high burnup Zirc-2 and Zirc-4
13 currently at the hot cells. We also have -- these are
14 fuel segments, fuel rods cut into segments. We also
15 have 8-centimeter long tubes of defueled high burnup
16 ZIRLO in M5 for our testing program. That's what we
17 currently have in the hot cell.

18 In addition to just generating data, we're
19 trying to develop some mechanistic understanding of
20 cladding behavior, with the emphasis on effects of
21 high burnup and effects of fuel on the cladding at
22 high burnup during LOCA events. We kind of added
23 additional responsibility, and that is to develop a
24 rate correlation for ductile or brittle transitions,
25 something we'd integrate over a time/temperature LOCA

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 trace as a function of hydrogen content and the
2 particular time history that you have in steam. And
3 I'll have a presentation on that probably after lunch.

4 The other advantage -- the nice thing
5 about this program. It doesn't make our work any
6 better than anybody else's work, but because it's
7 sponsored by NRC we try to document and distribute all
8 of our data and correlations to NRC, industry, and our
9 technical advisory group for their independent
10 assessment. We don't wait until we've, you know,
11 crossed the last "t" and dotted the last "i". We
12 actually issue the data pretty close to when we
13 generate it. It may be in the form of a PowerPoint
14 presentation, letter reports, eventually journal
15 articles and NUREG reports. And for us, this has
16 worked very well because we get some very good
17 feedback from technical experts all over the world.
18 So hopefully that ends up being a better final
19 product.

20 Okay. A little more specific about the
21 scope of the work in terms of steam oxidation kinetics
22 meaning weight gain versus time, if you will. And
23 post-quench ductility, as I showed, we concentrate on
24 1000, 1100, 1200 degrees C oxidation of those short
25 segments. And these are all samples quenched at 800

NEAL R. GROSS

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

1 degrees C. We've done ring compression tests to
2 determine post-quench ductility at room temperature,
3 100 degrees C, and 135 degrees C. We're pretty much
4 now focusing on the 135 because as soon as you add
5 hydrogen to the material, jack the temperature up to
6 1200, you embrittle quite quickly at room temperature.
7 And if you're going to look for any ductility, you're
8 going to be looking for it at that temperature.

9 Those are all essentially ring tests. In
10 addition, as I mentioned, samples approximately this
11 long with high burnup fuel, or with zirconium pellets
12 if you're doing out of reactor work. Those are our
13 LOCA integral tests. And those are followed by four-
14 point bend tests, and a lot of characterization to
15 determine what the effects of the fuel are in the
16 cladding.

17 Our advanced alloys, we're using 17 x 17
18 Zirc-4 as a basis modern belt polish, 17 x 17 Zirc-4,
19 and comparing that, the behavior of ZIRLO and M5 to
20 the 17 x 17 Zirc-4. We also have 10 x 10 Zirc-2,
21 which is in our program and will be tested in the
22 fall. That came a little later than the other alloys.

23 E110 is really added to the program
24 because you really want an alloy that behaves badly to
25 test your test techniques. I mean, is post-quench

1 ductility a good screening test? Well, if what you
2 saw in the E110 pictures, if that stuff comes out
3 ductile there's something wrong with your test. So
4 it's in there for really two reasons, understand a
5 little bit about how bad alloys perform with these
6 tests, and try to gain some insights into maybe why it
7 behaves so badly at the same time. That's kind of a
8 bonus.

9 I already mentioned that we looked at pre-
10 hydrided 17 x 17 Zirc-4 rings, high burnup defueled,
11 ZIRLO and M5, are at ANL. We'll be doing the same
12 kind of ring double-sided steam oxidation tests on
13 those. LOCA integral tests, eventually we'll get some
14 fueled M5 North Anna to INL, eventually to IANL. How
15 we're going to get fueled ZIRLO is yet to be
16 determined for our program.

17 The high burnup Zircaloy program. We have
18 Limerick BWR cladding, fuel cladding, and we've
19 conducted four tests with that. We're now switching
20 our focus to the Robinson PWR Zirc-4 cladding. We've
21 completed some tests with short rings, and we're
22 trying to move on to the LOCA integral tests with the
23 materials. So, for Zirc-4 15 x 15, we had a lot of
24 baseline material. Framatome was generous with the
25 material it gave us. So we did a lot more tests than

NEAL R. GROSS

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

1 even our advanced alloy tests in terms of as-
2 fabricated material duplicating tests, seeing we got
3 the same results, pre-hydrided from 5 to 800 weight
4 parts per million, and of course the high burnup
5 hydrogen levels are at 400 - 800 ppm.

6 So, tests that have been completed are
7 tests that I'll show you data. This is another shot
8 of the alloys that we have. And this is really just
9 put in there for your records. But we have cladding
10 thicknesses from 0.57 millimeters to 0.7 -- well,
11 throw this one out. This is really tubing. And one
12 thing we learned in this is you don't want to test
13 tubing. You want to test whatever the final steps
14 are, it could be etching, it could be belt polishing.
15 You'd like to test the cladding in its final form
16 before fuel is put in it. And so throw out that one.
17 So let's say 0.57 to 0.76 wall thicknesses, and
18 diameters ranging from about 9.2 if you count E110
19 millimeters to about 11.2. So we have a range of
20 alloys in terms of composition, a range of geometry,
21 and a range of surface finishes. And the last number
22 on the right is the surface roughness ranging from
23 about 0.1 micron mean square roughness for belt polish
24 material up to about 0.3 to 0.35 for material that
25 hasn't been belt polished.

NEAL R. GROSS

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

1 Okay. You should be familiar from
2 previous presentations, we're just going to
3 concentrate on these two high burnup fuel types. The
4 Robinson Zirc-4, and with up to 800 ppm of hydrogen,
5 and up to 100 micron oxide layer. Excuse me, it's
6 called a corrosion layer for this talk. That's the
7 in-reactor stuff. And the Limerick, and please notice
8 in the column on the far right that the Limerick after
9 57 gigawatt days per metric ton only has about a 10
10 micron oxide layer, and about 70 ppm of hydrogen. It
11 makes these -- it's not that this is Zirc-2 and this
12 is Zirc-4, this is what makes these alloys extremely
13 different, the hydrogen content. And you would expect
14 different test results as a result of it.

15 Okay, this is one I pulled out for my
16 discussion. Well, you know, this is too much fun.
17 I'm not going to do this. I have to go through this.
18 Ralph talked about embrittlement, and Ralph actually
19 showed you, and I have to contradict you on this,
20 Ralph. Sorry. He showed you E110 breaking up after
21 about 300 seconds, and the surface looking rather
22 wretched. It appears that we just caught the
23 beginning of this process. And if you take this
24 grayish white oxide, which is, we call it "bad oxide".
25 It's the monoclinic oxide that tends to crack and

NEAL R. GROSS

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

1 break up. And next to it is the black oxide, it
2 doesn't show up that well in this contrast, which
3 tends to be an adherent layer that maintains its
4 integrity, and is a barrier for -- a traditional
5 barrier for oxidation.

6 Anyway, if you look under this region,
7 this is the oxide layer, and it has delaminated from
8 the metal layer. Question is, is that ductile or is
9 that brittle? And I'll show you in a second. Now, if
10 you go to the extreme case, 1,400 seconds, Ralph
11 showed that picture. That's got 4,000 ppm of
12 hydrogen. That's clearly brittle. This only has
13 about 120 ppm, which means we caught this early in the
14 process. So the answer to the question is it ductile
15 or is it brittle, that E110 that looks so terrible
16 because we caught it at the beginning of the process
17 happens to have about 60 percent ductility, meaning if
18 I look at load and displacement, I can essentially
19 squeeze that E110 flat, even though the surface looks
20 like a nightmare. That's about 300 seconds. If I go
21 another additional 300 seconds at 1000 degrees C and
22 cool, it's extremely brittle, and it's picked up about
23 300 ppm of hydrogen. So this is the E110 ring
24 compressed, and again, this green line is the offset
25 strain. You get essentially offset strain within the

NEAL R. GROSS

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

1 noise at about 7 percent ECR. So about 300 seconds
2 after the picture Ralph showed you, the alloy -- "goes
3 to hell" is not a proper thing to say at a meeting.
4 The alloy behaves badly.

5 All right. Ralph showed you this picture.
6 Is it brittle or ductile? He gave you the answer,
7 essentially. And that's the load displacement curve.
8 This is the offset strain, which is about 5 - 6
9 percent. Five percent for me, 6 percent is the number
10 I gave Ralph.

11 Okay. This picture looks really nice, so
12 I'm obviously setting you up. This is 17 x 17 Zirc-4,
13 13 percent ECR at 1200 degrees C. Is it brittle or
14 ductile at room temperature? Is it brittle or ductile
15 at 135 degrees C? And the answer is that 1200 degrees
16 C is a very embrittling temperature, and at room
17 temperature this material is brittle, and at 135
18 degrees C it happens to be ductile. Hopefully I've
19 got the results. This is the measure at ECR in terms
20 of weight gain is shown on here. But this is the load
21 deflection curve. At room temperature you get
22 essentially displacement, permanent displacement
23 that's within the noise. And this is the load
24 deflection curve. You get about 10 times the
25 displacement when you test at 135 degrees C.

NEAL R. GROSS

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

1 Okay. This is an even nicer picture,
2 which I have the punchline just cued up in front of
3 you. What happens if you add 600 ppm of hydrogen,
4 drop the ECR or the oxidation down to 7.5 percent of
5 the wall thickness, and you oxidize at 1,204 degrees
6 C? This is your classic oxide layer, your classic
7 oxygen stabilized alpha layer. This is your prior
8 beta layer. It is loaded with oxygen, even though
9 your oxidation time is not that long. It's loaded
10 with oxygen because you've jacked up, at this
11 interface you've jacked up the boundary condition from
12 about 0.6 percent to about 1 percent oxygen. You've
13 increased the steepness of the initial gradient of
14 oxygen across the material, and your pumping oxygen in
15 rather fast. So, the question at room temperature
16 isn't worth asking. It's extremely brittle at room
17 temperature, so brittle I didn't even ask Tanya to
18 draw this up in the fancy way. And if you test that -
19 - sorry. This test was performed at 135 degrees, our
20 highest test temperature. Material is extremely
21 brittle at 135 degrees, with 600 ppm of hydrogen, and
22 that level of ECR. Okay.

23 CHAIRMAN POWERS: In this particular
24 sample, you loaded it with hydrogen artificially?

25 DR. BILLONE: Pre-hydrided in hydrogen, 4

1 percent hydrogen plus argon gas.

2 CHAIRMAN POWERS: And you'd anticipate
3 that real cladding would acquire its hydrogen during
4 normal operation.

5 DR. BILLONE: Right.

6 CHAIRMAN POWERS: So when Ralph sets up
7 his criteria, his proposed criteria, and says look for
8 embrittlement based on un-irradiated cladding, you're
9 taking issue with that?

10 DR. BILLONE: Well, the un-irradiated
11 cladding has to be both fresh, as-fabricated, because
12 that's what you're putting in the reactor. But in
13 looking at the burnup effect, and I thought he had
14 that in there, you have to pre-hydride the un-
15 irradiated cladding at a level that you expect based
16 on your corrosion layer. And it may not have been
17 said explicitly enough. He may have said corrosion
18 layer, because the two are correlated. But certainly
19 if it's M5 and you expect the maximum of 200 ppm of
20 hydrogen at your highest burnup, you would want to
21 know how the non-irradiated material, M5, behaves up
22 to that hydrogen level. So yes, it's essential that
23 the non-irradiated test, the inexpensive tests with
24 hydrogen be done. But they need to be done within a
25 realistic range of expectations.

NEAL R. GROSS

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

1 CHAIRMAN POWERS: Well, I mean, nothing in
2 this criteria seems to mention that pre-hydriding it.

3 DR. BILLONE: I'll have to sit down with
4 Ralph and look at it. I thought he had something in
5 there about corrosion layers.

6 CHAIRMAN POWERS: He said the oxide, the
7 corrosion oxide should be determined and expressed as
8 a percentage of cladding thickness for fuel rods and
9 burnups of interest. I mean, okay, list it down.

10 DR. BILLONE: All right, then Step 2 from
11 that, once you've done that, you have a correlation
12 that tells you how much hydrogen -- well, maybe I need
13 to talk to Ralph. Maybe we need to talk. There's one
14 more step after what he said, and that is if M5, you
15 expect 20 microns of corrosion at high burnup, and 120
16 weight parts per million of hydrogen, that go hand in
17 hand, then you need to know how your non-irradiated
18 material's going to behave up to that hydrogen level.

19 DR. MEYER: This is Ralph. I did not have
20 a test proposed for pre-hydrided material.

21 DR. BILLONE: Oh, I know why. Because you
22 had the corrosion.

23 DR. MEYER: Because we used the corrosion
24 sickness as a surrogate for that. But he can explore
25 the effects of hydrogen with those kind of tests. So

1 he's doing more tests than we have skimmed off for the
2 proposed criteria.

3 DR. BILLONE: Yes. Let me back off. I'm
4 thinking in a laboratory timeframe, looking for
5 mechanisms, and definitely you want to do this test.
6 In terms of what regulation requires, and what their
7 final criteria, they do criteria, I do tests and
8 correlations. I've got to keep remembering this.
9 It's not a disconnect, it's just the flow of
10 information from us to RES, and then their
11 reinterpreting the information in licensing language.
12 For us it's essential to do these tests because you
13 can do a lot of them very cheaply, and before you go
14 into a reactor with a Robinson sample containing -- a
15 high burnup sample containing 600 ppm of hydrogen, you
16 darn well better have these results because you don't
17 know what test time to run at if you're trying to
18 bracket the ductile to brittle transition. So these
19 tests for us are critical in running our high burnup
20 tests. But I'm sorry, Dana, I keep interpreting you.
21 Did you want to finish?

22 CHAIRMAN POWERS: Well, just, I mean,
23 maybe you've succeeded in really confusing me.

24 DR. BILLONE: I talk too much.

25 CHAIRMAN POWERS: You seem to -- I mean,

NEAL R. GROSS

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

1 this seems to say that there is a synergism between
2 hydrogen acquired during operation --

3 DR. BILLONE: Right.

4 CHAIRMAN POWERS: -- and the subsequent
5 embrittlement by oxidation.

6 DR. BILLONE: Which was in the words in
7 Ralph's slides, yes.

8 CHAIRMAN POWERS: But I don't see in the
9 criteria that he's laid out here any recognition of
10 that, save that he wants you to measure the thickness
11 of the corrosion layer during normal operation, which
12 presumably comes from a lead test assembly.

13 DR. BILLONE: And Ralph's answer to that
14 was he's trying out the idea of if you subtract that
15 from the allowable ECR, he thinks, he hopes that
16 you're essentially accounting for the effects of
17 hydrogen.

18 CHAIRMAN POWERS: But if I look on your
19 previous slide, was that the case?

20 DR. BILLONE: You know, if I could
21 remember my previous slide.

22 CHAIRMAN POWERS: Well, you showed a list
23 of various sources of Zircaloy, you showed a list of
24 oxide thicknesses, and you showed a list of hydrogen
25 thicknesses. And at least operating from memory, I

NEAL R. GROSS

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

1 did not see a linear correlation between the two.

2 DR. BILLONE: Well, that's because -- of
3 course, in a boiling water reactor, once you get to
4 the mixed regime, about 20 inches above, then your
5 temperature is flat at about 288 degrees C, and you
6 don't get much axial variation due to the coolant
7 temperature. So your oxide is like 10 microns, and
8 your hydrogen level's about 70, for our particular
9 material. In the PWR, of course, you have this
10 temperature gradient coolant, which has a huge effect.
11 So you have -- I just listed maximum values of oxide
12 and --

13 CHAIRMAN POWERS: But what I'm not seeing
14 is how just subtracting off the corrosion layer
15 compensates --

16 DR. BILLONE: Oh, but you've got to take
17 that up with Ralph. Really.

18 CHAIRMAN POWERS: Well, I get to do that
19 kind of simultaneously --

20 DR. BILLONE: That's what he did. He kept
21 pointing to me when you asked.

22 CHAIRMAN POWERS: And that's fair. You
23 can point to him and explain how his criterion
24 accounts for this.

25 DR. BILLONE: From a mechanistic point of

NEAL R. GROSS

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

1 view, I am not interested in that. I'm interested in
2 providing the data, and Ralph is free to use the data
3 to check an information letter from 1998 to see if it
4 happens to hold. If it doesn't, then he's got to move
5 off that position. So Ralph's using something from
6 1998, am I correct? '98? Information letter, and
7 testing it against the data that I'll be showing.

8 CHAIRMAN POWERS: I'm still --

9 DR. BILLONE: This material had no
10 corrosion layer to begin with. So obviously Ralph's
11 scheme would not work for bare cladding.

12 CHAIRMAN POWERS: I understand that.

13 DR. BILLONE: You don't have bare cladding
14 in a reactor.

15 CHAIRMAN POWERS: What you're showing us
16 is the results of a test somewhat different than
17 what's specified in his candidate criteria.

18 DR. BILLONE: All these tests were done
19 long before he came up with those specifications, yes.

20 CHAIRMAN POWERS: Okay. And it's showing
21 an interesting physical phenomena that's pertinent.
22 And so all I'm asking is how did the criteria account
23 for this interesting physical phenomenon that looks
24 pertinent.

25 DR. BILLONE: Ralph?

1 DR. MEYER: Let me comment here that there
2 is a direct relation between the corrosion thickness
3 and the hydrogen absorption. It's one that's been
4 measured before. It's in our codes. And although we
5 don't have it explicitly factored in, because we're
6 not generating a mechanistic model here, it is -- I
7 think it is linear, and it's just a factor. It's
8 something. And so we're taking advantage of that. If
9 I could go ahead and jump to a good variety of the
10 question, a good question would be is the fraction of
11 absorbed hydrogen the same for the different alloys.
12 And we had essentially assumed that that would be the
13 case at the outset when we decided that we would test
14 the burnup effect in Zircaloy, and assume that the
15 burnup effect played out the same in all of them.
16 That may not be correct. We have the test that will
17 show if there's some gross discrepancy. The initial
18 test with the M5 and the ZIRLO using the Stusvick
19 material should reveal that. But for the moment I
20 think it's still a reasonable assumption to say that
21 using the dull pencil that we're using here for
22 regulation, that it is a good chance that this is
23 going to work out.

24 CHAIRMAN POWERS: I must be very, very
25 slow. You're perfectly willing to specify the

1 oxidation model to be used, but you will hide and
2 obscure the hydriding model you want to use. I mean,
3 you have some knowledge of how this corrosion layer
4 relates to the amount of hydrogen in the alloy.

5 DR. MEYER: Yes. About 15 percent of the
6 freed hydrogen is absorbed into the metal cladding.
7 And that's a number we use in our computer codes for
8 relating hydrogen to the corrosion process. We simply
9 don't introduce that number explicitly into this
10 process. It's more empirical. We simply test the
11 specimens with a given corrosion level, and check to
12 see if they're brittle or ductile, and look and see if
13 the method works. It appears to work.

14 CHAIRMAN POWERS: But I guess what I'm
15 asking -- every answer seems to get me a little more
16 confused. Here we see something, an alloy that is
17 taken to 7.5 percent effective oxidation here. It's
18 got a bunch of hydrogen in it. Okay, and it's brittle
19 at room temperature. It's not brittle at 135 --

20 DR. BILLONE: I'm sorry. It's brittle at
21 both.

22 CHAIRMAN POWERS: It's brittle at both?

23 DR. BILLONE: I made a slight --

24 CHAIRMAN POWERS: Okay, it's brittle at
25 both.

NEAL R. GROSS

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

1 DR. BILLONE: It's gone.

2 CHAIRMAN POWERS: Okay. This is a long
3 ways away from 17 percent. It had zero corrosion
4 thickness, but I suppose that 600 weight parts per
5 million hydrogen corresponds to a pretty healthy --

6 DR. BILLONE: About 70 to 75 microns of
7 oxide layer, which Ralph converted to ECR.

8 DR. MEYER: This is pre-charged with
9 hydrogen. This is not a --

10 CHAIRMAN POWERS: I understand that.

11 DR. MEYER: Okay.

12 MR. SCOTT: Dana, this is Harold Scott.
13 Six hundred ppms hydrogen is probably 70 - 80 microns.

14 DR. BILLONE: That's right.

15 MR. SCOTT: So 7 and a half -- 70 - 80
16 microns is 7 and a half plus 7 and a half's 15. We're
17 pretty close to 17.

18 CHAIRMAN POWERS: Okay. Well, you can do
19 these calculations in your head faster than I can.
20 Why don't you just show that? I mean, why not say
21 look, my corrosion layer will account for this
22 phenomenon, and then I don't have to worry about it.

23 DR. BILLONE: Well, it was too small on
24 Ralph's graph. He has red data points, and he has
25 blue points that do that on his graph for high burnup

NEAL R. GROSS

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

1 material. And that was material with 550 +/- 100
2 weight parts per million hydrogen naturally from in-
3 reactor, and about 70 micron corrosion layer. He
4 needs to enlarge that graph, I think, and make it jump
5 out at you.

6 DR. MEYER: I botched up the presentation
7 of that graph, too, because I mean it was plotted sort
8 of backwards of the way we generally approach it.
9 They took the experimental data and added the
10 corrosion thickness and compared that to the number.
11 And I didn't explain it well. So I think it's there.

12 MEMBER SHACK: Well, the other question,
13 shouldn't all your experimental results be expressed
14 somewhere in terms of those criteria? Instead of
15 showing it as 600 weight ppm, show that as you
16 projected equivalent ECR, and demonstrate whether or
17 not it's consistent with the criteria.

18 DR. MEYER: Well, certainly in my
19 presentation I think I did, or at least tried to
20 express all of the data in terms of the criteria that
21 we were trying to outline. I don't see that
22 constraint applying to Mike's work, where he's going
23 to --

24 MEMBER SHACK: Because he's got a much
25 larger database. You'd like to know that it's

NEAL R. GROSS

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

1 consistent with the proposed criteria.

2 DR. MEYER: Well, but I used his data. I
3 mean, everything I used came from his program. So.

4 DR. BILLONE: But really, what I'm going
5 to try to lead towards is presenting data, and this is
6 not -- I'm not doing licensing. And I'm not being the
7 interface with NRR. I'm trying to understand
8 phenomenologically what's causing the embrittlement,
9 how to calculate it, and ...

10 CHAIRMAN POWERS: I think we understand
11 that. I'm just trying to understand how it gets taken
12 into account in the criteria.

13 DR. BILLONE: Okay.

14 CHAIRMAN POWERS: And I think I understand
15 now. It looks correct. I just don't have this
16 correlation between hydrogen absorbed versus corrosion
17 thickness.

18 DR. BILLONE: It's actually -- at low
19 burnup it's a higher number, and it flattens out at
20 about 15 percent. But I'm not sure it's true of all
21 alloys.

22 Discussion, discussion, okay. Ring
23 compression I talked about. The way we run our tests
24 is we use 8 millimeter samples. We have a bottom
25 support plate that's fixed, a top support plate that's

NEAL R. GROSS

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

1 moved at a prescribed displacement rate, and the load
2 cell measures the force in response to it.

3 Standardly we run our tests at room
4 temperature. We get all the way to 20 percent
5 calculated ECR with ductility. We call it quits. If
6 we have any ambiguity, or if we drop to essentially no
7 ductility at 8 to 10 percent ECR we will run the tests
8 at the higher temperatures, which is essentially
9 what's said right here. And at the time we had set,
10 hit brittle at 17 percent ECR at room temperature, we
11 would retest at the higher temperatures.

12 CHAIRMAN POWERS: Do I take it from that
13 note on the graph that when it says it was tested at
14 135, that's any temperature between 100 and 135?

15 DR. BILLONE: Yes. When I say 135, I mean
16 135. There are other tests that haven't been shown
17 that I'll show where we did the tests at 100. One of
18 those samples that I showed you.

19 CHAIRMAN POWERS: It's just that the data
20 presentation has not been replete with test error
21 bars, so I was just --

22 DR. BILLONE: Right. Okay. All right.
23 Accepted. Let me point out that some organizations,
24 some labs, some tests are conducted not by us with a
25 curved or grooved support, and a grooved loading

NEAL R. GROSS

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

1 plate. And that's a more benign loading than the flat
2 plate loading. The important thing about a screening
3 test is whatever you start doing at the beginning you
4 keep doing at the end. The only thing you want to
5 change is the material. Alloy to alloy, degradation
6 due to hydrogen, degradation due to oxygen, keep the
7 tests the same. Otherwise you lose the advantage of
8 the screening test.

9 For the double-sided oxidation tests, for
10 two reasons you'd expect that you get your maximum
11 tensile bending stress at the ID right here, the inner
12 surface right there. You would expect your crack to
13 start here, and progress to the OD. So under bending
14 loads you're getting hoop bending stresses that are
15 tensile here, compressive there. You go 90 degrees
16 either way and it reverses. Your maximum tensile
17 stresses are out there.

18 But anyway, I want to get on to what we
19 call offset strain, and why we have an error
20 associated with offset strain. This may be too small
21 for you to read on the screen. I have to apologize
22 for that. But this is a material we know and can
23 predict how it behaves. To make sure I'm going to
24 pick this piece. This is 15 x 15 Zirc-4. It's not
25 oxidized. We're just doing benchmark tests. And we

NEAL R. GROSS

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

1 essentially -- we would displace it a total of 2
2 millimeters. And you get the elastic response, which
3 exactly -- the slope of this measured curve exactly
4 matches the calculated stiffness, or spring constant
5 of the ring. So we're not getting any interference
6 with the machine.

7 And then you get into the elastic/plastic
8 regime. You stop the test, and you unload. The
9 reason we want to do that is because in a real test,
10 you're not going to have this luxury. You're going to
11 come to some point in displacement and you don't know
12 where it is. You're going to crack, and you get a
13 load drop. You don't have the luxury of unloading.
14 So this test, experimentally we went up to this value.
15 Traditionally you take this point of maximum load, and
16 you come down at the dotted green curve, which is the
17 same slope that you loaded with. That's what you do
18 in tensile tests. That assumes you haven't changed
19 the material, shape, or anything else, and it's going
20 to spring back with the same spring constant that it
21 loaded as. That's how you interpret all mechanical
22 properties tests. That gives you your error, because
23 in fact it's a little springier, and this blue line is
24 how it actually unloads. And the traditional offset
25 displacement is 1.32 millimeters using this slope to

NEAL R. GROSS

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

1 mathematically unload the curve, which is what you do.
2 The actual permanent displacement determined by this
3 curve is about 1.19. This is also exactly what we
4 measure if we measure the new and old diameter.

5 So there is inherent in this procedure, by
6 having to use -- this is the only slope you know from
7 the real test that you're going to run. You unloaded
8 this slope, and for all the alloys we've tested under
9 these conditions, every single one of them, E110, M5,
10 the maximum difference between these two numbers is
11 less than 0.2 millimeters, which corresponds to 2
12 percent change in displacement, or 2 percent strain.
13 So what we're saying is anything below 2 percent
14 strain is either brittle, because it's in our noise
15 where we're not sure about the unloading slope, or we
16 really need to measure after the test what the change
17 in diameter is. So this is what I mean by offset
18 strain. It's the linearly unloading that curve at
19 maximum load at this particular rate, the same rate
20 that you loaded at. This is what I mean by permanent
21 strain. This is something we actually measure,
22 diameter before and after the test. You can only do
23 that if you interrupt the test after the first
24 through-wall crack, and the crack is very tight.

25 Dana, does that clarify what we mean by

NEAL R. GROSS

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

1 offset strain? We're calling that ductility. And for
2 this, it obviously is. I mean, it's the highly
3 ductile sample. So this is not failure, it's really
4 just a benchmark. Okay. On discussion. Now I have
5 to do it. This is really part of -- I'll get back to
6 this. You have to be very careful comparing data sets
7 from different organizations, because people's
8 definition of "displacement" is different during
9 compression tests. People's interpretations of curves
10 are different. This interpretation is from over two
11 years ago. I wasn't as smart as I am now, and in
12 fact, well let's look at this. This load drop is not
13 enough to signify through-wall failure. This load
14 drop is enough of signify through-wall failure.
15 You're looking for something like 30 to 50 percent
16 load drop in the through-wall failure. But, let's
17 ignore that point.

18 The point is some people use offset
19 displacement, which would be this 0.38 millimeters.
20 It would correspond to about 4 percent strain. The
21 real point should be out here, which would correspond
22 with about 6 percent strain. Some people use total
23 elongation of the first crack, which would be about 10
24 percent strain. In other words, they don't subtract
25 out the elastic part. And some people use total

NEAL R. GROSS

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

1 displacement until you've completely destroyed the
2 sample. And that would be an answer of 20 percent.
3 So you could take two identical materials oxidized
4 under identical conditions, given the same load
5 displacement curve, and you could get four different
6 answers, depending on how people define things. We
7 think that for a ductility screening test, this is --
8 well, not this one actually. This is a tough curve to
9 analyze, but this one at 6 percent is the right
10 answer.

11 Okay. ANL results. I'm going to show you
12 results This is like a drama. This is like, you
13 know, the rise in ductility, the fall in ductility,
14 the rise in ductility, the fall in ductility as we do
15 different things. Basically, we started our testing
16 at 1100 degrees C, not realizing that was the most
17 benign temperature and the least interesting, but it's
18 one that everyone tested at, and that's why we know
19 why everyone tested at 1100. The alloys behave very
20 well at 1100 degrees C. So we went from 1100 to 1000.
21 And as I mentioned, our samples are all slow cooled to
22 800 degrees C and quenched from these temperatures.
23 Oxidation temperatures. And we got good room
24 temperature ductility to greater than 17 percent
25 calculated ECR, which in some cases is the same as

NEAL R. GROSS

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

1 measured ECR, in some cases it's very different. And
2 I'll mention why.

3 The 1200 degrees C samples, again, the
4 same procedure. We got severe room temperature
5 embrittlement room temperature. The test was
6 conducted at room temperature. And about 9 percent
7 for Zirc-4, and about 9 percent for ZIRLO and M5. I
8 mean, far below the 17 that we had set our sights on.
9 We got significant ductility improvement by retesting
10 at 135 degrees C. Embrittlements greater than 17
11 percent ECR. By "embrittlement" I mean the ductile to
12 brittle transition ECR, where you go from ductile
13 behavior to brittle behavior.

14 So that's the rise of ductility. And then
15 you knock it out when you add hydrogen. This helps a
16 lot, and adding hydrogen severely embrittles material.
17 So, for 300 to 600 ppm of hydrogen, which is the range
18 we tested, your transition ECR will be less than 10
19 percent, even if you test at 135 degrees C. You're
20 just going to knock out. And again, this is oxidizing
21 at 1200 degrees C, 300 - 600 ppm of hydrogen. You're
22 going to lose a lot of that improvement that you got
23 in this step.

24 And okay.

25 CHAIRMAN POWERS: So I take it 300 ppm

1 hydrogen corresponds to a layer some 35 microns thick
2 of corrosion oxide.

3 DR. BILLONE: Yes, 35 to 40. Yes.

4 CHAIRMAN POWERS: And that corresponds to
5 something more than 7 percent ECR?

6 DR. BILLONE: No. Three and a half or
7 something like that. Harold does it in his head
8 better than me. We haven't tested this for the
9 intermediate -- we haven't tested intermediate.

10 CHAIRMAN POWERS: So I'm still struggling.
11 Now, your criterion is like 17 percent ECR.

12 DR. BILLONE: Uh oh.

13 CHAIRMAN POWERS: Subtract three --

14 DR. BILLONE: How is this going to damage
15 --

16 CHAIRMAN POWERS: I get something on the
17 order of, what, 13 and a half percent oxidation that
18 I can tolerate during the LOCA. Yet, add 10 percent
19 it gets embrittlement. Severe embrittlement.

20 DR. MEYER: I did the number -- I can't
21 remember the numbers. I did the numbers, and the
22 procedure works for the pre-hydrided test that he's
23 done, as well as for the high burnup test that he's
24 done.

25 DR. BILLONE: Oh, the test that -- oh.

NEAL R. GROSS

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

1 Never mind.

2 CHAIRMAN POWERS: Okay. So if I went
3 through all the numbers everything would work?

4 DR. MEYER: Yes.

5 DR. BILLONE: I haven't done that
6 exercise, I'm sorry.

7 CHAIRMAN POWERS: Neither have I, so we're
8 in the same place.

9 DR. BILLONE: All right. To finish this
10 part of the advanced alloy program, which again is
11 two-sided oxidation of the small samples, we're in the
12 process of setting up to oxidize ZIRLO first, then M5.
13 We're going to start at 1200 degrees C, jump to 1000
14 degrees C for reasons that you'll see in a minute.
15 That's where alloy differences become rather
16 significant. Then finish it off at 1100.

17 For our high burnup BWR Zirc-2, we see
18 significant embrittlement in the balloon region
19 associated with significant secondary hydriding and
20 oxidation. That's all been room temperature testing,
21 the four-point bend test. Because in the balloon
22 region you have non-uniform wall thinning, it's
23 thinnest near the burst opening, gets a little thicker
24 as you go around the back, you have two-sided
25 oxidation, you have high secondary hydrogen pickup

NEAL R. GROSS

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

1 towards the ends of those regions. We did manage to
2 produce for you one sample that if you only allowed it
3 to be at 1,204 degrees C for one second it seemed to
4 do pretty well, has high ductility. The high burnup
5 PWR Zirc-4. The LOCA integral test, we're going to
6 base that on the baseline ductility data we've already
7 generated for as-fabricated and pre-hydrided, 15 x 15
8 Zirc-4, and the high burnup Zirc-4 rings that I will
9 show you that were oxidized to about 1200 degrees C.

10 This is too wordy. Okay. Apparatus, and
11 I'll just say that we have a particular test train.
12 I know this is the top because steam flows out through
13 here essentially. That's the bottom, so you've got to
14 rotate it 90 degrees clockwise to get a feeling for
15 it. It's a significantly long test train, and the
16 sample's only 25 millimeters in the test train. It's
17 all Inconel. What's going to be important is the next
18 slide, is that when we run oxidation tests, we don't
19 want to weld thermocouples directly to the sample.
20 You only weld them during your benchmark testing.

21 This is an essential thing to understand
22 about our program. This is a blowup of the sample
23 region. And what we have above the sample on the
24 Inconel is thermocouples welded at 320 degrees C,
25 around it. That stays with the test train. And what

NEAL R. GROSS

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

1 changes from test to test is there's an Inconel stem
2 that's threaded down the middle, where you can
3 assemble and disassemble this unit.

4 So what's a thermal benchmark? A thermal
5 benchmark is you start out with bare cladding, or pre-
6 oxidized cladding, and -- well, bare cladding, and you
7 weld two thermocouples 120 degrees apart, because we
8 only have channels for five readings. And then you
9 put in the new sample with two other thermocouples
10 welded 120 and 240. And that's your benchmark. And
11 what you're benchmarking really is the temperature
12 ramp of this, which is much faster than the
13 temperature ramp of the much heavier Inconel. They
14 come pretty close to a steady state temperature, but
15 the temperature ramps. So you do your thermal
16 benchmark at the beginning, and then you keep running
17 tests. After each test, you do a weight gain
18 measurement. If that weight gain starts to get off,
19 you know your test train is shot. Or it's on its way.
20 Because with quench, this test train can warp over
21 time. The thermocouples can pop off, which is pretty
22 easy. So it's -- in giving you a data set, my
23 experience in the literature, and at conferences, if
24 someone just shows you a graph of post-quench
25 ductility versus any parameter square root of time

NEAL R. GROSS

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

1 ECR, and doesn't tell you how they prepared their
2 sample, controlled their temperatures, monitored their
3 temperatures, the data set isn't meaningful to me
4 personally.

5 Okay, this is an example. Let's start
6 with 1000 degrees C. This is an example of our two-
7 sided oxidation tests in which I'm showing you the
8 three thermocouples that are permanently fixed to the
9 Inconel. And it's got the slower temperature rise.
10 It doesn't matter for a long-time test like this. And
11 these are the -- I'm sorry. This one, I'm off one.
12 This is on the sample, that's on the sample. Maybe
13 I'm right. These two are on the sample. And so we do
14 this at the beginning, and we assume this is our
15 temperature history for ever after, every test we run
16 until the weight gain starts to get too high or too
17 low. And then we know we're off in temperature.

18 All right. 1000 degrees, interesting
19 because, you all know this already. If we look at the
20 offset strain versus measured ECR, measured ECR is
21 just simply the measured weight gain divided by the
22 wall thickness times the constant conversion factor.
23 And we all know M5 has a very low weight gain, because
24 that oxide layer grows very slowly on M5 at 1000
25 degrees C. The point is that you don't get a very

NEAL R. GROSS

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

1 good correlation. This is Zirc-4 at room temperature,
2 and you get the expected behavior as you increase the
3 oxide. With M5, what you don't appreciate is there's
4 a huge difference in test time between these points.
5 As a matter of fact, it's even crazier than that.
6 This is 3,400 seconds, with a higher weight gain than
7 the 4,100 seconds. So let's look at M5 in a different
8 way. Let's not look at M5 in terms of how fast the
9 oxide layer grows, and therefore how the weight gain
10 increases. It's not relevant. The question is how
11 fast does it embrittle, does oxygen get inside, and
12 that correlates much better with the square root of
13 time for an isothermal test, which essentially the
14 Cathcart-Pawel prediction, that is the time
15 dependence. It's a diffusion model, so it's the
16 square root of time dependence.

17 So if we re-plot M5, we see that it comes
18 down and embrittles at the higher test times. And
19 let's see if I can get this straight. The M5 is a
20 little bit thicker.

21 MEMBER KRESS: Is it supposed to have a
22 square root sign?

23 DR. BILLONE: But essentially these two
24 points are oxidized for the same time. These two are
25 oxidized for the same time. The ECRs are a little

NEAL R. GROSS

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

1 different just because the wall thickness is
2 different. So each of these points you can match up
3 as being oxidized for the same amount of time.

4 Okay. Let's quickly look at what happens
5 if we go to the extreme case of 3,400 seconds. Why is
6 the weight ECR so high for Zirc-4, the measured. This
7 is the -- these are to scale, these two pictures. And
8 again, the M5 is 0.61 millimeter wall thickness. This
9 is 0.57. That's why there's a difference in wall
10 thickness. But anyway, you grow a really fat, thick
11 oxide layer on the Zirc-4. The M5 layer sort of hits
12 a point and doesn't seem to grow very much anymore.
13 So what is important is, as you go out in time at 1000
14 degrees C is how much oxygen is getting into the base
15 metal.

16 A better picture of M5. And an amazing
17 thing is with all the complexity of this picture,
18 which Jean-Paul Mardon could explain much better than
19 I can, except I can pick out the oxide layer, I could
20 pick out what's trying to be an oxygen stabilized
21 alpha layer. And then you've got all these
22 precipitated layers that are stabilized by oxygen and
23 niobium. And what's interesting is the microhardness
24 across this sample is almost identical to the
25 microhardness across the Zry sample. And the

NEAL R. GROSS

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

1 microstructures -- I mean, this is within experimental
2 error. If I look at the middle 200 microns on this
3 picture of 0.2 millimeters, and look at the
4 microstructure across that middle where you're going
5 to get your ductility, they're essentially the same
6 for the two materials in terms of -- DPH is diamond
7 pyramid hardness. It's a Vicker's hardness number.
8 And to me it's amazing, unless the microhardness is
9 just not fine enough to pick it up. But the two
10 oxidized for the same period of time would have
11 essentially the same microhardness, even though
12 they're different alloys and have very different
13 microstructures.

14 Okay. ZIRLO is a lot closer at 1000
15 degrees C to Zirc-4. Again, these two points of
16 extreme were for the same test times, and they start
17 to fall apart there. But if you go to lower test
18 times in terms of measured ECR and offset strain
19 they're pretty close.

20 CHAIRMAN POWERS: Maybe the definition of
21 ECR is confusing to me. Because you showed the data
22 for M5, and Zircaloy 4 at 1000 degrees, and when
23 plotted against measured ECR things didn't correlate.
24 They looked very different.

25 DR. BILLONE: They looked very different.

1 Right.

2 CHAIRMAN POWERS: When plotted against
3 calculated ECR, they look very similar.

4 DR. BILLONE: Right. And I'm going to get
5 you -- by the end of the talk, hopefully before the
6 end, I want to get you away from ECR as a meaningful
7 metric.

8 CHAIRMAN POWERS: I know where you're
9 going, but unfortunately I've got some criteria here
10 I'm looking over that -- they focus a lot on ECR. And
11 so I've got to understand this a little better.

12 DR. BILLONE: Okay.

13 CHAIRMAN POWERS: If I take some
14 zirconium, bare, clean, pristine, stick it into the
15 steam and measure the amount of hydrogen coming out,
16 does that give me the -- can I convert that into a
17 measured ECR?

18 DR. BILLONE: Where are you taking the
19 hydrogen? What's coming out --

20 CHAIRMAN POWERS: Yes, out of the
21 experiment.

22 DR. BILLONE: That's a very poor way of
23 doing it. There's a lot of error associated with it.

24 CHAIRMAN POWERS: Assume my measurement is
25 fantastically perfect.

NEAL R. GROSS

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

1 DR. BILLONE: Oh, I'm sorry. Okay. We
2 actually use the heating to melting, and measuring how
3 much hydrogen comes out to determine the hydrogen
4 content. Assuming you have a good measurement of
5 hydrogen content, finish the question.

6 CHAIRMAN POWERS: Well, what I'm trying to
7 understand, exactly why there's a difference between
8 measured ECR and calculated ECR.

9 DR. BILLONE: Oh. There's very little
10 difference at 1100, very little difference at 1200.
11 There's very little difference for Zirc-4 between
12 measured and calculated, because the calculated is
13 based on a correlation for Zirc-4. M5, the oxide
14 layer just stops growing. I can't explain it.

15 CHAIRMAN POWERS: Okay. So your ECR is
16 not an effective amount of oxygen taken into steam and
17 put someplace. It is in fact the amount of oxide
18 layer?

19 DR. BILLONE: No, it's literally the
20 change in sample weight due to all the oxygen that's
21 been picked up, most of which is in that oxide layer.
22 All the oxygen that's picked up adds to the -- you
23 know, you take the sample before the test.

24 CHAIRMAN POWERS: That's kind of what I
25 thought going into this, because --

NEAL R. GROSS

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

1 DR. BILLONE: That's how we measure weight
2 gain.

3 CHAIRMAN POWERS: See, if I measured the
4 hydrogen, I would know how much oxygen was put
5 someplace.

6 DR. BILLONE: I know, I know.

7 CHAIRMAN POWERS: Okay. But I would
8 assume then that there should be a very close
9 correlation between that and what Cathcart-Pawel comes
10 up with.

11 DR. BILLONE: For Zirc-4 there is. For
12 Zirc-2 there is. For ZIRLO it's not too bad. And
13 ZIRLO is nominally 1 weight percent tin, 1 weight
14 percent niobium. For M5 and E110, they're the Zry-1
15 niobium at 1000 degrees C, and probably maybe even 950
16 to 1,050, somewhere in that range. There's something
17 that I can't explain to you, that I think maybe they
18 can. You have to go to extremely high test times to
19 get higher weight gains. And as a matter of fact, you
20 have trouble doing it. We did, anyway. Because that
21 oxide layer just falls off. And it's -- the oxide
22 layer is where most of the oxygen is, therefore it
23 governs the weight gain. It's just not increasing
24 with time very fast, yet the oxygen that's diffusing
25 into the metal continues to go along. And the

NEAL R. GROSS

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

1 evidence for that is if you essentially plot these
2 results versus the square root of time, just think of
3 this as the square root of time, and all these tests
4 are run for the same time. You end up at about the
5 same place for both alloys. This has a really fat
6 oxide layer and a high weight gain, and this has a
7 really thin oxide layer and a low weight gain. It's
8 just -- it means it's not a good metric. For me,
9 anyway, working in the laboratory.

10 DR. MEYER: So that's the reason, Dana,
11 that we don't use a measured or true oxide as the
12 limit. And this time in our proposed criteria, the
13 Cathcart-Pawel equation would be included in the
14 criteria. I mean, you need to use that in order to be
15 calculating the time rather than the true amount of
16 oxide. Because it's the time that's important for the
17 diffusion of oxygen into the base level.

18 MEMBER SHACK: Is this an oxygen
19 penetration depth now? Is that what I'm looking at
20 when I plot it against the calculated Cathcart-Pawel?

21 DR. MEYER: I'm sorry. Is an oxygen what?

22 MEMBER SHACK: Is it oxygen penetration
23 depth. Is that --

24 MR. SCOTT: You could say that, because
25 ECR is equivalent cladding reacted, so it's some

NEAL R. GROSS

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

1 weight of Zircaloy on the surface.

2 MEMBER SHACK: I mean, it's got a square
3 root of prime in it. It has an oxygen diffusion.

4 DR. BILLONE: Yes, no, that's because the
5 oxide layer moves, grows as a square root of time.
6 The oxygen stabilized alpha layer grows as a square
7 root of time, ergo the beta layer shrinks as kind of
8 the square root of time. But in addition, you have a
9 source of oxygen always there, whether you have a
10 thick oxide or not to diffuse into that beta layer.
11 And that also goes as a square root of time. So it's
12 not a coincidence, but you don't need more -- let's
13 just pretend from Time Zero you had this oxide layer,
14 and it never grew. It's probably enough oxygen to
15 continue to diffuse into this metal, the metal's very
16 hungry for oxygen, and increase the solubility of
17 oxygen and decrease the ductility. And that's why ECR
18 measured, which is based on weight gain, that's what
19 I'm saying is not a good metric. I mean, these two --
20 this is a classic case. These embrittle at about the
21 same rate in time as you go to higher time values at
22 1000 degrees C, but their weight gain behavior is
23 totally different, and that's what skews the results
24 on this slide. It doesn't matter how thick this is,
25 except for Zirc-4 there's a nice correlation between

NEAL R. GROSS

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

1 how thick this is, how thick this is, and how much
2 oxygen made it in there, for Zirc-4. And I'll show
3 you that later in the embrittlement correlation.

4 CHAIRMAN POWERS: I guess --

5 DR. BILLONE: For M5 there's not.

6 CHAIRMAN POWERS: I guess what you're
7 telling me is that if I did the experiments Cathcart
8 and Pawel did, but I did them with M5 --

9 DR. BILLONE: You get different answers.

10 CHAIRMAN POWERS: -- I would not find a
11 good agreement with the correlation I developed with
12 Zirc-4?

13 DR. BILLONE: Correct.

14 CHAIRMAN POWERS: Very interesting.

15 DR. BILLONE: That's correct. And 1000 C.
16 The correlation's valid.

17 MR. SCOTT: 1000 C is the lower limit of
18 Cathcart-Pawel. It's no good below that.

19 DR. BILLONE: It's the lower limit, but
20 actually works pretty good, the weight gain part, not
21 the rest of it. The weight gain part really works
22 pretty good to 950, to tell you the truth. Not how
23 thick is the oxide layer, how thick is the alpha
24 layer. That's where it starts to break down. But,
25 all right.

1 ZIRLO, again, shows about the same
2 embrittlement with time, and yet at the highest test
3 time of 3,400 seconds, you can see the ZIRLO not only
4 has a thinner oxide layer than the Zirc-4 -- this is
5 at 20 percent calculated ECR, this is about 22 percent
6 measured, this is about 18 percent measured -- but the
7 interface is rougher. This is a precursor to
8 breakaway oxidation. And this material's picked up
9 about 10 weight part per million hydrogen during all
10 this time, and this material's picked up 100. So,
11 this is 3,400 seconds single-sided oxidation. You're
12 not in breakaway, but you're in a transition regime
13 where your oxide isn't growing as fast as initially it
14 should be. It's going to start to break up, perhaps.
15 We haven't tested for a longer time. But that's part
16 of my focus, that the difference in measured is
17 really, again, the difference in the thickness of the
18 oxide layer.

19 My real focus is that you're going to have
20 a microstructure. This is now etched where this is
21 the oxide layer. Maybe. Yes, that's the oxide layer.
22 You're going to have a microstructure that looks very,
23 very, very different from Zirc-4, and even different
24 from M5, and you're going to have a range of
25 microhardnesses that are the same as the ones I just

NEAL R. GROSS

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

1 showed you in this middle region. And somehow,
2 somehow, roughly the same amount of oxygen made it to
3 that middle region and caused the same degree of
4 embrittlement. It's kind of interesting, because if
5 you get into the metallurgy, and you get into the
6 details of modeling that, it's really tough to do.
7 And it's possible that there's some simplifications
8 just by the fact that you're running these tests, and
9 you're getting about the same answers for the same
10 test times.

11 Okay, skip that. I want to skip the 1100
12 degrees C results. You've got them in there. They're
13 just not interesting. All three alloys have weight
14 gains that are consistent with the Cathcart-Pawel
15 prediction. All three alloys behave very well. They
16 all kind of flatten out to the same 3 percent offset
17 strain at high values.

18 I want to go to 1200. Okay. This is our
19 thermal benchmark for 1200. I'm just showing you the
20 thermocouples that were welded at the sample. The
21 1200 degrees C test, double-sided to get to 20 percent
22 ECR is only 400 seconds. And that's where how you get
23 there matters a little bit. If you're talking about
24 a 5 percent ECR test, a significant part of that 5
25 percent was picked up here. If you're talking about

NEAL R. GROSS

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

1 20 percent ECR, this doesn't matter so much. Our
2 temperature ramps are designed to not overshoot.

3 Okay, this is room temperature
4 embrittlement. We've already talked about this. This
5 is M5 versus Zirc-4 ring compressed at room
6 temperature, and you can see the curves nosedive down.
7 Just again, the microstructure, and I've reversed
8 sides. I apologize for that. This is the Zirc-4.
9 But you could see the rather thick oxide and alpha
10 layers. And actually, at 20 percent ECR, your oxide
11 layers -- it doesn't matter whether it's 1000 degrees
12 C, 1100 degrees C, or 1200 degrees C, it's 20 percent
13 measured ECR, your oxide layers are about the same
14 thicknesses. But again, very different
15 microstructures, but very similar microhardness
16 values. And this is ZIRLO, and Zirc-4.

17 Now, this is what I wanted to get to.
18 Let's compare Zirc-4 to itself. This is same sample,
19 with multiple rings cut from it. So, it's the same
20 oxidized sample. We didn't have a whole low left.
21 But this is your baseline curve, and this is offset
22 strain. For the room temperature data this is
23 retesting the adjacent ring at 135 degrees C. You get
24 significant enhancement in ductility in this regime.
25 Eventually you're going to lose it at maybe 18 -- oh

NEAL R. GROSS

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

1 this is measured. Okay, that's the problem. All
2 right. You're going to lose it at a measured ECR of
3 about 20 percent. It would be a calculated ECR closer
4 to 18 percent. So this is all as-fabricated material,
5 artificially pre-hydrided -- not pre-hydrided yet.
6 I'm sorry. As-fabricated material. And all we're
7 doing is elevating the test temperature. So the same
8 is true of ZIRLO. You get even more enhancement. And
9 the same is true of M5. So if you're looking for
10 ductility at 1200 degrees C, the higher ECR values,
11 you've got to go the higher test temperature.

12 CHAIRMAN POWERS: Just a clarification.
13 You have plotted these things for M5 against the
14 measured ECR. If you were to plot them against
15 calculated ECR, how would the curves change?

16 DR. BILLONE: Oh, very little. 1200
17 degrees C --

18 CHAIRMAN POWERS: Everything's fine.

19 DR. BILLONE: Everything's fine. Another
20 hundred degrees, everything's fine. 1000 degrees,
21 very different.

22 CHAIRMAN POWERS: Not so fine.

23 DR. BILLONE: I think I do do that in the
24 next slide. Okay, so this is Cathcart-Pawel ECR. I
25 just wasn't quick enough in punching it. And now

NEAL R. GROSS

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

1 we're going to switch. We're going to just compare
2 Zirc-4 to M5. And just to show that the M5 for the
3 same amount of test time shows greater improvement in
4 ductility when you increase its temperature to 135.
5 So, these are both 135, but again, it's almost -- and
6 this may not be true of all alloys, but if you can
7 sort of capture the behavior of Zirc-4, with the
8 massive amount of Zirc-4 data, blindly apply it to the
9 new M5 and ZIRLO data coming out, just to see if it's
10 a conservative bound, or lower bound, maybe not a best
11 estimate. It's a game that we're in the process of
12 playing.

13 And again, this is -- I'm going to add one
14 more data point, which is the test we did for Paul
15 Clifford and Harold Scott. We didn't want to do a
16 meaningless demonstration test, so we took ZIRLO up to
17 21 percent calculated ECR, and we essentially just
18 barely got the transition between ductile and brittle
19 behavior, up around 21 percent. And for Zirc-4 we
20 expected in terms of CP-ECR to be about 18 percent.
21 So that's just the new data point we threw in there.

22 This I want to skip. Fascinating stuff.
23 That's for discussion. Okay, that wraps up everything
24 we did for the 17 x 17 PWR alloys, fresh or as-
25 fabricated, or the French call it as received. Now

NEAL R. GROSS

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

1 we're going to add some hydrogen and see what the
2 effects of hydrogen are on modern Zirc-4. And then
3 we're going to switch over to 15 x 15 Zirc-4, which is
4 our baseline for a Robinson test. And you can cut me
5 off anytime you need to.

6 CHAIRMAN POWERS: We are scheduled to stop
7 for lunch at 12:30.

8 DR. BILLONE: Fine.

9 CHAIRMAN POWERS: And I see no real reason
10 not to do that since you're the speaker right after
11 that.

12 DR. BILLONE: Right. Let's do that. I
13 just have a couple of slides on the pre-hydriding.
14 Again, we pre-hydrided in 4 percent hydrogen-argon
15 mixture at 400 degrees C. Anyone who's done pre-
16 hydriding knows it's very tricky. It depends on
17 whether you get impurities. If you get any oxide at
18 all, even a fine film on the surface, that's what
19 controls the kinetics and slows everything down. If
20 you keep the surface clean, the kinetics are very
21 fast. And we got some rather wild axial
22 circumferential gradients in hydrogen concentration in
23 our samples. We turn this into a benefit because we
24 were cutting small rings. We could take one 4-inch
25 sample and have anywhere from 400 to 800 ppm of

NEAL R. GROSS

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

1 hydrogen. So what it made us do is after each ring
2 compression test, we had to measure the specific
3 hydrogen in there. And that's why --

4 CHAIRMAN POWERS: -- do a blind test here.

5 DR. BILLONE: Well, nobody else does tests
6 this way. They perfect their method of hydriding, and
7 they run a bunch of tests at 300. You learn
8 everything you can learn at 300 weight parts per
9 million. Well, because we were amateurs at this at
10 the time, and we've improved since then, we ran tests
11 at a fixed ECR, fixed test time, for hydrogen levels
12 in the range of 150 to 600 weight parts per million.
13 And basically what we determined is that if you fix
14 the ECR and run a bunch of tests at 8.5 percent,
15 measured, I'll convert this to 7.5 percent CP-ECR,
16 then at 400 weight parts per million hydrogen that's
17 where you lose the ductility. At 350 you have
18 ductility. At 400 you've lost it. And I'll show you
19 that curve.

20 CHAIRMAN POWERS: Let me ask you this
21 question, just as a matter of experimental technique.
22 You're always doing 8 millimeter long specimens?

23 DR. BILLONE: Right.

24 CHAIRMAN POWERS: Have you ever --

25 DR. BILLONE: Sometimes we do 5 and 6,

1 because that's all we have left, 5 and 6 millimeters.

2 CHAIRMAN POWERS: Well, what I was
3 wondering is did you ever take a specimen that's fixed
4 of the same composition and run 8, 16, 32?

5 DR. BILLONE: No. Our Russian colleagues
6 did that before we got started with their E110 and
7 maybe some Zirc-4. And of course, it's not conclusive
8 necessarily to take fresh cladding, not oxidized, and
9 find out that there's no length effect. But they did
10 some oxidation. I guess based on --

11 CHAIRMAN POWERS: Well, really what I was
12 wondering --

13 DR. BILLONE: We haven't done it.

14 CHAIRMAN POWERS: What I was wondering is
15 --

16 DR. BILLONE: On purpose. We haven't done
17 it on purpose.

18 CHAIRMAN POWERS: -- if you're -- when you
19 cut the ring out, you're changing the -- you can
20 change hydrogen content in the cut ends of it.

21 DR. BILLONE: It's pretty low temperature
22 cutting, and I don't --

23 CHAIRMAN POWERS: It's pretty low
24 temperature cutting except where the teeth hit the
25 metal.

NEAL R. GROSS

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

1 DR. BILLONE: Okay. How about my next
2 slide to address that point. No, we haven't explored
3 -- it's more in the spirit of, okay, this is how we're
4 going to do our screening tests. We're keeping the
5 length the same, we're keeping the test methods the
6 same, and we're going to just change the material.
7 Other labs have done an exploration of different
8 length size. Sometimes we run out. We don't have
9 enough material, so I would say 5 to 10 millimeters
10 just as a range that we've tested. Sometimes we cut
11 too big, and sometimes we don't have enough material.

12 All right. The point is that what I show
13 you is all you're going to get because we have no more
14 17 x 17 Zirc-4. It's very hard for the vendors to
15 come up with it because they switched to ZIRLO and M5.
16 And we can't continue this. So we continue these
17 kinds of studies with 15 x 15 cladding, which is
18 easier for us to get. It's our Robinson-based line.

19 Here's something that was interesting to
20 me. This is a 25 millimeter long sample, one inch.
21 And before we oxidized it we cut a 2-millimeter ring
22 from this end, a 2-millimeter ring from the other end,
23 and in round numbers there's a 440 to 540, there's 100
24 ppm of hydrogen gradient across it. It may be worse
25 than that because you don't know if it's a linear

NEAL R. GROSS

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

1 gradient or not. What was interesting is when you
2 bring this up to 1200 degrees C for about a minute,
3 you figure the hydrogen diffusion -- first of all,
4 you've got 100 ppm of hydrogen as a concentration
5 gradient. And I haven't mentioned the circumferential
6 gradient that's also there. You'd expect the hydrogen
7 to homogenize. You're in the beta phase, you've got
8 hydrogen, you've got high diffusivity, and it don't,
9 because when we finish the test, we then cut three
10 rings, ring compression test, and measure the
11 hydrogen, and lo and behold, this is the -- goes from
12 low to high. The hydrogen has not moved along axial
13 distance. It has not moved along circumferential
14 distance. Definitely moved across the radius,
15 particularly since the beta layer sucks up hydrogen.
16 So this has implications on how we select our high
17 burnup LOCA samples. If you pick, for example, corner
18 rods, which have extreme variation in circumferential
19 hydride -- in the density of hydrogen as you move
20 around the circumference, whatever you start with
21 you're liable to end up with, and so picking your
22 sample to be prototypic is very, very important. And
23 again, these are the results I mentioned. Fixing each
24 test the same ECR, and also having the benefit of up
25 to three rings from each sample at different hydrogen

NEAL R. GROSS

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

1 levels, and the hydrogen didn't move. Basically we
2 were able to map out at our lower value, and again,
3 this is 7.5 percent, and this is 10 percent in terms
4 of CP-ECR. But essentially we know what no hydrogen
5 does, and this is -- with the Zirc-4 we have this is
6 the best we could do was to generate these points.
7 And then when you get to about 400 ppm you've lost all
8 your ductility. You go to a higher oxidation time,
9 and you're going to lose your ductility sooner.

10 The shape of these curves are strictly
11 artistic. They're trend curves. We don't have enough
12 data points in this region to really shape these
13 curves. It's how we think the material would behave.
14 But, the ductile to brittle transition is as good as
15 we can define it with the limited amount of material
16 we had.

17 CHAIRMAN POWERS: If you were to put --

18 DR. BILLONE: And by the way, 135 degrees
19 C test temperature. This is the highest -- this is
20 the most optimum test temperature we can do.

21 CHAIRMAN POWERS: If you were to put error
22 bars, I guess they would be on the hydrogen content?

23 DR. BILLONE: They would be on the
24 hydrogen content because we haven't done enough
25 duplicate samples. But, yes. There are error bars,

NEAL R. GROSS

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

1 and you'll see with the irradiated stuff typically for
2 our Robinson samples, it's something like, near the
3 mid-plane it's 550 weight parts per million +/- 100
4 weight parts per million.

5 CHAIRMAN POWERS: I guess what I was
6 fishing around with there was that the offset strain,
7 if you have -- suppose we knew the hydrogen content
8 exactly, it was given to us by God.

9 DR. BILLONE: Or CEA.

10 CHAIRMAN POWERS: Or CEA. And we did
11 replicate tests on the offset strain, there would not
12 be much variation from sample to sample?

13 DR. BILLONE: Shouldn't be, right.

14 CHAIRMAN POWERS: Okay. So your error
15 bars would all be horizontal for those?

16 DR. BILLONE: And also, if you do have a
17 circumferential variation that stays in the material
18 throughout the oxidation, then randomly how you orient
19 the sample will have an effect. Okay. All right,
20 let's switch off to now, that's the end of our
21 advanced alloy program up to now, because the next
22 stage is to test the high burnup Zirc-4 -- I'm sorry,
23 the high burnup ZIRLO and M5. So let's drop back, and
24 let's build up to our LOCA program, and our testing of
25 irradiated cladding, which is H. B. Robinson cladding.

NEAL R. GROSS

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

1 And we're going to focus now on 135 degrees C tests,
2 post-quench ductility tests, of samples that have been
3 oxidized at about 1200 degrees C.

4 CHAIRMAN POWERS: Is this an appropriate
5 place to break for lunch?

6 DR. BILLONE: Yes. It's excellent.

7 CHAIRMAN POWERS: Why don't we do that
8 then. We'll recess for lunch, and we will resume at
9 the scheduled time, which I think is 1:30.

10 (Whereupon, the foregoing matter went off
11 the record at 12:22 p.m. and went back on the record
12 at 1:29 p.m.)

13 CHAIRMAN POWERS: Let's come back into
14 order. First I want to make a couple of comments.
15 The Reactor Fuel Subcommittee have always been well
16 attended, and I think we're among the best technical
17 subcommittee meetings that I enjoy as a member of the
18 ACRS. The technical presentations have been uniformly
19 outstanding during my tenure on the committee. From
20 all sides of the house, certainly Ralph has brought us
21 an award-winning speaker today. Rosa Yang brings
22 speakers of the quality of Robbie Montgomery and Joe
23 Rashid, who I think make outstanding presentations.
24 What we do find is useful is some audience
25 participation, and so that if you do want to make

NEAL R. GROSS

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

1 comments during the course of the presentation, we do
2 have microphones located around the room. I think on
3 either side of this post. And the only criterion is
4 that you do state your name and speak clearly when you
5 make your comment.

6 The subcommittee meetings are open to
7 participation by all members of the affected
8 community, and the ACRS has found this to be very
9 valuable to get this broad input into our information-
10 collecting regards. The security forces have chosen
11 to impose some new rules to make that cumbersome, and
12 I apologize to everyone. Like many large
13 institutions, they're very good at making rules, very
14 poor at figuring out how to accommodate that. And I
15 hope that that has not made this participation any
16 less satisfactory for you, and I assure you that I
17 will ensure that it will not have this cumbersome
18 character for it in the future. With that, Mike, pick
19 up where you left of.

20 DR. BILLONE: I think I better pick up,
21 and pick up a little faster than we left off.

22 CHAIRMAN POWERS: Yes, we're going to try
23 to hold you to schedule a little bit.

24 DR. BILLONE: I will, I will, I will.
25 Okay. Let's switch gears. Let's switch from the

NEAL R. GROSS

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

1 advanced alloy 17 x 17 Zirc-4, ZIRLO, M5. Let's go to
2 what we're using as baseline for our high burnup
3 cladding. And these baseline studies prove to be very
4 important in planning our in-cell tests. Remember,
5 they're inexpensive, you can run lots of them, you run
6 very few in-cell tests.

7 So, as-fabricated Zirc-4. The dimensions
8 are up there. It's a thicker wall than you're used
9 to, thicker than a lot of the 15 x 15 currently used.
10 And we did a lot of work with temperature control and
11 temperature monitoring. And I'll show you those
12 results. We also did a lot more work with pre-
13 hydrided 15 x 15 Zirc-4. We're also using this
14 material for our advanced alloy -- no, for our spent
15 nuclear fuel program to study radial hydrides.

16 What I'm basically going to show you is
17 that we -- this material we dropped down to lower ECR
18 levels, and at 5 percent Cathcart-Pawel ECR we got
19 embrittlement at 600 ppm of hydrogen. We haven't run
20 any tests with 600 to 800 ppm of hydrogen where we got
21 any ductility at all. We just haven't run tests at
22 low enough times. 135 degrees C post-quench ductility
23 versus hydrogen content. We fixed the ECR at 7.5
24 percent, which essentially means we fixed the time of
25 the test. And we got embrittlement, at the higher

NEAL R. GROSS

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

1 oxygen level we got embrittlement at 400 weight parts
2 per million hydrogen.

3 MEMBER KRESS: Now on your pre-hydride --

4 DR. BILLONE: Yes.

5 MEMBER KRESS: The 400 weight parts a
6 million, that's the amount pre-hydrided?

7 DR. BILLONE: Right. And we don't pick up
8 any hydrogen during the test.

9 MEMBER KRESS: Don't pick up any hydrogen
10 at the 7.5 percent.

11 DR. BILLONE: Well, with these alloys that
12 I'm talking about. And we're excluding E110. They
13 grow a protective oxide layer in the sense that
14 hydrogen and oxygen, that this associated the outer
15 surface of the oxide layer, the hydrogen doesn't go
16 through. It's swept away. So we're talking strictly
17 what you put in at the beginning. When we get to the
18 LOCA tests of the samples like this, it's a different
19 story. But, okay.

20 It's very, very important -- I'll say it
21 one more time. Anybody that shows you data in terms
22 of ECR and ductility, you have to know at what
23 temperature is that ECR accumulated. We are very
24 conscious of not overshooting our goal temperature.
25 You can obviously ramp up much faster and overshoot,

NEAL R. GROSS

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

1 and then come down. And so we ramp up very fast to
2 about within 100 degrees C, and then you have this
3 slower rate. It's important in two-sided tests
4 because you've already picked up about 1 percent ECR
5 here. And at 5 percent ECR you're just barely
6 touching 1200. So when I say we're running these
7 tests at 1200, you have to keep this in mind if I'm
8 going to show you results for 5 percent ECR because it
9 picked up most of its oxygen at a lower temperature.
10 And we know that the test temperature's extremely
11 important for the solubility and the embrittlement.
12 So, all data sets are linked with this. This is not
13 a problem when we leave the world of ECR and go into
14 the world of how much oxygen did we pump into the beta
15 layer, and how does that correlate with embrittlement.
16 Because for that you'll have a rate equation that
17 could integrate over any experimental temperature
18 history, as well as a calculated history for a LOCA.
19 As long as we are willing to leave this simple concept
20 of ECR -- for mechanistic understanding, Ralph, I'll
21 add that -- then it doesn't matter whether a CEA goes
22 straight up like that very fast, and we go up more
23 slowly, we'll be able to integrate out that effect in
24 a proper correlation.

25 Okay. Because we had more material we ran

NEAL R. GROSS

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

1 more tests. We ran duplicate tests. And basically,
2 now this is in terms of measured ECR. This is the
3 real permanent strain measured diameter before the
4 test, diameter after the test. This is the real
5 thing. And basically we're able at room temperature
6 to show at about 8 percent measured ECR, 7.5 percent
7 CP-ECR, which is my next figure so I won't say it.
8 You lose ductility. You drop below that 1 percent
9 criterion we have for this parameter of permanent
10 strain, with a 2 percent criteria for offset strain
11 that you get off of graph. This is a physical
12 measurement.

13 Now, increasing the test temperature to
14 100 degrees C is a significant improvement in that you
15 get up about 12 percent, and then 135 you get up about
16 14 percent in terms of measured. Because we're going
17 to use this to plan our in-cell tests we don't care
18 about measured ECR. We care only about predicted ECR.
19 That's all you can do for test planning.

20 CHAIRMAN POWERS: Do you understand why
21 the ductility changes so dramatically with a
22 relatively small increase in temperature?

23 DR. BILLONE: No, but I understand that
24 the same results are produced at other laboratories,
25 so I have a lot of confidence in the quality of the

NEAL R. GROSS

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

1 results.

2 CHAIRMAN POWERS: I don't doubt it. I
3 just wondered --

4 DR. BILLONE: But I don't have an
5 explanation for why the prior beta phase is so
6 sensitive to temperature, because the as-fabricated
7 material is not this sensitive. The alpha, the stuff
8 that you make in the factory that's alpha phase
9 material doesn't show this high sensitivity.

10 Okay. Let's change now, because we're in
11 a predictive mode. We want to use these test results
12 to try to predict how the high burnup cladding is
13 going to behave. So this is the same data set I just
14 showed you, only in terms of the square root of time
15 essentially, or CP-ECR. And now I'm going to switch
16 back to offset strain. And these are trend curves
17 that show roughly where you hit embrittlement for the
18 different test temperatures. Different way of
19 plotting the same data set. But more data points than
20 we had for the advanced alloys.

21 Okay. And this is the, again, well more
22 data points in one case. This is the pre-hydrided
23 stuff. Again we had variation in hydrogen. These
24 three data points are all from the same 25 millimeters
25 sample, three rings cut. Each one had different

NEAL R. GROSS

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

1 hydrogen content. And I cringe because I want this
2 point and this point to be reversed, but I just can't
3 change Mother Nature. That's the scatter. But
4 anyway, this is roughly -- we barely got samples to
5 test it, but roughly 400 degrees C, 400 weight parts
6 per million hydrogen. You back off a little bit, you
7 start picking up some ductility. This is all an
8 artistic rendition.

9 And again, around 600 weight parts per
10 million you lose it at 5 percent ECR. This is
11 important because our Robinson samples, some were
12 around the middle of Grid-span 2 are at about this
13 hydrogen level, and some were -- Grid-span 3 is the
14 midplane there. Some were around Grid-span 4. You're
15 up to here and you're as high as 800. So where did we
16 pick our samples to do our studies? We picked our
17 samples from Grid-span 3 with about 550 weight parts
18 per million to look for ductile to brittle transition.
19 So, again, we're using all this to help pick the axial
20 location of the samples as well as to pick the test
21 time.

22 Okay. So let's get to the high burnup
23 stuff. We took -- we're going to show you ductility
24 of high burnup oxidized 15 x 15 Zirc-4 rings. And the
25 way this works in-cell is quenches is kind of violent

NEAL R. GROSS

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

1 on our apparatus. If we quench, we most likely knock
2 out one of the control thermocouples. And so the way
3 these tests are run, you run several tests with slow-
4 cooling, and then you repeat one of those tests with
5 quench, and then your test train is finished. And
6 then you go on and build another test train to do
7 another series. So, you're not getting post-quench
8 ductility of all these points for very practical
9 reasons.

10 We very carefully selected a rod from
11 within the assembly rather than an edge rod because of
12 this issue of non-uniform hydrogen distribution. And
13 we looked at a variety of things. I'll show you the
14 characterization. Again, then cut these 25 millimeter
15 long samples from near the midplane. They had about
16 a 70 micron corrosion layer, and about 550 weight
17 parts per million hydrogen. I said +/- 100, +/- 90,
18 close enough. And very significantly there was about
19 a 10 micron fuel cladding bond layer that contains
20 oxygen. That's going to play a role in what I'm going
21 to show you. There was one sample higher up on the
22 rod with 95 micron corrosion layer, 800 weight parts
23 per million hydrogen. I didn't know this till after
24 we tested it, actually. This doesn't really have a
25 prayer of ductility. That's the one we quenched.

NEAL R. GROSS

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

1 CHAIRMAN POWERS: Of course.

2 DR. BILLONE: So, after the tests were
3 run, we improved our benchmarking tests. And we're
4 now claiming more like 1190 degrees C rather than 1200
5 degrees C. Let's not quibble about 10 degrees C. And
6 these are the calculated CP-ECRs. We had no idea
7 whether we'd have any ductility at all with 550. So
8 we ran low and high. This is the sample with the high
9 hydrogen. That's the one we quenched. We knocked the
10 heck out of the ductility. That was zero.

11 So, I'm going to show you what I'm going
12 to call post-oxidation ductility -- I hope I don't use
13 this acronym very much -- and post-quench ductility of
14 this. Okay. Just for your own record, this just
15 shows we took the samples from near the midplane of
16 the rod. This shows that there is some variation, but
17 it is very small, in the corrosion layer. Yong Yan's
18 a metallurgist. He did not use the word "corrosion".
19 He doesn't know that - he doesn't think there should
20 be a distinction. This is what you grew in reactor,
21 about 71 microns +/- 5. And traditionally we take
22 eight segments around the circumference to determine
23 that.

24 All right. This is going to be very
25 interesting because the very next test we run after

NEAL R. GROSS

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

1 this meeting's over is going to be a test with a long
2 segment with fuel in it, one-sided oxidation, it will
3 be sealed at both ends. And this is fuel. There is
4 extra oxygen in the fuel. There's a model and macro
5 for how that extra oxygen might get into the cladding.
6 No one really thinks it will, but no one's really
7 tested it. This is the fuel cladding bond, which is
8 an oxide layer. It's about 10 microns in round
9 numbers. And this we found is reduced without the
10 fuel here when we run on one- or two-sided oxidation
11 tests. And the oxygen from this layer does get into
12 the cladding and form a bond layer. So, I'm very
13 excited about this next test which you will not see
14 the results of because we haven't run it yet, because
15 it will have all the features of high burnup fuel, and
16 we can stop arguing does it matter or does it not
17 matter.

18 Okay. We looked carefully at the hydrides
19 to make sure that, you know, we didn't have huge
20 densities of hydrogen on one side and low densities on
21 the other. This is low mag. You're not going to see
22 much from that. This is your traditional Zirc-4 high
23 burnup profile of hydrides, very dense near the oxide
24 surface, and progressing in. What's interesting is
25 someone asked -- Bert I think asked the question does

NEAL R. GROSS

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

1 the as-irradiated material have any ductility. If you
2 take it out of the pool and then just subject it to
3 the ring compression, does it have ductility. And
4 what happens is when you test it without any
5 additional oxidation, you get a brittle failure -- you
6 get a failure. It's not brittle. You get a failure,
7 a crack across the oxide layer, a crack across the
8 hydrogen layer, and as you move in, the crack starts
9 moving off in another direction, and you actually have
10 very high ductility -- relatively high ductility in a
11 ring compression test for the stuff coming out of the
12 reactor. And that's at room temperature and at 135.

13 Okay. So we built the new test train.
14 These are the results for -- this is what we went into
15 the test with. This is based on bare cladding, no
16 corrosion layer, no steam oxide layer. We used this
17 for test planning. And of course, because the heat of
18 oxidation is going to be slowed down by the corrosion
19 layer, you're not going to steam oxidize as fast
20 having that corrosion layer, these are all over-
21 estimated ECRs. And so let me show you the results of
22 a benchmark in which we weld the thermocouples, we
23 grow an oxide layer, we cool down, then we ramp up
24 again. And what we're interested in is for bare
25 cladding you have a high heat of oxidation during this

NEAL R. GROSS

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

1 ramp, for cladding with an oxide layer you have a low
2 heat of oxidation. How does it affect this ramp, how
3 does it affect the approach to the steady state, and
4 how does it affect the steady state temperature?

5 So, this is what we used to correct our
6 data. This is the thermocouple welded above the
7 sample in the Inconel. It's the same in both tests.
8 The blue is the bare cladding, and the red is cladding
9 with about 37 -- let's call it 40 micron steam oxide
10 layer that we grew on it. What's the difference? The
11 difference is you've knocked the heck out of the
12 reaction rate, the heat rate released. And so you
13 reduce this early temperature, and you basically come
14 to about the same steady state temperature.

15 Let me show a graph in terms of the table.
16 What does it do, bare cladding versus the pre-oxidized
17 cladding? It knocks this early peak down by about 40
18 degrees C, and it only knocks the steady state
19 temperature down by about 8 degrees C. And in this
20 business, that's pretty good for the steady state
21 temperature.

22 So, it's really -- let me go back. The
23 data I'm going to show you are all analyzed in terms
24 of this red temperature curve with the steam oxide
25 layer grown on it. Okay. These are basically our

NEAL R. GROSS

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

1 data. I'll show them to you graphically in a second.
2 We ran the tests in this sequence. These are the
3 corrected ECRs. They go from 2.6 to 9.3, instead of
4 3 to 10. So that temperature correction made a
5 difference of about 0.7 in the calculated ECR. Not
6 huge.

7 This is the calculated oxide layers that
8 are predicted at both the inner and outer surfaces,
9 assuming they're bare. You can see that where we did
10 get really good data for the 7.4, you see our sample.
11 It's predicted to be 30. We're only measuring a steam
12 oxide layer under the corrosion layer of 17 to 20. So
13 it's a different question -- it's not an embrittlement
14 answer I'm going to give you, but the corrosion layer
15 did slow down the weight gain due to steam oxidation.
16 And if we compare that, the best comparison is to
17 compare what happens at the outer surface to what
18 happens on the inner surface. You grow a thicker
19 steam oxide layer. You only have 10 microns of fuel
20 cladding bond, and that oxygen gets sucked up by the
21 metal.

22 Okay. And again, we did some quantitative
23 net on this one too, the sample number 4. Same basic
24 results. I mean, eventually this kind of catches up
25 a little bit. You predict 38 microns, you measure 28.

NEAL R. GROSS

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

1 This is just measuring the steam oxide layer, which is
2 very subtle to do. Okay. What I'm going to show you,
3 I'm just going to point out what's in red. Based on
4 quantitative metallography, and your estimates, and
5 published estimates of what the oxygen content is at
6 each phase boundary, what we call our measured weight
7 gain converted to ECR is 5.6 percent when you have the
8 corrosion layer versus 7.4 percent assuming it's bare
9 cladding. That doesn't mean you get that much benefit
10 in terms of ductility, or it just means that's the
11 difference in the weight gain between this kind of
12 corroded cladding and bare cladding.

13 And finally, the other thing we did, we
14 had trouble determining boundaries between corrosion
15 layer and steam oxide layer, so we went to SEM imaging
16 to get a better picture of what was going on. This is
17 just to show you grossly this is the sample coming out
18 of the reactor, coming out of the reactor pool. It's
19 basically monoclinic oxide, but it's a little bit
20 dark. And you're looking through a hot cell, colors
21 are distorted. After the test, this corrosion layer
22 has picked up oxygen from the steam, become more
23 stoichiometric, become more white in appearance. We
24 also lost a lot of it during the test, probably during
25 the cool-down.

1 CHAIRMAN POWERS: What's the non-
2 stoichiometric range for monoclinic oxide?

3 DR. BILLONE: Pardon?

4 CHAIRMAN POWERS: What's the non-
5 stoichiometry range for monoclinic oxide?

6 DR. BILLONE: It's only -- it's like
7 instead of ZrO_2 , it's $ZrO_{1.98}$ to 2. It's a small
8 difference, but it has a huge impact in terms of what
9 phase you're in. And what stabilizes the good oxide
10 is being hypo, a little under in oxygen. And what
11 drives you to the bad oxide is whatever drives you to
12 $ZrO_{2.000}$.

13 Okay. This is why we went to SEM imaging.
14 This is a low mag image of the cross-section, just to
15 show you, I want to show you the outer surface layer.
16 By the time we mounted these samples, they've already
17 come out of the furnace. They've already been cooled
18 down, come out of the furnace, now prepared. They
19 started with a 70 micron oxide layer. We can't find
20 70 micron corrosion layer. We can't find 70 microns
21 anywhere. It's disappeared partially, and it may be
22 during cool-down that it goes, some of it goes. Some
23 of it does get absorbed into the metal. The corrosion
24 layer is a source of oxygen. But our main concern
25 here is although we could -- in different images we

NEAL R. GROSS

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

1 could pick out the alpha layer, the oxygen stabilized
2 alpha layer, and the beta layer, this transition, we
3 weren't sure where the boundary was of the steam oxide
4 layer based on metallography, or optical microscopy.
5 So, you go to SEM, and you get a very clear contrast
6 between how the corrosion layer appears in the SEM,
7 the steam oxide layer that grows underneath it, the OD
8 alpha, and the beta phase. And we were able to use
9 that to improve our calculation of how much oxygen
10 pickup there was for this sample. So we went back to
11 the optical metallography and redrew these boundaries.
12 And it effectively reduced our steam oxide layer a
13 little bit.

14 Now, in saying this I'm using very
15 simplistic language. Let me go back to Ralph's
16 diffusion expertise. I can't guarantee you that the
17 oxygen atom -- steam atom, steam molecule that arrived
18 here where the oxygen disassociates, that that oxygen
19 is the one that comes through all the way to the
20 surface of this, and forms --

21 CHAIRMAN POWERS: It surely does not.

22 DR. BILLONE: I know. I can't. But in
23 terms of really simplistic models, it acts that way.
24 But it does not -- I'm not offering you a mechanistic
25 explanation. I just want to make the point that the

NEAL R. GROSS

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

1 corrosion layer slows down the weight gain.

2 CHAIRMAN POWERS: Sure.

3 DR. BILLONE: But not -- you don't get the
4 full benefit of that in terms of ductility because
5 it's also a source of oxygen for diffusion. So even
6 if you didn't have any steam and you heated this up in
7 a certain environment, non-oxidized environment, you
8 will eventually embrittle the metal, even without
9 steam.

10 CHAIRMAN POWERS: You're generating
11 vacancies at the metal oxide interface, and those are
12 coming out at you.

13 DR. BILLONE: Right.

14 CHAIRMAN POWERS: And the oxygen's hopping
15 --

16 DR. BILLONE: It's hopping in.

17 CHAIRMAN POWERS: -- into the vacancies.
18 And so the oxygen that got generated on the surface is
19 lost to history --

20 DR. BILLONE: It's lost to history,
21 correct.

22 CHAIRMAN POWERS: -- some other oxygen
23 that pops in.

24 DR. BILLONE: All right. If you look at
25 the ID, there's better definition because you only

NEAL R. GROSS

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

1 started out with 10 microns of fuel cladding bond. So
2 it's pretty easy to pick out what you grew with steam
3 even thought that's not a great picture compared to
4 the next one I'll show. That's a better picture.
5 This is SEM. The trouble with SEM is you can only
6 look at little spots. And so this is the steam oxide
7 layer, and that pretty much grew as if you didn't have
8 a fuel cladding bond layer of 10 microns. The 10
9 microns is kind of lost. It's too small to really
10 pick out. But we were able to identify those layers
11 much better with the SEM.

12 All right. This is Dana's favorite
13 sample. We wanted to compare steam oxide layer alpha
14 layer and beta layer for the pre-hydrated non-
15 irradiated, exposed for about the same amount of time,
16 and with about the same amount of hydrogen. This is
17 non-irradiated pre-hydrated. We want to compare these
18 layer thicknesses to what we measured for the
19 irradiated stuff. So this is bare cladding, and this
20 is how -- we've already seen this picture. And
21 basically it's the same kind of data that I showed you
22 before where on the outer surface if we compare these
23 two samples, you obviously grew a thicker steam oxide
24 layer on the bare cladding than you did on the
25 corroded cladding. And even to some extent grew a

NEAL R. GROSS

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

1 little bit more on the bare cladding on the ID than
2 you did with the irradiated cladding.

3 CHAIRMAN POWERS: Argonne is apparently
4 the only place in the world that thinks corrosion is
5 good.

6 DR. BILLONE: Corrosion is bad because it
7 dumps hydrogen in the material. It's not as bad as we
8 used to think when we thought it was completely
9 transparent, and you had the double whammy of having
10 a lot of hydrogen, and a really rapid oxidation rate,
11 and a rapid embrittlement. You're right, I'm the only
12 one that says that.

13 CHAIRMAN POWERS: No, your colleague Dr.
14 Shack tells me corrosion's been very good for his
15 career, too.

16 DR. BILLONE: Oh, that's true. That's
17 exactly what this -- this is just to show in terms of
18 the oxygen stabilized alpha layer, and I guess I
19 probably did not move -- no, this is okay. The red
20 points are the irradiated. This is what Cathcart-
21 Pawel would predict for bare cladding. This is the
22 one data point we got from our 600 ppm sample. Even
23 at our lowest test time, where it looked like we had
24 no steam oxide layer on the outer surface -- and this
25 is the sum of the inner and outer surface alpha layer

NEAL R. GROSS

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

1 -- we were still pumping oxygen into the material, and
2 stabilizing the alpha phase, even though it didn't
3 look like any steam oxide. So, in terms of alpha
4 layer growth, the corrosion layer didn't protect you
5 from that, basically. Or if it did, the protection
6 was small.

7 Okay. Let's plot the ductility results,
8 remembering that all these open circles are slow-
9 cooled, and only one was quenched, and that's
10 unfortunate. I'll take responsibility for that. But
11 basically, at our lowest test time, with 550 ppm of
12 hydrogen, we got almost as much ductility -- more
13 ductility as you would in the stuff coming out of the
14 factory. We didn't see any intrinsic hydrogen
15 embrittlement. We had a fairly low level of oxygen
16 embrittlement. And this arrow means the test was
17 stopped before the sample failed. This is done at 135
18 degrees C. You've got thermocouples. You don't have
19 as much room to squash the thing.

20 We ran two tests, two rings, at about 4.3
21 percent ECR because I didn't believe the results. The
22 first ring -- I predicted we would have zero ductility
23 right here. First result we got was about 12 percent,
24 but it didn't look like it really failed. And I
25 thought they had mixed up the samples, so I insisted

NEAL R. GROSS

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

1 on running the second ring, and the second ring had
2 about 38 percent ductility. So, this is a non-failed
3 sample. This is a failed sample. And that's why I'm
4 putting the arrow up. That's what the arrow means.
5 And then eventually we slowly coaxed down to zero
6 ductility at about 9 percent predicted ECR.

7 Now the unfortunate thing. The last test
8 we ran was with this sample, with 800 ppm hydrogen.
9 That's what we quenched. And of course it's got zero
10 ductility. The question is if the 800 ppm of
11 hydrogen, yes. Is it the quench? I don't know. Next
12 time we do this we would want to take a sample like
13 this sample here which has pretty good ductility,
14 slow-cooled, and we're going to want to quench it at
15 800 degrees C.

16 CHAIRMAN POWERS: So, what you really
17 should have done is have an arrow horizontally coming
18 from that 8 down toward 4 off that black point?

19 DR. BILLONE: Well, I plotted it as it is
20 because this is not plotted as a function of hydrogen.
21 It's all the more reason to get away from --

22 CHAIRMAN POWERS: But at 800 weight parts
23 per million hydrogen, it may have had zero ductility,
24 7 percent CP-ECR, or 5 percent --

25 DR. BILLONE: Yes. Right. Oh yes, you're

1 right.

2 CHAIRMAN POWERS: Okay.

3 DR. BILLONE: Because at zero, it doesn't
4 mean that's a transition. But I'm not going to put
5 the arrow, though.

6 All right. Let's compare what we just
7 did, but let's not do it in terms of CP-ECR. Let's do
8 it in terms of something else. You don't need this
9 graph. Or yes you do. I'm sorry, you do need this
10 graph. But let's re-look at our data in terms of
11 measured ECR. Just as an exercise. So, now we're
12 going to talk about non-irradiated pre-hydrided Zirc-4
13 at two measured ECR levels, and the HBR Zirc-4, the
14 high burnup Zirc-4 at two measured ECR levels. And we
15 don't have enough data points, but the point is that
16 when plotted in terms of measured ECR and hydrogen
17 content, you really can't almost pick out the fact
18 that this is the irradiated slow-cooled, and this is
19 the non-irradiated quenched. And this is the
20 irradiated slow-cooled, big deal, 800 is brittle in
21 both cases. So as far as the samples where we got
22 quantitative metallography to determine measured ECR,
23 measured weight gain, they fall within the scatter.
24 That's the honest way of saying it. They fall within
25 the scatter of our database for non-irradiated

NEAL R. GROSS

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

1 material.

2 Okay. What we're trying to say is what is
3 the deal with the corrosion layer. What are the
4 effects on steam oxidation kinetics and embrittlement?
5 It's clearly a source of oxygen for growth of the
6 alpha layer, ergo it must be a source of oxygen for
7 oxygen diffusion into the beta layer, even without
8 steam. And I still claim, based on just looking at
9 the OD and the ID, you're getting partial protection
10 from steam oxidation in terms of weight gain, in terms
11 of how thick of an oxide layer you're growing. And
12 this is primarily my evidence, not just comparing it
13 to calculation. The net effect of post-quench
14 ductility improvement, there appears to be a small
15 benefit of cladding with the corrosion layer versus
16 bare pre-hydrided cladding in terms of how much time
17 at temperature it takes to embrittle it, assuming that
18 these two have the same hydrogen content. It doesn't
19 mean corrosion is good. So be very careful. Assuming
20 these two have the same hydrogen content, there seems
21 to be a small benefit in terms of post-quench
22 ductility.

23 The fuel cladding bond is clearly a source
24 of oxygen for alpha layer growth. We see it, and
25 diffuse it into the beta layer. It's essentially non-

NEAL R. GROSS

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

1 protective, or very small protection with respect to
2 steam oxidation. And what's interesting with slow
3 cooling, anyway, we don't see what has been proposed,
4 which is that even without oxygen, if you got enough
5 hydrogen in there that you would embrittle these
6 samples. If you just took them up past the phase
7 change temperature up to 900, 1000 degrees C, and then
8 cool them down, you would get embrittlement due to
9 hydrogen. That's observed in certain tests. We don't
10 see that in our tests, but again, our tests are slow-
11 cooled. And what I'm talking about is the low ECR
12 tests which most of the oxidation occurred between
13 1000 and 1200 degrees C.

14 CHAIRMAN POWERS: Do we know what the
15 hydrogen-zirconium phase diagram looks like?

16 DR. BILLONE: We know what the hydrogen-
17 zirconium phase diagram looks like, but the hydrogen-
18 zirconium-oxygen phase diagram is a little more
19 challenging.

20 CHAIRMAN POWERS: What does HZR look like?

21 DR. BILLONE: What is the hydride ZRH?
22 1.66 or something like that. What does it look like.
23 I know what it looks like in the alpha phase for
24 normal reactor conditions. The problem with when you
25 take it up into the beta phase, the beta phase has at

NEAL R. GROSS

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

1 1200 degrees C a hydrogen solubility of as much as
2 5000 weight parts per million, and so if you're at 600
3 to 4000 or something, and you cool down slowly or
4 quench, you never see any hydrides. There is an
5 effect of the hydrogen, increasing the oxygen
6 solubility. There's probably an additional effect
7 which the Framatome presentation will cover very well
8 and answer your question in much more depth. Because
9 they have data they're going to show that I'm not
10 allowed to talk about until they show it. So let's
11 leave it to them.

12 Okay. I want to do this quickly because
13 these experiments didn't work. They weren't as
14 controlled. Coming out of the February 10 meeting,
15 and I'm taking you up to that meeting that the data on
16 the previous slide were presented, we decided that we
17 really needed longer test times at 1200 degrees C to
18 investigate high temperature embrittlement. We're
19 also -- most of the rod is exposed to one-sided
20 oxidation. It's only the balloon and burst region
21 that's two-sided.

22 Ramp effects become less significant
23 because you're running much longer time tests. And
24 you notice our early ECR tests never got up to 1200.
25 So there was a recommendation from the technical

NEAL R. GROSS

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

1 advisory group to do these tests. Let's go to the
2 results because we presented these results on May 10,
3 and what I learned on May 11 is we probably shouldn't
4 have run these tests because no one's done them
5 successfully. But it's proprietary information, and
6 so it wasn't available to me. Essentially what
7 happened is the way we run them, we have an argon
8 purge gas flowing on the ID. We had a little bit of
9 steam leakage. We were worried about hydrogen pickup
10 in the steam leakage. We sort of forgot the fact that
11 the only thing keeping that hydrogen in the beta
12 layer, that 550 ppm, is the fact that you've got that
13 bond layer on the ID, and once that bond layer is
14 consumed, you're going to lose hydrogen to the argon
15 purge. It sounds really trivial, but I was banking on
16 that not happening, or I didn't know about it at the
17 time. So basically, these samples were not controlled
18 in the sense that what hydrogen you started with is
19 not the hydrogen you ended up with. That's why in our
20 next test we're going to not mess around with small
21 samples defueled. We're going to go to larger
22 samples, truly one-sided steam oxidation, and have all
23 the effects in there.

24 We did do some good thermal benchmarking.
25 We're proud of that. And this just summarizes the

NEAL R. GROSS

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

1 results. It includes our two-sided oxidation results,
2 but basically the 550 went to 360 to 190, and then up
3 to 770. So it's something varying in time during the
4 test. It's not a controlled parameter. The clue was
5 we had these data points for the one-sided test before
6 we had the hydrogen values, and they didn't make sense
7 because the embrittlement should have been much
8 steeper than that. But the embrittlement wasn't
9 steeper because this had lost more hydrogen than the
10 one before. I'll find a way to make this useful in my
11 embrittlement correlation, but it's going to be a
12 stretch.

13 Okay. So the new test that we're going to
14 do, let's go back to the same sample. This is where
15 we did our two-sided oxidation test. Up in Grid-span
16 4 we had already cut a 12-inch long, 300-millimeter
17 roughly, LOCA sample. We were going to use it for a
18 LOCA test. Now, since we've already characterized
19 that this has 550 weight parts per million for
20 hydrogen here, 800 weight parts per million hydrogen
21 out here, what you have is a hydrogen gradient in the
22 sample. You do one ECR, you do quench, and then you
23 get ductile to brittle transition as a function of
24 hydrogen content. Let me move this a little faster.

25 So these are the numbers I was talking

NEAL R. GROSS

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

1 about. This is the bottom of the sample, and that's
2 the top of the sample. This is the midplane. And we
3 only have uniform heating over these four and a half
4 to five inches. So that's where the rings will be
5 cut. And that's what we'll do with each sample that
6 we oxidize. We'll cut rings for metallography and
7 ring compression.

8 Let me try to wrap up. Test plans for
9 high burnup ZIRLO and M5. We do have these samples at
10 Argonne. The ZIRLO is from North Anna. It's not
11 heavily corroded, the samples we have, 18 to 32 micron
12 corrosion layer. I just threw down something for
13 hydrogen, 200 to 300 weight parts per million. I'm
14 not sure -- we're going to measure the hydrogen, as
15 well as what the corrosion layer is. The M5 is what
16 we call European M5, European reactor. That's
17 probably typical. It's about 18 micron corrosion. I
18 don't know the hydrogen content. I just estimated 100
19 to 200. And we're planning on loading those this
20 week, and transferring them for sectioning, and then
21 the steam oxidation tests.

22 We're going to do two-sided oxidation
23 tests. I have to write this up as a test plan and
24 separately send it to Framatome and Westinghouse, kind
25 of get their blessing, and NRC at the same time. But

1 basically, we're going to do the 1200 degrees C test
2 first because that's most embrittling, 1000 degrees C
3 test next because that's an interesting alloy. That
4 shows the differences in alloys at 1000 degrees C.
5 And when we get time and more samples we'll do the
6 1100. And the idea for each of these is to do a 10
7 percent calculated CP-ECR, see where you are, are you
8 ductile or are you brittle, and then either move up or
9 move down accordingly. And I'm very excited about
10 those tests.

11 CHAIRMAN POWERS: If I recall, your --
12 what you want to do is a quench test on something
13 that's in the steep part?

14 DR. BILLONE: Something that's got about
15 10 to 20 percent slow cooling ductility.

16 CHAIRMAN POWERS: Ductility. And see if
17 that drops way down?

18 DR. BILLONE: Right. And I pray it
19 doesn't, honestly. Otherwise our expenses go way up.

20 CHAIRMAN POWERS: What you'd like to know
21 is your slow-cooling is fast enough.

22 DR. BILLONE: Right. What I'm banking on
23 is our experience with as-fabricated cladding that's
24 not -- doesn't have hydrogen. And that may be the
25 flaw. And that whether we quench at 800 or slow-cool

NEAL R. GROSS

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

1 makes no difference whatsoever in the post-quench
2 ductility. You don't have hydrogen in the sample, and
3 these have hydrogen. And we're going to wait for the
4 Framatome presentation to find out what the effects of
5 slow-cooling versus slow-cooling/quench versus quench
6 directly from the oxidation temperature. It's a
7 fascinating area.

8 Okay, just quickly. LOCA integral tests.
9 We've completed four high burnup fuel samples, the BWR
10 Zirc-2. We did non-destructive examinations on all to
11 determine how much swelling -- I don't like the word
12 "swelling" -- what the diameter profile was, and also
13 characterizing the burst. We cut up two of those
14 samples to do metallography, hydrogen content, and
15 oxygen content. And as Ralph, the picture Ralph
16 showed, the 20 percent maximum ECR, meaning ECR in the
17 burst region, that sample failed at three locations
18 during handling. So we really don't expect any room
19 temperature ductility from three of these tests that
20 were run at the 20 percent ECR.

21 A few samples that are available for four-
22 point bending, one should be ductile, and we just ramp
23 to burst and then cool down. Never made it to 800
24 degrees C, we just wanted to study the burst
25 characteristics. And the 20 percent ECR, we already

NEAL R. GROSS

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

1 basically know from me messing around with the 2
2 percent with -- this is five minutes at 1204 degrees
3 C versus what I showed you at the beginning, which was
4 two minutes. So we pretty much know it's going to be
5 brittle.

6 We plan to do four tests with the high
7 burnup Zirc-4 cladding. There are certain things we
8 need to do in the hot cell to get ready for that. And
9 as I showed you, we just got our out-of-cell four-
10 point bend apparatus going. We've got it benchmarked.
11 We've tested a few LOCA samples. And we found out
12 that somewhere between one second at 1204 degrees C,
13 and two minutes is where the ductile to brittle
14 transition is for a balloon and burst sample.

15 Just quickly, these are the four tests we
16 ran. What's really interesting to me is except for
17 two things there was almost no difference in the
18 ballooning characteristics between the non-irradiated
19 stuff that I showed you and the high burnup stuff.
20 The difference is basically the shape of this opening.
21 And you can see fuel in this. This is the one that
22 was just ramped to burst, and then cooled without
23 quench. This was ramped and held for five minutes,
24 and then slow-cooled. This was partially quenched,
25 and this was the good test that was the whole

NEAL R. GROSS

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

1 sequence. And so we cut up this, and we cut up that.
2 And what's really different about high burnup fuel
3 versus fresh fuel in terms of cladding hopefully is
4 the following diagram. Almost the following diagram.
5 When we profile the oxygen content, convert it to ECR,
6 and that's the blue. It does peak in the burst region
7 as you expect. And it tapers off as you go to the
8 one-sided oxidation region. Again, this is thin
9 cladding, double-sided oxidation, and you're moving
10 out towards single-sided oxidation of thicker
11 cladding.

12 What's interesting is that the hydrogen
13 peaks were not out here at the edge of the balloon.
14 The hydrogen peaks were in closer to the burst region.
15 It pretty much tells you your answer that -- well, I
16 don't want to talk about criteria. As far as this
17 level of ECR, and you'd have to do a test at a lower
18 ECR, you not only knock the heck out of the ductility
19 with oxygen, you really knocked it out with hydrogen.
20 Because now you've got both oxygen and hydrogen
21 essentially peaking in a very narrow region. So it's
22 really highly unlikely that high burnup fuel would
23 have any ductility, unless maybe you went to the one
24 second at 1204 degrees C, maybe you can make it there.
25 So that's a major difference between what Ralph showed

NEAL R. GROSS

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

1 for non-irradiated. He showed these sharp spikes in
2 hydrogen out beyond the balloon region, the neck
3 region. Japanese results and our results are pretty
4 consistent that the hydrogen peaks move in when you
5 have fuel and a fuel cladding bond in our case, and
6 fuel cladding bond in their case.

7 All right. I'm not going to --

8 CHAIRMAN POWERS: Do you understand why
9 they move in?

10 DR. BILLONE: Well, it's not the fuel.
11 Because the Japanese drill the fuel out. And it seems
12 to occur when you have a fuel cladding bond like our
13 10 micron oxide bond, which is something -- the
14 Japanese samples are more like 45 gigawatt days per
15 metric ton, and it's marginal whether all the samples
16 have a bond. And sometimes they see the peak move in.
17 Sometimes they see the peak move out. And sometimes
18 they see no peak. And in their case, they're right at
19 that transition burnup where the fuel cladding bond is
20 partially forming, or fully forming, or not formed at
21 all. So based on their experience, and our experience
22 being similar, it seems like when you have a -- and
23 this is not an explanation. This is just like a
24 coincidence. When you have the fuel cladding bond
25 present, that peak seems to move in. And when you

NEAL R. GROSS

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

1 don't have it, it seems to move out. So it's not an
2 explanation, it's just -- so, for burnup below 40
3 gigawatt days per metric ton, you still expect the
4 peaks at the neck. If you get above 45 you expect
5 them to move in.

6 I am ending right here. Let me end this
7 right here. I've shown you the data we've generated
8 to date. I've indicated that we will be generating
9 high burnup M5 and ZIRLO data. This will be defueled,
10 small segments. We will be getting some fueled M5
11 through the EPRI Framatome contract, which will be
12 available for the LOCA program. And we're juggling,
13 based on what we can do in the hot cell, between the
14 M5 and ZIRLO tests, and the LOCA integral test. So we
15 basically -- if we get stalled someplace on one set of
16 tests, we jump over to the other set. And that's the
17 end of my long presentation. If you have any
18 questions I'd be amazed.

19 CHAIRMAN POWERS: Any of the members have
20 questions they'd like to pose at this time? Anyone in
21 the audience want to interrogate Mike? Comment about
22 what he has to say. You're truthfully free to do so
23 if you do have questions.

24 DR. BILLONE: Don't leave me any more
25 time, because I have another presentation I didn't

NEAL R. GROSS

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

1 give. I was going to just skip it.

2 CHAIRMAN POWERS: Okay. Seeing none,
3 you're done.

4 DR. BILLONE: Okay, thank you very much
5 for your attention.

6 CHAIRMAN POWERS: Let's see. I guess
7 Odelli you're going to talk to us?

8 MR. OZER: Yes.

9 CHAIRMAN POWERS: It may take Mike a
10 little bit to get unwrapped up here.

11 DR. BILLONE: All right, Odelli. I'll
12 leave it to you how to get out of this.

13 MR. OZER: Oh, thanks.

14 CHAIRMAN POWERS: We've got a resident
15 geek here that can help you.

16 MR. OZER: Thank you, Mr. Chairman. And
17 I appreciate this opportunity to present our views in
18 front of the subcommittee. I'd like to preface my
19 presentation by stating that our presentation
20 materials, the handouts, were prepared before we had
21 a chance to listen to the presentation this morning by
22 Ralph in which he proposed how to address the new
23 criteria. We find these criteria very interesting,
24 and we certainly appreciate his attempt to try to
25 minimize the impact on the industry. Certainly we

1 think that these criteria deserve some additional
2 evaluation.

3 Now, as far as the Argonne program, we
4 think that it's a very interesting, very good program.
5 There's a lot of good data being generated in there.
6 There are some important accomplishments, and we heard
7 all of these earlier this morning, and in Mike's
8 presentation. Essentially confirm the historic best
9 estimate cladding oxidation kinetics. By the way, I'm
10 going to try to cut my presentation rather short in
11 order to give additional time to the presentations
12 that will follow. What I would like to do is just
13 identify maybe some of the concerns that we have, and
14 I think they will be addressed in much more detail in
15 the following presentation, and then their potential
16 impact will be addressed by the third presentation
17 that we have by Robert Montgomery.

18 But anyway, as far as the accomplishments
19 of the ANL program, they confirmed the Hobson ring
20 compression test results at 135 degrees Centigrade.
21 They identified the reasons for the differences in the
22 western niobium-based alloys versus the eastern ones.
23 And we heard that this morning.

24 CHAIRMAN POWERS: What you're speaking
25 here is the difference between M5 and E110?

NEAL R. GROSS

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

1 MR. OZER: Exactly.

2 CHAIRMAN POWERS: Okay.

3 MR. OZER: Yes, there was this concern
4 that all niobium-based alloys may be behaving as E110,
5 and Argonne was able to demonstrate that that was not
6 the case. And then they were able to identify the
7 root causes of it.

8 CHAIRMAN POWERS: Yes, I think our actual
9 concern is we didn't understand why, and we didn't
10 know whether suddenly M5 might suddenly evolve over
11 into being like E110 or something like that.

12 MR. OZER: Exactly.

13 CHAIRMAN POWERS: Having understood a
14 little bit of why helps a lot.

15 MR. OZER: They found, as we just heard,
16 the BWR cladding to balloon and burst for irradiated
17 material, and a very similar way as for unirradiated
18 material. The oxidation kinetics and embrittlement is
19 similar. I do need to point out, however, that we
20 still are waiting for the first integral PWR test to
21 be conducted. So a lot of these assumptions are
22 really being made on the basis of integral BWR tests.

23 Successful approximation of irradiation
24 effects via pre-hydriding. This is very important for
25 us because if this is true, then we can use pre-

NEAL R. GROSS

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

1 hydriding as a surrogate for irradiation in testing
2 material properties..

3 CHAIRMAN POWERS: And that seems like a
4 terrific idea, but the criteria that have been
5 advanced doesn't seem to include that kind of
6 precaution.

7 MR. OZER: I think Ralph was saying that
8 it's implicit in there, and that's why I think we need
9 to study it some. I really couldn't comment on this
10 at this time.

11 CHAIRMAN POWERS: But I think the idea is
12 that you use this corrosion oxidation and subtract it
13 from your criterion to account for this effect. But
14 a much more direct way seems to be just what you have
15 up there, is that you pre-hydride and oxidize the
16 material.

17 MR. OZER: Exactly. And we feel that
18 there is -- still we are evaluating the applicability
19 of the current acceptance criteria to high burnup
20 cladding materials, especially the advanced claddings.
21 The issues are that it appears to us that schedule
22 considerations are being given higher priority than
23 trying to resolve some of the questions that have come
24 up. And there has been some gaps in understanding
25 that have been identified. The program is very

NEAL R. GROSS

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

1 interesting, but it has also raised a lot of questions
2 that we think need to be addressed.

3 The Fuel Reliability Program and the
4 industry have been very active in the Argonne program,
5 not only through participation and technical advisory
6 groups, and providing both fresh and irradiated
7 cladding specimens, as well as full length PWR and BWR
8 irradiated rods. That's really a very expensive
9 proposal for these tests. But in addition to that, we
10 have continued monitoring the data and analyzing data
11 from other international LOCA-related programs, such
12 as Halden, CEA, JAERI, and some other European
13 countries have produced LOCA-relevant data. This is
14 not only to provide a reference to the ANL results,
15 but also to evaluate the potential impact of other
16 experimental conditions, such as heating/cooling rate
17 differences, and alternate post-transient mechanical
18 test results, and assessment of measured versus
19 calculated ECR.

20 Briefly, our main concerns are due to the
21 fact that NRC-RES has stated its intent to really
22 begin the rulemaking process by September 2005. We
23 are concerned that this schedule is too ambitious and
24 premature. You know, these are just some samples of
25 questions, and I'll be going through those in some

NEAL R. GROSS

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

1 more detail later. But we feel that a complete and
2 well understood database is really needed before we
3 can move to rulemaking. And obviously, the current
4 database is still evolving, and the limitations in the
5 ANL program, we're not sure that they are being
6 considered adequately. We didn't have really much of
7 a chance to review the proposed correlation.

8 This is one slide that I would like to
9 skip in view of what Ralph has presented this morning,
10 because he has tried to address a lot of these
11 concerns that we had in this area. But you know, as
12 far as evaluating whether the data is mature enough to
13 initiate rulemaking, we feel that a cladding ductility
14 test obtained from the high burnup fuel rods in ANL
15 program are not conclusive regarding the effects of
16 irradiation of fuel survivability during a LOCA. Many
17 of the observations are not consistent with the
18 results obtained at overseas facilities, in particular
19 the effect of heating and cooling rates, and quench or
20 no quench on residual ductility. The ANL, there are
21 some boundary conditions at the ANL. If you remember,
22 the samples are being heated externally, usually they
23 are small samples, and Mike mentioned the possibility
24 of using flat versus curved plates during the
25 compression tests. And the difficulty of running one-

NEAL R. GROSS

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

1 sided tests versus two-sided tests.

2 CHAIRMAN POWERS: On the issue of that, my
3 experience with the equivalent of ring compression
4 tests is all based on ceramics, brittle materials to
5 begin with, and it works very well for those. And
6 that was my understanding, that it worked so well for
7 basically brittle materials because you could
8 interpret the results very easily. When you go to
9 these ductile to brittle transitioning materials, is
10 it a case of just not being able to interpret the
11 ductility very well? Or is it --

12 MR. OZER: Well, we are concerned that
13 when you squeeze the samples in a -- I'm sorry.

14 CHAIRMAN POWERS: Probably means the
15 battery is dying.

16 MR. OZER: When you squeeze the samples,
17 we would expect that the crack would initiate from the
18 outside at the three o'clock and nine o'clock
19 position, whereas most of the cracks in the Argonne
20 tests initiated at the six o'clock or twelve o'clock
21 position. Starting from the inside. So we are using
22 really inside generated crack information for
23 something that really will have an impact on the
24 outside, because we're trying to specify criteria for
25 the outside of the cladding. So we feel 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.nealgross.com

1 a little bit of an imbalance there. There's a concern
2 in there. But I think, again, those may be addressed
3 somewhat greater extent in the third presentation.

4 CHAIRMAN POWERS: Okay.

5 MR. OZER: Other questions are things like
6 the protectiveness of the preexisting corrosion layer.
7 And a big question is really the effect of hydrogen on
8 the embrittlement. Are we taking that into account
9 adequately? And you know, we have some doubts in that
10 area. And we feel that these inconsistencies need to
11 be resolved before rulemaking is initiated. We
12 understand that Argonne is going to do some additional
13 tests, but some of these tests will require also
14 repetition at the outside organizations. And they
15 have a completely different -- they certainly will not
16 be ready by September.

17 And we don't really see a safety concern
18 that would be driving this ambitious schedule at this
19 point. There's no safety significant event that has
20 been identified. In fact, the recent research
21 performed both in U.S. and Japan have confirmed that
22 fuel can survive the quench-related, you know, thermal
23 shock quench events very easily up to and even under
24 conditions greater than the current criteria, current
25 limits specified in 10 C.F.R. 50.46. What we are

NEAL R. GROSS

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

1 looking at is really after surviving quench, you know,
2 how much ductility do we have by relying on the ring
3 compression test.

4 CHAIRMAN POWERS: I got the impression
5 that the staff had not identified a pressing safety
6 significant issue either, that they were driven
7 primarily by the fact that we're evolving 50.46 in
8 general, but more for the clad generality problem. I
9 mean, they're just trying to make life easy for all
10 concerned here. I mean, I don't think -- am I correct
11 that there was no safety issue drove you here?

12 MR. ELTAWILA: We agree with you. There
13 is no safety issue, and as you articulated correctly,
14 it's the 50.46 rulemaking process, you know, changes,
15 and the M5 issue that really right now is still out of
16 the regulations. So that's -- we try to make the rule
17 to encompass that because either we will have to
18 change the rule right now to add M5, or we change the
19 rule to make it a performance-based. And maybe at the
20 end I would like to say something about it.

21 CHAIRMAN POWERS: Yes. I mean, I think
22 it's worthwhile to do that, but I think there's a
23 community of belief here, and that we just have a
24 historic opportunity to make one change.

25 MR. ELTAWILA: Absolutely, that's what it

1 is. I would like to make one clarification so nobody
2 gets bent out of shape here. The Office of Research
3 will provide the technical basis for rulemaking.
4 Research does not do any rulemaking. So we provide it
5 to NRR. They might not proceed with the rulemaking.
6 Just for the record.

7 MR. OZER: But --

8 DR. MEYER: Could I add something, Dana?

9 CHAIRMAN POWERS: Please.

10 DR. MEYER: To Farouk's comment. And I
11 don't disagree with anything he said. We haven't
12 found any safety problems. But that isn't to say that
13 the rule as written does not have some problems with
14 it. For example, the rule as written now talks about
15 a limit on oxidation. And as far as applying that
16 rule goes, you could use a true value of oxidation for
17 M5, and it wouldn't -- now my words are failing. M5
18 will lose its ductility before 17 percent true
19 oxidation. But it will hold on as long or longer than
20 the other alloys in a time temperature domain. So I
21 would say that while -- I just don't want to leave the
22 impression that the current rule is just fine.

23 CHAIRMAN POWERS: I think your articulated
24 aspiration in your presentation, that we understand
25 it's not oxide but oxygen in the metal that counts was

NEAL R. GROSS

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

1 successfully accomplished, if not by you, certainly by
2 the combination of you with Mike. So I understand
3 your concern about the existing rule.

4 MR. OZER: Thank you. Yes, we do
5 recognize that there is a unique opportunity to revise
6 -- to update the criteria. But you know, the bottom
7 line is if we're going to do it, let's do it right.
8 Let's make sure that we have all the data that is
9 necessary for this in hand or available.

10 We do have some concerns about, as you
11 know, about demonstrating quench survivability using
12 thermal quench tests as directly related to the fuel
13 performance demands during a LOCA event, whereas ring
14 compression tests measuring local properties are not
15 indicative of the load-bearing capability of the fuel.
16 The ring compression tests, we need to recognize that
17 they result in more severe requirements than just
18 quench survival.

19 So really, in conclusion, we feel that the
20 current data set is insufficient to support the
21 rulemaking at this time. Some exploratory research is
22 still needed. There is no pressing safety significant
23 event. And the industry's position is that the
24 initiation of the rulemaking process should be delayed
25 until some of these inconsistencies that we'd like to

NEAL R. GROSS

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

1 address are resolved, and the validation experiments
2 needed to support are completed consistently with a
3 risk-informed regulation approach.

4 I just wanted to say that the following
5 presentation before the presentation by Jean-Paul
6 Mardon, Bert Dunn is going to make a couple of
7 introductory statements to introduce Jean-Paul.

8 CHAIRMAN POWERS: Okay. If I could go
9 back to your last point on Slide 7. The question's
10 not about your point, but do you understand how the
11 quench program in Germany interfaces with this kind of
12 study? Are the two just not related, or is there
13 something to be learned from that program?

14 MR. OZER: We have not followed the German
15 program because of the assumption that it was more
16 severe accident oriented. But the Japanese quench
17 tests we feel are very relevant, where they do, you
18 know, they heat up the rods, and then they clamp them,
19 and then cool them, and determine whether they survive
20 the quench under those conditions or not. Those are
21 much more representative.

22 CHAIRMAN POWERS: I think the German
23 program has not been so severe accident related. I
24 think they're driving it toward severe accident
25 relations. But I'm not -- maybe they're in some sort

NEAL R. GROSS

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

1 of a transition regime between the two, but maybe
2 there's something there that we could learn.

3 MR. OZER: I certainly think it's worth
4 pursuing it, if the information's available to us.

5 CHAIRMAN POWERS: It's probably the most
6 open program I can think of. I mean, they seem to be
7 willing to put everything up on the website just as
8 quick as they generate it. I mean, it's not like one
9 of these consortium programs where things are
10 embargoed and stuff like that. Maybe there's
11 something there. And certainly the people working on
12 it are extremely expert in oxidation of zirconium.

13 MR. OZER: We'll make a point of
14 contacting them. Thank you.

15 MEMBER DENNING: I have a question on the
16 viewgraph that you jumped over, and I think you jumped
17 over it because you really hadn't been exposed earlier
18 to what Ralph or RES was really proposing here. Would
19 you agree that the major comments you've made there
20 are probably overstated?

21 MR. OZER: That the major?

22 MEMBER DENNING: The comments, like the
23 second and third. I realize you may not have had
24 adequate time to decide whether you would change this
25 viewgraph. But just from your exposure, do you really

NEAL R. GROSS

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

1 believe the things that are said on the second and
2 third ones now, or do you see this as a fundamental
3 change?

4 MR. OZER: I think the attempt has been
5 made to not have any fundamental changes, to make it
6 as easy as possible. So if I had my opportunity, I
7 would take this bullet out.

8 MEMBER DENNING: Yes. And do you think
9 that it also --

10 MR. OZER: However, I think that there are
11 some assumptions that are being made which if are
12 proven not to be true, then we may need to really
13 follow the hydrogen and oxygen content in materials
14 that we would like to qualify much more closely than
15 the current proposal would.

16 MEMBER DENNING: So you have concerns
17 about the time-related criterion that's being proposed
18 as to whether it will really be technically
19 justifiable in the long term?

20 MR. OZER: Yes.

21 CHAIRMAN POWERS: As I understand -- I
22 mean, what people say to me about this evolution of
23 50.46, and the choice of the break size, is no
24 decision has been made yet. But I wondered if for
25 those range of break sizes that are under

1 consideration now, do we have temperature signatures
2 of the type that we currently use for large breaks?

3 MEMBER DENNING: You mean, like do we
4 uncover the core to the extent implied there and have
5 as high temperatures? And I truly don't know where
6 that -

7 CHAIRMAN POWERS: I've just never seen
8 calculations of the kind that we get for --

9 MEMBER SHACK: It depends on the plant.
10 Some plants are definitely high temperatures, and high
11 --

12 CHAIRMAN POWERS: I recognize that it will
13 always be somewhat plant-specific, and somewhat
14 scenario-specific. But the kind, you know, we all
15 have kind of in mind what the temperature signature of
16 a large break LOCA is if you allow me to draw it with
17 a big enough paintbrush. And I don't know that I've
18 ever seen any for these transition break size, you
19 know, the candidates for transition break size.

20 MEMBER SHACK: I just don't think there's
21 anything that you could say is typical.

22 MR. DUNN: This is Bert Dunn of Framatome.
23 At the transition break sizes, most of the
24 calculations show relatively low temperatures. But as
25 you go into the smaller break arena where you're

NEAL R. GROSS

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

1 challenging the high pressure injection system, you
2 will have slower heat-up rates, some degree of
3 plateau. It depends a little bit because you're
4 working against decay heat drop-off versus a
5 relatively fixed ECCS injection. And then you'll have
6 a slow cool-down rate afterwards. And some plants do
7 approach 2000 degrees. And they may push it a little
8 bit higher after they get relief.

9 MEMBER DENNING: Do you have a feeling
10 about the time regime? Ralph talked about a time
11 regime, and maximum times. I'm not sure, were you
12 here at the time?

13 MR. DUNN: Yes. I would expect that a
14 half hour would be a fairly long time for even those
15 small breaks I was talking about. Forty-five minutes
16 for most of them would be fairly -- would cover them
17 all fairly well. There are some unique breaks that we
18 might have to look at associated with failure of the
19 injection systems. So it's not 100 percent clear.

20 CHAIRMAN POWERS: Okay. Rosa?

21 MS. YANG: Yes. Rosa Yang. Just want to
22 clarify one point reflecting to the question. I think
23 the comment that was presented by Odelli was based on
24 this embrittlement correlation that is part of your
25 handout that was not discussed earlier. And that was

NEAL R. GROSS

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

1 a correlation shared with us in May meeting, and that
2 involved the, you know, parameters like the solubility
3 of oxygen as a function of hydrogen, the diffusion,
4 the kinetics, and all that. So from us, that's more
5 of a fundamental change in the criteria.

6 CHAIRMAN POWERS: If it's the correlation
7 that I think I know about, yes, you're right, it
8 needed some real look.

9 MS. YANG: You need quite a lot of
10 parameters.

11 CHAIRMAN POWERS: Any other questions for
12 the speaker? Well, thanks Odelli. Bert, you're going
13 to lead us out first, here?

14 MR. DUNN: Yes, I wanted to introduce the
15 next speaker. Framatome's been interested in this
16 program and cooperated with this program for a long
17 time. We have participated in providing information,
18 baseline information, some of our own data. And we
19 want to cooperate with it.

20 I'd like to add two or I guess three
21 things. Ralph a moment ago said that M5 would not
22 reach 17 percent perhaps. I think he was primarily
23 talking about the oxidation rate at 1000 degrees. I
24 think as you get up to the higher temperatures, 1100,
25 1200 degrees, that cladding performs essentially the

NEAL R. GROSS

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

1 same as the rest of them. That low oxidation rate at
2 1000 has been verified in three nations and four
3 separate labs. So it's not just something that
4 Argonne has found. I wanted to put that on the table.

5 Second thing I'd like to correct, Mike's
6 expectations on the hydrogen pickup. And I'd like to
7 use this to state that hydrogen pickup, or hydrogen
8 content of cladding could very well be, and in fact
9 probably is, alloy dependent. Framatome expects the
10 stiff examples to come in at about 70 ppm hydrogen,
11 even though they've been exposed to pretty -- I guess
12 their exposure is 63 megawatt days per metric ton. So
13 I just wanted to inject that in people's minds.

14 Jean-Paul is from Lyon, France. He's a
15 metallurgist and has worked in this area quite a bit
16 of time. He's going to talk about two main items.
17 One is the effect of cool-down rate on the results of
18 these types of tests and embrittlement functions.
19 Second thing is some results on tests we've performed
20 on pre-corroded cladding. We have a loop in which we
21 store cladding in real conditions. This is not
22 autoclave stuff. It's real water, and we build up
23 corrosion on that. So I'll invite Jean-Paul to go
24 ahead.

25 MR. MARDON: Okay, thank you. First of

NEAL R. GROSS

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

1 all I would like to thank my French colleagues. We
2 participate in this study. The experimental work was
3 done in the civil CEA, the Saclay labs. And the
4 scientific analysis has been done by these people.
5 But also this work was done in close cooperation with
6 EDF, and Manley and Nicolas Waeckel.

7 In this presentation I try to specifically
8 address four main questions. The first one is, "Is
9 the cooling rate impact the cladding residual
10 ductility?" The answer is clearly yes. The second
11 question is, "Is the mechanical test boundary
12 conditions impact the residual ductility?" Again, the
13 answer is clearly yes. My third question is, "Is the
14 type of oxidation test - this means one-sided versus
15 two-sided oxidation - impact the initiation and
16 azimuthal location of cracks?" The answer, again, is
17 yes. And the last question is, "Is the pre-corrosion
18 layer impact the high temperature - high temperature
19 steam oxidation kinetics?" The answer is yes. And
20 "Is this pre-corrosion layer impact the residual
21 ductility?" The answer is no.

22 Now I come back on the first question,
23 what is the impact of the cooling scenario. And the
24 question is is the cooling rate increasing or
25 decreasing the cladding residual ductility? For that

NEAL R. GROSS

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

1 we have to check several parameters, and mainly direct
2 quench from the oxidation temperature, the effect of
3 cooling rate on the emergency of quench. First of
4 all, I would like to present you the several
5 transient, thermal transients used in Number 2 to show
6 the effect of the cooling scenarios on the cladding
7 residual ductility.

8 The first one, I come back later in more
9 details on each thermal transient. But the first one
10 then is the thermal protocol used by the CEA in the
11 device which is called Dezirox. And we use a fast
12 heating rate with a heating rate between 50 to 25
13 degrees Celsius per second. What we reach is the
14 oxidation temperature, what oxidation is found in
15 isothermal conditions. And this oxidation is followed
16 by a direct quench, with a very high cooling rate,
17 which is greater than 1000 degrees Celsius per second.

18 The second side of thermal transient is a
19 trial test, also performed in the Dezirox device,
20 where we performed the same heating rate, the same
21 oxidation in isothermal condition, followed by the
22 slow cooling rate with a cooling rate around 0.4
23 degrees Celsius per second up to the temperature of
24 quench of 800 degrees Celsius, where we perform the
25 direct quench with the same cooling rate. You can

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 compare this thermal transient with the thermal
2 transient used by Argonne, an unirradiated material
3 as-fabricated or pre-irradiated material, which is the
4 standard protocol of Argonne. We perform a slow
5 heating rate, followed by the stop at 50 degrees
6 Celsius, just below the oxidation temperature. This
7 means that the oxidation is performing under
8 anisothermal condition compared to isothermal
9 condition of the Deziroxi device, and followed by a
10 slow cooling rate up to 800 degrees Celsius on the
11 direct quench.

12 And the third trial performed in the
13 Deziroxi device is the same heating rate, same
14 isothermal condition, followed by a slow cooling rate
15 from the oxidation temperature up to the room
16 temperature with a very low cooling rate. We stopped
17 around 0.4 degrees Celsius, and we end at 0.25 degrees
18 Celsius per second. And we can compare with the
19 standard protocol proposed by Argonne for irradiated
20 material.

21 DR. BILLONE: Excuse me, Jean-Paul. Just
22 a small correction.

23 MR. MARDON: Yes.

24 DR. BILLONE: For the kind of test you're
25 talking about, our heating rate is an order of

1 magnitude higher. It's 50 to 70 degrees C per second
2 for the oxidation samples, down there. It's the LOCA
3 integral tests that are 5 degrees C per second. But
4 the data that you're going to be referring to is more
5 like that. But it slows down to 1 to 2 degrees C per
6 second.

7 MR. MARDON: But we don't discuss this --

8 DR. BILLONE: Okay.

9 MR. MARDON: -- on the oxidation. It's
10 also another question. Is the heating rate impact the
11 oxidation.

12 DR. BILLONE: You're going to focus on
13 cooling.

14 MR. MARDON: But I discuss only cooling
15 this condition, the cooling condition. In that case,
16 it's 10 times higher in your condition than in the
17 condition of the irradiated.

18 Now, this figure shows a typical record
19 for temperature versus time for a test performed at
20 1200 degrees Celsius. I record the Dezirox sample is
21 oxidized on one side, in isothermal condition. And I
22 can show to you that there is no temperature overshoot
23 when you reach the isothermal condition of oxidation.
24 We have -- on the specimen we have already several
25 thermocouples on the OD surface. And we have recorded

NEAL R. GROSS

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

1 the temperature each degree of 5 milliseconds in order
2 to plot the relation of the temperature versus time.
3 In the Dezirox device, the sample is introduced in the
4 furnace in temperature with a steam flow. This means
5 that when we introduce the sample in the furnace, we
6 have an articulation of the temperature up to 400
7 degrees Celsius. But from 400 degrees Celsius up to
8 1000 degrees Celsius the heating rate is about 55
9 degrees Celsius per second. And this temperature
10 decreased progressively to 25 degrees Celsius in order
11 to reach the temperature of 1200 degrees Celsius
12 without overshoot of temperature. We have -- the
13 Dezirox device has been carefully designed in order to
14 obtain no overshoot when sent with very high heating
15 rate conditions. And the stabilization of the
16 temperature is reached after about 35 seconds. And in
17 that case we are in isothermal condition. For
18 example, at 1200 degrees Celsius, after around 50 - 55
19 seconds, we have reached 3 percent ECR CP.

20 Now, I'm going to present the direct
21 quench cases. Again, I record we have the test
22 heating rate, isothermal condition, and a direct
23 quench. And in the standard protocol, Dezirox
24 protocol, this transient is followed by several
25 mechanical tests. Samples are taken from the 15

NEAL R. GROSS

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

1 centimeter per second sample. On this oxidized
2 sample, in the standard Dezirox protocol we perform
3 normally a room temperature test, but for several
4 loading mode, first one is ring compression test,
5 second one is three-point bending test, and the third
6 one is impact test. And also we can perform ring
7 compression test and three-point bending test at 135
8 degrees Celsius and at various temperatures between
9 room temperature and 135 degrees Celsius.

10 But today I will only discuss the ring
11 compression test. As mentioned this morning by Mike,
12 the loading mode is different from CEA that the one
13 used by Argonne. On the upper part we have a plate,
14 but on the lower part we have a plate cover, which is
15 what I discuss later this point and mechanical
16 notation. The sample is a 10 millimeter length
17 sample, and the displacement rate used in the ring
18 compression test is 0.5 millimeters by minute.
19 Generally we test the failure rate of oxidation
20 temperature when between 1000 and 1250 degrees
21 Celsius, with four or five levels of measured ECR
22 between 3 and 25 percent. And the tests on as-
23 received material and pre-hydrided sample, pre-
24 hydrided in order to simulate in-reactor corrosion.

25 The first result that we obtained on as-

NEAL R. GROSS

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

1 received Zirc-4 and M5. And this material after
2 direct quench exhibits a similar post-quench behavior
3 at the three levels of temperature, 1000, 1100 degrees
4 Celsius, and 1200 degrees Celsius. In red we have the
5 ductile train as we see the Zirc-4 -- Zirc-4. And in
6 blue the top 10 as we see in M5. We can observe the
7 post-quench ductility decreases when the ECR
8 increases, and that both materials exhibit exactly the
9 same behavior.

10 CHAIRMAN POWERS: But you -- on that slide
11 you seem to have the identical phenomenon at 1000
12 degrees Centigrade that Dr. Billone showed on his M5
13 tests at 1000 degrees. Something funky happens on
14 your next to last sample. I mean, it's identical to
15 yours, Mike. The 10 percent measured has worse
16 properties than the 17 percent measured at 1000
17 degrees for M5.

18 MR. DUNN: Talking about the blue dot
19 that's underneath the red triangles which you can
20 hardly see?

21 DR. BILLONE: To me it's possible, but I
22 don't understand M5 as well as I should because it's
23 difficult to run the same test twice and get the same
24 results. I'm not sure -- it's not breakaway
25 oxidation, but there's not stable, consistent weight

NEAL R. GROSS

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

1 gain the way there is with Zirc-4. I hadn't seen that
2 point.

3 MR. MARDON: This one?

4 DR. BILLONE: The last one.

5 MR. MARDON: This one?

6 DR. BILLONE: Yes, that one I didn't
7 remember. That test I'd never seen before. I'd just
8 seen the others. For M5 you'd have to run several
9 tests in that regime, if it's important, at 1000
10 degrees C. If it's important, because that's a very
11 long time test.

12 MR. MARDON: This one, yes?

13 DR. BILLONE: That's a very long time. So
14 I don't know what that data point means. I have no
15 comment.

16 MEMBER DENNING: Well, let me ask a
17 question since we do seem to have some reproduced test
18 data here, particularly at 1100. That, I assume that
19 those differences are a measure of the variability of
20 a similar test. So that can we draw some conclusions
21 that the error bend over on the 1000 would be similar?

22 MR. MARDON: Yes, probably. The
23 scattering due to the test itself is the same at each
24 level of temperature. But it's true that we have less
25 result at 1000, and we'd have to increase the number

NEAL R. GROSS

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

1 of tests in order to have a better view of this type.
2 But probably we can observe the scattering is
3 independent of the level of temperature.

4 The following question is the impact of
5 pre-hydriding content on the cladding residual
6 ductility, again in the direct quench conditions. In
7 blue we have the ductile on plane of M5 at the three
8 levels of temperatures between 1000 and 1200 for M5
9 pre-hydriding at 135 ppm, which is the volume of end
10 of life content in M5 at regular. And for Zirc-4 we
11 have testing the Zirc-4 pre-hydrided at 600 ppm, which
12 corresponds to the end of life hydrogen content, again
13 for the same three levels of temperature. We can
14 observe that the M5 with the lower hydrogen content
15 exhibits significantly higher residual ductility than
16 the Zirc-4 with higher hydrogen content. Whatever the
17 oxidation temperature.

18 And this result is to be related to the M5
19 lower in-service hydrogen pickup, because there is not
20 only a lower content in the M5 in-service, but also
21 there is lower hydrogen pickup, which is two times
22 lower than the hydrogen pickup I showed for the Zirc-
23 4. This means that the ductile/brittle transition
24 versus hydrogen is located in the range of 30 ECR
25 percent for M5. Why this ductile/brittle transition

1 is located around the 5 more or less percent for Zirc-
2 4 with 600 ppm of hydrogen. And we have tried to
3 explain why the Zirc-4 with the 600 ppm hydrogen is
4 greater with an ECR value of 6 percent. On this
5 sample of thermal oxidation at 1200 degrees Celsius,
6 and the 6 percent ECR, we have determined the hydrogen
7 distribution by a nuclear analysis in the CEA. And we
8 have obtained this figure. We show the hydrogen
9 content in the arbitrary unit because at that time the
10 analysis is ongoing, versus the thickness of the
11 materials.

12 On the right we start with zirconium.
13 Zirconium we can observe there is no hydrogen in
14 zirconium. Followed by the alpha layer, which
15 exhibits also no hydrogen, and all the hydrogen is
16 located in the prior beta phase with a very high level
17 of hydrogen, which can explain the brittle behavior of
18 this material for so low ECR values.

19 This slide summarizes the hydrogen impact
20 on the hydrogen and oxygen migration and the residual
21 ductility. First, the hydrogen increases solubility
22 of oxygen into the prior beta layer, even at very low
23 ECR values. Second, the hydrogen content increases
24 the oxygen kinetics diffusion into the metal. The
25 third, most of the hydrogen migrates into prior beta

NEAL R. GROSS

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

1 layer. This is supported by the nuclear analysis
2 performed by CEA. This means that we are probably --
3 the residual hydrogen content into prior beta layer
4 could consequently becomes a more relevant key
5 parameter than the initial hydrogen content in the
6 metal in order to explain the brittle behavior. And
7 the last one is higher is hydrogen content lower is
8 ECR value corresponding to the ductile to brittle
9 transition.

10 MEMBER SHACK: Have I got a wrong picture.
11 You know, somehow I always picture, the pictures of
12 the hydrides are always in that outer layer. And
13 you're telling me it's really the other way in these
14 tests.

15 MR. MARDON: This one?

16 MEMBER SHACK: When I see a micrograph,
17 and I see hydrides, they'd all be on your right-hand
18 side, which would tell me that the hydrogen's there.
19 And yet you're telling me it's all over here in this
20 test. Is there something different about this than
21 there is in those pictures that I see?

22 DR. BILLONE: Yes, you're looking at
23 pictures of the stuff coming out of the pool that's
24 been exposed to 400 degrees C and it's all in the
25 alpha phase. He's taken this up to 1000 degrees,

NEAL R. GROSS

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

1 1100, 1200, changed phase, and the hydrogen is
2 diffused.

3 MEMBER SHACK: It's driven it down.

4 DR. BILLONE: Has driven it down. The
5 beta phase is hungry for hydrogen. That's why they're
6 different.

7 MR. DUNN: So, have we got that clear?
8 This is post-transient hydrogen distribution. The
9 other one is normal operations. Okay. This is Bert
10 Dunn.

11 MR. MARDON: Well, the next comparison is
12 the effect of slow-cooling rate case. This case, we
13 have tested some very low slow-cooling rates between
14 0.4 degrees Celsius up to 0.25 degrees Celsius. We
15 compare with the Argonne results. This figure shows
16 the typical cooling rate obtained on the samples, with
17 the furnace turned off, but with steam during the
18 cooling phase. We start at 1200 degrees Celsius and
19 up to 800 degrees Celsius the cooling rate is all 0.4
20 or 0.5 degrees Celsius, and the third, this cooling
21 rate decreases drastically in order to reach 0.1
22 degrees Celsius up to 21 degrees Celsius.

23 In this condition we perform ring
24 compression tests at room temperature and at 135
25 degrees Celsius. In blue we have the data obtained in

NEAL R. GROSS

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

1 the slow-cooling case, and in the pink we have the
2 data obtained on the direct quench. This is for room
3 temperature. You can observe that at room temperature
4 there is only a slight effect or no effect of the
5 slow-cooling rate on the residual ductility for ring
6 compression tests performed at room temperature. Why
7 ductility is strongly improved for slow-cooling rate
8 when the ring compression test is performed at 135
9 degrees Celsius? Mainly for the low ECR value. These
10 results have been obtained on Zirc-4 primarily at 600
11 ppm, and oxidized at 1200 degrees Celsius.

12 In order to try to explain why the slow-
13 cooling rate induces an improvement of the ductility,
14 we have performed some analyses, microstructure
15 analyses. These two figures show the optical
16 micrography in polarized light for the slow-cooling
17 rate and direct quench. We can observe that we have
18 two different microstructures with a uniform
19 microstructure and a varied microstructure for the
20 slow-cooling. And these samples conform to material
21 with large ductility, slow-cooling rate, and this
22 sample corresponds to zero ductility with the same
23 gradient. Directly comparable.

24 Now, on these materials we have performed
25 some scanning electron micrography. This is a

NEAL R. GROSS

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

1 viewgraph from the direct quench. And you can observe
2 that you have in this case a very homogenous structure
3 with a very high microhardness around 400 - 450
4 figures, which is much higher than the critical
5 hardness for Zirc-4, which is located around 350.
6 This means that the ductility is higher than the
7 critical value, and this material is fully brittle.

8 In comparison, for the slow-cooling rate
9 with the same weight gain, we can observe that we have
10 a more complex microstructure. In this microstructure
11 we can observe some similar area with a hardness of
12 the same level as this one in some part. But some
13 other part exhibits very low microhardness, around 150
14 - 200, which is lower than the as-received materials.
15 This means we have a very low oxygen content. And
16 also, on this microstructure, we can observe some
17 hydrides between the alpha layer. This means that the
18 slow-cooling rate induces a two-phase structure with
19 very strong alpha area embedded in the softer matrix,
20 very soft matrix plus hydrides. This produces higher
21 ductility than the homogeneous quenched structure.
22 But mainly this is due to the redistribution of oxygen
23 and hydrogen during the slow cooling. But in order to
24 now understand this phenomena, additional
25 investigations are needed, mainly at room 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 and 135 degrees Celsius.

2 MEMBER DENNING: Excuse me. Do you pursue
3 the slow-cooling rates just to get a better
4 understanding of the processes that are going on? Or
5 do you think that there's -- if you look at the
6 prototypical accident, you wouldn't expect to have
7 slow-cooling rates like this, would you? Wouldn't you
8 expect to have much faster cooling rates, or am I
9 misunderstanding the accident scenario as you
10 understand it? Did you understand the question? In
11 the real accident, would you ever expect to see slow-
12 cooling rates of this nature?

13 MR. MARDON: Can you --

14 MR. DUNN: This is Bert Dunn. I'm
15 probably a little bit better at answering it. I think
16 the slow-cooling rates are probably not too off the
17 mark for the small break regime. In large break, we
18 would expect a little bit slower cooling rates than
19 what's been advertised here, perhaps for the first 100
20 seconds post-peak until -- but 800 degrees Celsius is
21 not a bad quench temperature. When we get to small
22 breaks, we will expect a process that's more like a
23 dry-out be-wet situation, and probably quenching would
24 take place with a delta T of I would guess between 200
25 and 300 degrees. So it wouldn't be complete -- so we

NEAL R. GROSS

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

1 don't have -- we probably shouldn't advertise this as
2 being characteristic, but it's an explanation for
3 differences between behaviors from one lab to another,
4 and it illustrates that it can have an effect.
5 Whether the slow-cooling geometry there sets in before
6 we get to that quench in a small break, I don't think
7 we know right now. I hope that answered.

8 MEMBER DENNING: Thanks.

9 CHAIRMAN POWERS: It's my impression that
10 you look at this comparison more to understand whether
11 an experimental convenience is really useful, and how
12 to calibrate those slow-cooled results relative to
13 things that might cool down faster. What Bert
14 introduces is of course another important point, it's
15 in small break LOCAs you don't see the same sort of
16 quenching at all. And that's a good point.

17 MR. DUNN: That's correct. And as we move
18 forward with one of the other activities of the NRC
19 recently, an activity I support, which is to eliminate
20 the larger breaks, this becomes more important.

21 CHAIRMAN POWERS: More important, yes.
22 And what I had was actually completely backwards. It
23 is the percolation through the soft matrix that's
24 important, not the percolation through the hard
25 matrix. Yes. It's just interesting.

NEAL R. GROSS

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

1 MR. MARDON: Now the third case is slow-
2 cooling followed by the direct quench cases. In that
3 case we have performed again a test on the Zirc-4 at
4 1200 degrees Celsius with a cooling rate of 0.4 - 0.5
5 degrees Celsius up to 800 degrees Celsius. We are
6 performing direct quench in water with a barrier
7 cooling rate. As regards the -- we have performed
8 tests on 1200 degrees Celsius and Zirc-4 with 600 ppm.
9 And recognize that we have only for the previous
10 result observed an effect of the slow-cooling rate at
11 135. And on this data, in view of the data obtained
12 with the slow-cooling post-quench rate, we have the
13 following results. At room temperature, the slow-
14 cooling samples with quench is fully brittle, and in
15 the same condition, the slow-cooling post-quench
16 condition with testing at 135, the ductility is also
17 very low. Displacement conclusion, we have a similar
18 residual ductility for direct quench case of zero-zero
19 case which is slow-cooling post-quench. This means in
20 most cases we have a brittle material.

21 This slide summarizes conclusions on the
22 impact of cooling rate on the residual ductility. The
23 slow-cooling rate improved considerably the residual
24 ductility at 135 degrees Celsius for pre-hydrated
25 materials. This improvement is mainly due to a shift

NEAL R. GROSS

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

1 of the ductile/brittle transition. In addition to
2 cooling rate, this shift in the ductile/brittle
3 transition depends also on other parameters, such as
4 hydrogen content, hydrogen and oxygen redistribution,
5 oxidation temperature, ECR value, and may be alloy.
6 This means it's very complicated.

7 Before some effect of this parameter can
8 be opposite, and the following figure shows the
9 expected impact of the different parameters. On this
10 figure that is ductility versus test temperature. We
11 have brittle behavior on the top, ductile behavior.
12 And for example, in black you have the typical curve
13 obtained for Zirc-4, as we see in material testing
14 around 1200 - 1250 degrees Celsius, where the
15 ductile/brittle transition occurs between 60 and 100
16 degrees Celsius. And now, we expect that when we
17 increase the hydrogen content, when you increase the
18 ECR value, or when you increase the oxidation
19 temperature, this transition is shifted towards the
20 right, this temperature. This means that the material
21 is not brittle in this condition. And there is only
22 one parameter we can improve this ductile/brittle
23 transition. This is the impact of the decreasing of
24 the cooling rate. We shift towards the lower
25 temperature, the ductile/brittle transition. 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 means that same form of material with hydrogen
2 content, and the testing with the low cooling rate we
3 can have a ductile behavior at 135 degrees Celsius.
4 But you can observe it's very complex, and we are to
5 take in account several parameters. This means that
6 additional mechanical tests for various test
7 temperature ranging from 20 degrees Celsius up to 100
8 degrees Celsius, and also additional detailed
9 microstructural investigations are needed to support
10 this hypothesis, which the mechanicals results is a
11 function of the cooling scenario, mainly for the pre-
12 hydrided materials. Several tests are in progress in
13 CEA.

14 Now I will intend to discuss a second
15 question, which is, is the test boundary condition
16 impact the residual ductility, the initiation, and the
17 azimuthal location of the cracks in ring compression
18 test. First, I compare the Argonne loading mode for
19 the samples, compare with the CEA/Deziroxx device. For
20 me, both loading modes are very similar due to the
21 fact that in the CEA/Deziroxx device, the sample is
22 free to expanse due to a very large radius of
23 curvature of the bottom part of the device. This
24 means it's quite similar to the Argonne.

25 The second question, in what is the impact

1 of the post-LOCA at this temperature between room
2 temperature and 135. And the other question is,
3 depending on the test boundary condition and the type
4 of oxidation, one-sided versus two-sided, what is the
5 impact on the azimuthal location of the crack
6 initiation. And the second, the impact of the crack
7 initiation may occur maybe on the ID surface or the OD
8 surface.

9 In terms of impact of the test temperature
10 between room temperature versus 135. In that case we
11 are testing Zirc-4, as-received Zirc-4 oxidized at
12 1200 degrees Celsius, followed by a direct quench. In
13 red you have the ductile obtained at room temperature,
14 and in green the ductile obtained at 135 degrees
15 Celsius. You can observe that for the fully ductile
16 or for the fully brittle material, there is no impact
17 of the test temperature. This is an important result.
18 And the second, the ductility is improved, but only in
19 the intermediate value of ECR, when you increase the
20 temperature from room temperature up to 135.

21 We have performed the same comparison for
22 M5 and Zirc-4 pre-hydrated, M5 pre-hydrated at 130
23 ppm, and Zirc-4 pre-hydrated at 600 ppm. This
24 material have been oxidized at 1200 degrees Celsius,
25 followed by a direct quench. We observe that when we

NEAL R. GROSS

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

1 test the Zirc-4 pre-hydrided 600 ppm at room
2 temperature or 135, the Zirc-4 remains brittle. Same
3 rate increases the test temperature, because the scale
4 is very large. The percent in this region is about
5 0.5 percent. Why for M5 the ductility is improved?
6 Also for the intermediate value due to the very low
7 hydrogen content in the metal. We compare the solid
8 part in blue for the room temperature test, and in the
9 open sample in blue is obtained at 135 degrees
10 Celsius. In comparison with the same scale on this
11 axis, we can observe that the Zirc-4 600 room
12 temperature and 135 is located on the X axis. This
13 means that material is brittle. Y is the M5 remains
14 obtained.

15 The other question is where the crack is
16 initiated, where is located the rupture during a ring
17 compression test. For that we have performed in the
18 Dezirox device some oxidation one-sided condition, and
19 other oxidation in two-sided condition. These samples
20 have been oxidized at 1200 degrees Celsius in one
21 side. This is Zirc-4 600 ppm with 3.59 milligrams per
22 square centimeters during quench. You can observe
23 that the cracks is located at three or nine o'clock,
24 and the initiation of the cracks is located on the OD
25 surface. You can observe that this is a view of the

NEAL R. GROSS

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

1 curved plate on the bottom part. You can observe that
2 the sample is free to expand in this test.

3 And now we compare with the same materials
4 Zirc-4 600 ppm, direct quench, but with the same
5 weight gain, in the same oxidation time, in two-sided.
6 In that case, the cracks is located at six or twelve
7 o'clock, and the initiation in that case is on the ID
8 surface. We have for the two-sided oxidation, we have
9 an example which shows that the rupture is located --
10 the crack is located at six and twelve, for a higher
11 weight gain for Zirc-4 600 and direct quench. This
12 means that the initiation and the location of cracks
13 depends on the oxidation protocol, one-sided versus
14 two-sided, and not of the loading mode. If you
15 compare Argonne and CEA, this is independent of the
16 loading mode, but depends strongly on the oxidation
17 protocol.

18 Now the following question is what is the
19 impact of the pre-corrosion layer on the high
20 temperature oxidation kinetics and the residual
21 ductility. For that we have a testing at 1200 degrees
22 Celsius, 55 seconds. This means about 3 percent ECR.
23 The Zirc-4 cladding were pre-oxidized in Reggae loop,
24 which is a CEA loop, which has a condition very close
25 to the pre-hydrated environment, except as a neutron

NEAL R. GROSS

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

1 flux. And this material was characterized by
2 zirconium thickness on the OD surface of 15 microns,
3 5 microns on the ID surface, and about 150 - 200 ppm
4 of hydrogen in the metal.

5 This figure shows an optical viewgraph of
6 the samples after oxidation this time. You can
7 observe on the ID surface that all the ID corrosion,
8 pre-corrosion layer has been transformed in alpha.
9 There is no more oxide, pre-corrosion oxide. Why? On
10 the OD surface, we can observe that from the outer
11 part of the material we have the remaining pre-
12 corrosion layer. Just under you have the columnar
13 zirconium, which is obtained in high temperature steam
14 oxidation. The typical brittle alpha layer and the
15 prior beta phase.

16 We have characterized these materials. We
17 have in order to compare the effect of the pre-
18 oxidation, we have compared Zirc-4 as-received
19 materials, which has been tested at the same
20 temperature with the same time, 50 seconds, in order
21 to compare the different parameter. The first
22 conclusion is that the pre-transient corrosion layer
23 slowed down the steam oxidation. We can observe that
24 the weight gain is much lower for the pre-oxidized
25 sample than the fresh materials. This slow-down is

NEAL R. GROSS

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

1 effective up to the time for which the oxygen flux
2 settles across the preexisting corrosion layer. But
3 this hypothesis supposes that the corrosion layer is
4 not cracked under LOCA conditions for the balloon or
5 deformed area. It's probably not the case. This is
6 the first conclusion.

7 The second conclusion. At the early
8 beginning of the steam oxidation, the pre-transient
9 corrosion layer begins to transform by diffusion of
10 oxygen into the metallic sublayers, which are the
11 alpha and the beta layers. And thus its thickness --
12 and first its thickness first decreases. This is
13 observed on this value. We start with 15 microns of
14 oxidation, and the remaining corrosion is only 5.4
15 microns. This reaction is followed by a growth at the
16 interface metal/oxide of a steam columnar zirconium
17 layer, which is around 7.2 microns compared to the 23
18 microns obtained for the fresh materials. But the
19 more important result is that all these results induce
20 the same alpha layer thickness for the fresh
21 materials, 20 microns, compared to about 20 microns
22 for the pre-oxidized Zirc-4 materials. This means
23 what is the impact of this situation on the residual
24 ductility? There is no significant impact of the pre-
25 corrosion layer on the residual ductility due to the

NEAL R. GROSS

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

1 fact that the alpha layer has the same thickness for
2 fresh material than for pre-oxidized materials.

3 MEMBER DENNING: Can we discuss that a
4 little more, because I think that is an important
5 question. I want to make sure that I understand what
6 you're saying. You're saying that the existence of
7 the pre-corrosion layer didn't affect the ultimate
8 thickness of the oxide layer?

9 MR. MARDON: This one?

10 MEMBER DENNING: The final -- well, it's
11 your -- the alpha is unaffected.

12 MR. MARDON: We start with --

13 MEMBER DENNING: Yes. Right.

14 MR. MARDON: Oh, this. The layer of 15
15 microns. This layer, pre-transient layer slows down
16 the steam oxidation because we have a very low weight
17 gain compared to the weight gain obtained on the fresh
18 materials. This phenomena occurs up to the time for
19 which oxygen flux settles across the preexisting
20 corrosion layer. This means that the corrosion layer
21 remaining is 5.4 microns compared to the 15 microns.
22 But this difference between 15 microns and 5 microns
23 is transformed into alpha layer. The oxygen coming
24 from the zirconium pre-corrosion layer is transformed
25 in alpha layer. And after, when the flux of oxygen

NEAL R. GROSS

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

1 settled across the preexisting corrosion layer, we
2 have the typical high temperature oxidation which
3 occurs, and in that case you obtain 7.2 microns of
4 columnar zirconium coming from steam oxidation,
5 compared to the 23 microns obtained, result of pre-
6 corrosion. But in fact the oxygen coming from the
7 pre-corrosion layer plus the steam oxidation gives
8 exactly the same thickness of the alpha layer for the
9 fresh material than for the pre-oxidized material.
10 And this is the important parameter for the ductility
11 of the materials because this means that there is no
12 effect of the pre-corrosion layer on the ductility of
13 the materials. And I show you this result on the
14 following graph.

15 MEMBER SHACK: But couldn't you have an
16 effect on the prior beta layer? That is, are you sure
17 it had -- the prior beta layer has the same oxygen-
18 hydrogen content, since it's the one that gives you
19 the toughness, suppose you affected its properties?
20 You know, I'm not sure that the conclusion that the
21 alpha layer is the same thickness leads me to the
22 conclusion there's no impact on ductility if it
23 affects the prior beta layer.

24 MR. MARDON: Yes, there probably are some
25 results, some tests that are important, but we have

NEAL R. GROSS

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

1 not at that time measured the hardness of the beta
2 layer. But according to the results obtained in this
3 slide, we show that the pre-oxidized samples with the
4 150 ppm at 135 degrees Celsius up to room temperature
5 are located close to the result obtained on as-
6 received materials, show clearly that the ductility of
7 the pre-oxidized samples from room temperature to 100
8 is very similar to the one obtained on as-received
9 material, or as-received material plus the pre-
10 hydriding of 150 ppms. This means that the beta layer
11 is probably the same.

12 MEMBER SHACK: Is your weight gain here
13 the total weight gain, or just the weight gain in the
14 transient?

15 MR. MARDON: This is the weight gain in
16 the transient. Yes, the transient. Yes, because the
17 weight is the same before the test and after the test.
18 And this value is only the weight gain during the high
19 temperature transient. This is clear. And this is
20 the result. And we have exactly the same result on
21 M5. We have also tested M5 at 1200 degrees Celsius,
22 similar time 60 seconds, in order to reach about the
23 same ECR. This material was also oxidized in the
24 Reggae loop, similar OD thickness, 15 microns, similar
25 ID thickness, but less hydrogen in the material due to

NEAL R. GROSS

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

1 the fact that the hydrogen pickup of M5 is two times
2 slower than the one on Zirc-4. This is an important
3 result.

4 And also we have compared with fresh
5 materials, with the same times. Again, you can
6 observe the corrosion -- the weight gain is lower for
7 the pre-oxidized compared to the fresh material. We
8 obtain also a lower columnar, remaining about 10
9 microns compared to 15, the total zirconium thickness.
10 And again, the thickness of the alpha layer is quite
11 similar, and the beta layer is probably the same
12 hardness. You have exactly the same conclusions for
13 both materials. They show clearly that there is no
14 impact of the pre-corrosion on the ductility of the
15 material.

16 This slide summarizes my presentation. We
17 have mainly four main observations based on CEA data.
18 The first one is hydrogen content is a first order
19 parameter on the post-quench ductility. The second
20 one, that -- probably the main result, there is a
21 major effect of a slow-cooling rate combined with a
22 mechanical test performed at 135 degrees Celsius on
23 the residual ductility of pre-hydrided materials. The
24 third conclusion is pre-transient corrosion layer
25 slows down the high temperature steam oxidation, but

1 has no impact on the alpha layer thickness, and thus
2 no significant influence on the residual ductility for
3 the same oxidation temperature and the same expected
4 ECR value. And the fourth observation is both
5 initiation and location of ring failure depend on
6 oxidation protocol, one-sided versus two-sided, and
7 not on loading mode. To compare Argonne and CEA.

8 This is -- we propose two recommendations.
9 The first one is to use the same cooling rate and the
10 same mechanical test temperature for testing
11 unirradiated and irradiated materials for two main
12 reasons. In order to avoid to be located in the
13 transient brittle zone associated with natural large
14 scattering, when you have mainly high hydrogen
15 content. And if different protocols are used for
16 irradiated or non-irradiated materials, we have to
17 take into account a correction. This is the cooling
18 rate, the hydrogen content, the protocol of oxidation,
19 and even other parameters. And the second
20 recommendation is additional data are needed to
21 confirm the impact of pre-transient corrosion layer on
22 the residual ductility of cladding with higher
23 hydrogen content than the sample test up to now.
24 That's all.

25 MEMBER SHACK: Again, wouldn't your 150 to

1 200 ppm be a fairly low hydrogen level for a high
2 burnup Zircaloy-4? The Robinson is 800, right?

3 MR. MARDON: Yes.

4 MR. DUNN: Bert Dunn. I think that's
5 true. That is relatively low. The corrosion layer
6 was relatively low for -- you wouldn't expect --

7 MEMBER SHACK: So you wouldn't expect a
8 bigger flow of the pre-corrosion in this case, if the
9 pre-corrosion is meant to incorporate the hydrogen.

10 MR. DUNN: That depends whether it's
11 linear or not, but yes. That's one of the reasons for
12 asking for more data.

13 DR. BILLONE: Excuse me, Jean-Paul? Your
14 last point, just to support it even more, could you go
15 back two more slides to your graph of ductility for
16 pre-corrosion? One more. That was the one right
17 there. Really, the limitations on your test machine
18 are in the 50 to 60 percent range. So you're just --
19 I don't think you can use those data to support your
20 point that there's no effect on embrittlement or
21 ductility of one case versus the other because you
22 just reach your ductility limit of your machine.
23 You'd have to be at a lower -- you'd have to be at a
24 higher weight gain to make that point. I don't think
25 you can displace more than 60 percent, which is about

NEAL R. GROSS

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

1 6 millimeters, plus bring back about 7 millimeters.
2 I think you've reached your limit.

3 MR. MARDON: Yes, you are probably close
4 to the limit of the --

5 DR. BILLONE: But if you've reached your
6 limit, you can't say that there's --

7 MR. MARDON: But we are not at the limit.

8 DR. BILLONE: In that case there.

9 MR. MARDON: For this one too, also, the
10 limit, this means that maybe the ductility is much
11 higher in the first case, for as-received and pre-
12 hydrided.

13 DR. BILLONE: It would be a stronger point
14 if you were at 10 percent weight gain with the pre-
15 oxidized. If you were a little -- 20 to 30 percent,
16 even, displacement you could make a stronger point.
17 But it's like when two samples are completely brittle
18 you can't tell anything about them. When two samples
19 are completely ductile, you can't really compare them
20 very well. So I support your last point, but more
21 work is --

22 DR. BILLONE: I think this was a load --
23 regarding load versus displacement, we can say that
24 this material is ductile. It may be that we are close
25 to the limit of the device, but in a way, the record

NEAL R. GROSS

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

1 load versus displacement is typical of oxide material.

2 DR. BILLONE: I believe your conclusion,
3 I just don't believe that those data points support
4 it.

5 MR. MARDON: Maybe it's not the right
6 value. Maybe the ductility is much higher in that
7 case. But it's the same conclusion for this point.

8 DR. BILLONE: Okay.

9 MR. MARDON: According to the load versus
10 displacement figure, we can say clearly that this
11 material is ductile.

12 MEMBER SHACK: Just another question too,
13 on this one where you have the initiation on the OD at
14 six and twelve, and the other one where you get the
15 initiation on the OD at three and nine. Since none of
16 these tests are prototypical, you know, what I'd sort
17 of like to conclude is that none of these variations
18 in the testing would lead me to a different conclusion
19 whether this material was brittle or not brittle. Do
20 I really get to a different conclusion? Even though
21 I have these differences, I would still like to think
22 that when I'm all done, I get to the same conclusion
23 that a weight gain, or an EPR of something, or an ECR
24 of something percent is ductile or not ductile. I'd
25 be very worried if my conclusion was so dependent on

NEAL R. GROSS

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

1 my test protocol, since neither protocol really
2 represents the real world very well.

3 MR. MARDON: If we remember the previous
4 presentation of Mike, you see that at two-sided, we
5 expected the location of the cracks at six and twelve,
6 no? According to the two-sided oxidation.

7 DR. BILLONE: Basically, I have some
8 graphs I want to show when I have an opportunity to
9 get back up there where we've been able to compare our
10 results to CEA results, which included a variety of
11 things. It's basically as-received material. And I
12 don't see any difference in results for as-received
13 material.

14 MEMBER SHACK: Brittle material is brittle
15 material, and ductile material is ductile material?

16 DR. BILLONE: Yes.

17 MR. MARDON: Between these two situations
18 it's very clear, it depends on how you use the
19 ductile, but ductile is ductile, brittle is brittle.
20 But it's right, we expect for one-sided and this type
21 of loading, we expect that we have in that case we
22 have only zirconium on the OD surface. The initiation
23 is located on OD. And the location in here. And for
24 two-sided, we have an idea of initiation on the inner
25 surface. It's expected according to the load.

NEAL R. GROSS

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

1 MR. RASHID: I have a comment on that.

2 CHAIRMAN POWERS: Sure, Joe.

3 MR. RASHID: Joe Rashid here. I just want
4 to make a point regarding this observation, that the
5 assessments are always highest at the -- below the
6 load point. And therefore, if you are using
7 correlation that uses the local conditions for either
8 one of these tests, you will be exaggerating the
9 effect of these local parameters, because of the
10 failure occurring in the ID. In other words, for
11 equal conditions OD and ID, failure would be driven to
12 the ID first.

13 MEMBER SHACK: Okay, now in your
14 terminology, is ductility a local parameter?

15 MR. RASHID: Well, if the correlation
16 uses, for example, hydrogen content, local hydrogen
17 content, then that would be affected by these two
18 tests.

19 MR. DUNN: This is Bert Dunn. I think one
20 of the things we're looking for is to have some peer
21 reaction to the differences between an inside
22 initiated crack which we don't expect to happen in the
23 reactor, and an OD initiated crack, where we expect
24 the most embrittlement and highest alpha region to go.
25 We'd just like to be able to move from one to the

NEAL R. GROSS

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

1 other with some degree of confidence. So, all tests.

2 DR. BILLONE: Bert, you're not really
3 testing real materials. You're testing bare cladding,
4 basically, that's been pre-hydrided. You will with
5 real cladding have a source of oxygen on the ID. It's
6 not steam, but you will have some embrittlement on the
7 ID and a major embrittlement on the OD. So that's not
8 what we're really doing in these tests. We're not
9 trying to reproduce exactly what happens in the
10 reactor for a known mode. We're just defining a
11 screening test. And if the picture on the left leads
12 to 19 percent ECR as a transition, and the picture on
13 the right leads to 18.5, I'd call it a wash as a
14 screening test.

15 MR. DUNN: So would I. I would agree with
16 that. But right now I'll accept your word that you've
17 checked it and there's no difference.

18 DR. BILLONE: Well, I've checked it to the
19 extent of the data that you've published, and I
20 haven't checked it to all of the data generated. But
21 I'll show just a couple of graphs where I have
22 compared the two data sets.

23 MR. DUNN: Okay.

24 DR. BILLONE: I think what's more profound
25 than this picture is the results shown for the impacts

1 on cooling rates, and quench temperatures. Far wash
2 out anything that you're looking at here. Because
3 there you saw dramatic changes in samples that were
4 totally brittle that became, you know, reasonably
5 ductile. So that's the biggest difference in test
6 protocol. It's not going to be one-sided versus two-
7 sided, or the test method, it's going to be the
8 cooling method. The cooling conditions. That's what
9 I got out of the presentation.

10 MR. DUNN: Yes, and we've had discussions
11 on whether path is important before. And you know,
12 with the differences in the cooling rate we have at
13 least discovered one effect where path is important.

14 MEMBER KRESS: But your protocol in doing
15 the cool-down rate the way you did it would result in
16 a conservative screen, would it not? It would tell
17 you it was brittle when actually it was more ductile.

18 DR. BILLONE: I don't think the issue of
19 how we run the ring test is important. I think the
20 issue -- the most conservative thing you can do is to
21 quench directly from your oxidation temperature at
22 1000 degrees per second. That's mainly the CEA test.
23 That's the kind of conservative we can't live with
24 because it essentially gives you zero ductility after
25 50 seconds at 1204 degrees C.

NEAL R. GROSS

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

1 MEMBER KRESS: That's too conservative.

2 DR. BILLONE: Too conservative. And it
3 doesn't represent anything that happens in the
4 reactor. So it's fine to do it, but if you can't live
5 with the answer, then you try to get something a
6 little closer to what's really happening.

7 MR. MARDON: Direct quench is a more
8 severe condition. Slow cooling plus direct quench is
9 the same. It is also severe. There is only one case
10 which is different. This is the slow-cooling rate,
11 which is when you combine with high temperature in
12 compression test which is ductile. But for us, the
13 direct quench or slow-cooling plus direct quench is
14 similar.

15 DR. BILLONE: Jean-Paul, just let me ask
16 you a question about your opinion. As far as oxygen
17 redistribution during slow-cooling, oxygen has to
18 diffuse a short distance to redistribute. And the
19 diffusion rate is very high at 1200 degrees C, and it
20 falls off 800 degrees C. You've essentially turned
21 everything into alpha. Why would there be oxygen
22 redistribution below 800 degrees C? Do you think
23 there would be? Whether you've quenched or slow
24 cooled?

25 MR. MARDON: First, I think as you that

1 if you perform the slow-cooling plus the quench you
2 have time to redistribute the oxygen but it's not the
3 case. It's very surprising.

4 DR. BILLONE: I know it doesn't make a
5 difference for the as-received material, but with
6 material with hydrogen it seems to make a big
7 difference. Okay.

8 MR. MARDON: But at that time you have not
9 performed a microstructurally determination of direct
10 quench on very slow cooling, and we have to perform
11 examination of the slow cooling with quench in order
12 to achieve that. Is this microstructure is close to
13 the direct quench microstructure in the slow cooling.
14 But according to the mechanical result, probably it's
15 close to the direct quench microstructure.

16 MR. WAECKEL: Jean-Paul, you can go back
17 to your Slide Number 20.

18 MR. MARDON: Slide?

19 MR. WAECKEL: 20. That shows very clearly
20 there is not a big difference between direct quench
21 and slow-cooling plus quench. And the point we are
22 going to make here is only to show that the slow-
23 cooling from the top is not conservative enough.

24 DR. BILLONE: I'm sorry, Nicolas. Could
25 you say that again? Slow-cooling from.

NEAL R. GROSS

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

1 MR. WAECKEL: The slow-cooling is less
2 demanding --

3 DR. BILLONE: Yes.

4 MR. WAECKEL: -- than any other cooling
5 down scenario, both direct quench and quench plus --
6 slow-cooling plus quench.

7 DR. BILLONE: Okay.

8 MR. WAECKEL: Slide Number 20.

9 MR. MARDON: This one?

10 MR. WAECKEL: And my name is Nicolas
11 Waeckel from EDF.

12 MR. MARDON: This one?

13 DR. BILLONE: Right.

14 MR. MARDON: I know we have to change the
15 microstructure of these samples, but probably it's
16 very close to this one, and far to this one
17 microstructure, which is very typical with very soft
18 area, with on this lower than the other steam material
19 which is very unbelievable. It was very high on this,
20 similar to the hardness of the direct quench material.
21 And some hydrides which are probably located in the
22 ductile area, this means they have no impact on the
23 ductility. So probably in that case, saying we have
24 some hydrides in the materials, the ductility is
25 improved.

1 DR. BILLONE: Is there one more factor to
2 this? Because what I call slow-cooling is more like
3 10 degrees C per second, which isn't that slow, and
4 then we quench at 800. And some of your tests were
5 run at 0.5 degrees C to 1 degrees C per second.

6 MR. MARDON: But saying with very low
7 slow-cooling, this means the time between 1200 and 800
8 is very long.

9 DR. BILLONE: Right.

10 MR. MARDON: So for a very long time we
11 have, you know the rest, we have --

12 DR. BILLONE: Oh, I see. I see what
13 you're saying.

14 MR. MARDON: Greater behavior. We have
15 more time than -- because you do the very slow-cooling
16 rate of 0.4, 0.25. Same with the very long time in
17 this range of temperature between 1200 and 800 degrees
18 Celsius. The material is brittle.

19 MR. DUNN: Jean-Paul, relative to the
20 phase change kinetics, I hate to ask -- I probably
21 shouldn't go here.

22 MR. MARDON: Yes?

23 MR. DUNN: I already started. I guess I'm
24 going to go there. Relative to phase change kinetics
25 --

1 MR. MARDON: For zirconium?

2 MR. DUNN: Yes. Are we completely through
3 them by the time we do our quench here? I just, I
4 don't remember the numbers that well.

5 MR. MARDON: Due to the fact that it's
6 pre-hydrated Zirc-4 600 ppm, the transition alpha to
7 alpha, beta is very low because --

8 MR. DUNN: Very low in temperature?

9 MR. MARDON: Yes.

10 MR. DUNN: So perhaps even with the
11 quench, the slow-cooling plus quench --

12 MR. MARDON: Maybe --

13 MR. DUNN: -- we're still quenching in the
14 middle of the phase change?

15 MR. MARDON: Probably. What slide?

16 MR. DUNN: That would be a difference
17 between the two types of accidents we might want to
18 talk about.

19 MR. MARDON: Yes, probably.

20 CHAIRMAN POWERS: Any other questions for
21 the speaker? In that case we will take a break until
22 4:05.

23 (Whereupon, the foregoing matter went off
24 the record at 3:50 p.m. and went back on the record at
25 4:05 p.m.)

NEAL R. GROSS

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

1 CHAIRMAN POWERS: We have a presentation
2 now by Robbie Montgomery on his evaluation of
3 experimental results; given, of course, that he can
4 unwind the computer, which I'm in no position to help
5 you.

6 MR. MONTGOMERY: I think I can handle it.

7 CHAIRMAN POWERS: You young guys, you know
8 these things.

9 MR. MONTGOMERY: Just like Grand Theft
10 Auto, right? I guess I need to put this thing on.

1 Good afternoon. My name is Robert
2 Montgomery. I'd like to thank the sub-committee for
3 the opportunity to come here today and make a
4 presentation on kind of an industry evaluation of the
5 Argonne experimental programs and a summary of some of
6 the key questions that we have after taking a look at
7 this data.

8 As a consultant to EPRI, we've been asked,
9 myself and Anna Tech have been asked to take a look at
10 the Argonne data and support the experimental program
11 from a technical point of view. And one of our
12 mandates has been to take the Argonne data that's been
13 generated related to post-quench ductility and try to
14 compare it to other data sources that are out there
15 that are available that try to do the same thing. So

NEAL R. GROSS

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

1 one of my objectives of today's presentation is to
2 just compare what other people have done in this area.

3 There have been tests done not only at
4 Argonne, but at CEA, which you heard a little bit
5 about today already. The Czech Republic and Hungary
6 have all tried to do tests that are similar to what
7 has been done in the Argonne program. And these
8 programs have all been trying to evaluate in some way
9 the impact of irradiation on post-quench ductility.

10 When I get done with that, I will also try
11 to identify some of the questions that have been
12 raised by the current data on post-quench ductility
13 that's come out of the Argonne program and other
14 programs. We've already kind of hinted at that today
15 in Odelli's presentation, and also in Jean-Paul's
16 presentation, and those are what are the important
17 parameters in the test, the oxidation condition,
18 should it be one-sided or two-sided oxidation, the
19 heating rates and cooling rates, and the loading
20 conditions, should they be flat plates or a
21 combination of curved and flat plates? And also, I
22 won't dwell on this point too much, but the second
23 area of question is how do these results from these
24 specialized post-quench ductility tests, and I've kind
25 of labeled them specialized because they're very local

NEAL R. GROSS

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

1 effect tests, how do they relate to conditions for a
2 hypothetical loss of coolant accident? I'm not going
3 to answer any of these questions. I'm just going to
4 raise a few of them.

5 All right. Ring Compression Tests have
6 been done not only at Argonne, but at three other
7 organizations. We see that basically they span almost
8 all the types of different alloys that are out there.
9 The Argonne program, you've heard, has gone through
10 most of the more popular alloys out there, as well as
11 prehydrided Zirc-4 and irradiated Zirc-4.

12 In Hungary they've also looked at as-
13 received material and prehydrided material to simulate
14 the effects of irradiation, Zirc-4 and E110 primarily.
15 In the Czech Republic, they've also looked at as-
16 received and prehydrided material. They've look at
17 Zirc-4, several different variants of Zirc-4, Zirlo,
18 and some Zirc 1 percent niobium material. And
19 finally, you heard a little bit about the French
20 program that's really been looking at as-received,
21 prehydrided, and now recently some pre-corroded Zirc-4
22 and M5 material.

23 I have a few slides here. I didn't know
24 how much everybody in this room would be familiar with
25 ring compression tests, so I just thought I would show

NEAL R. GROSS

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

1 a couple of diagrams here. The ring compression tests
2 typically use short rings on the order of 8
3 millimeters, some use 10, some use 6, it varies a
4 little bit from lab to lab. And they're run at both
5 room temperature - I would say most of the data that's
6 been generated outside of the U.S. has been done on
7 room temperature data, room temperature tests. The
8 U.S. has focused primarily, or Mike has focused
9 primarily on the 135 degree C test, and NCA has
10 recently started to look at that temperature, as well.

11 We have data on samples that have been
12 oxidized anywhere between 800 degrees C, rather low
13 temperature, all the way up to 1200 degrees C. And
14 primarily what we're looking at are going to be the
15 low displacement curves coming from the Instron
16 machine with a variety of different grip devices. And
17 I've kind of illustrated here what we're talking
18 about, is we have a loading platen here and a seat or
19 a plate here that the sample rests on. Sometimes
20 these are curved, sometimes these are flat, and we're
21 applying a load, and we're watching the sample deform,
22 and we get a load versus displacement curve. And then
23 that curve is evaluated, and there's different ways to
24 evaluate it to determine transition between ductile
25 and brittle behavior, or a definition of what's a

NEAL R. GROSS

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

1 ductile material, and a definition of what a brittle
2 material is.

3 Effectively there are four ways that are
4 currently being used to evaluate the low displacement
5 curves. The first one is residual plastic strain or
6 the offset strain. You've seen that. That's the
7 standard method that Argonne uses. That's represented
8 here by these black lines where you have kind of a
9 Hooke's Law line, a line representing the linear
10 portion, and then at the maximum load position, which
11 represents the first fracture point, there's a line
12 drawn parallel, and the difference between those two
13 lines represents the plastic strain, residual plastic
14 strain.

15 We also have total displacement as one
16 option, and that's where the displacement out to the
17 first crack, or sometimes out to the last crack is
18 used as a parameter, and that would represent this by
19 this green line here, and this green point there.

20 Mike also referred briefly to permanent
21 strain. Permanent strain is the measurement of the
22 diameter before the test, before the loading, and then
23 a measurement of the diameter after the test, and the
24 difference between those. And then sometimes it would
25 be normalized to the initial diameter here, to get in

NEAL R. GROSS

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

1 terms of a percentage value.

2 And then finally, our foreign colleagues
3 in the Eastern Block countries, Hungary and Czech
4 Republic, have looked at fracture energy, and that
5 would be representative of the area under the low
6 deflection curve up to the first fracture.

7 In addition to the types of methods used,
8 there also need to be criteria defined that say okay,
9 so much offset strain represents a ductile material,
10 and so much represents a brittle material, and so I
11 have here a list of the different criteria that have
12 been used by the different organizations in defining
13 the threshold between brittle and ductile.

14 We have in the Argonne program - Mike,
15 actually I think he used 2 percent today, but it
16 varied between 2 and 3 percent offset strain, or
17 greater than 1 percent permanent strain represents a
18 ductile material. In the Hungarian work, they
19 primarily focus on the fracture energy, and they use
20 a number like 50 millijoules per millimeter as their
21 metric between ductile and brittle material, so
22 greater than 50 millijoules per millimeter fracture
23 energy would be a ductile material.

24 The Czech Republic generally has used an
25 offset strain of zero, better than zero represents

1 ductile material, and those that have no offset strain
2 are brittle material. And lastly, in the CAEDF
3 program several approaches are being currently looked
4 at. They're looking at the fracture energy, they're
5 looking at offset strain, and they're also looking at
6 photography features and micro hardness as ways to
7 differentiate between ductile and brittle material.
8 So that's another variable that's in the mix when we
9 try to compare some of these data points together.

10 This is an example of some low deflection
11 curves developed in the ring compression test
12 performed by KI, the Hungarian organization, research
13 organization, and we see here that the curves that are
14 ductile material with fracture energies greater than
15 50 millijoules per millimeter are shown here in blue.
16 And typically, they actually give a minimum fracture
17 energy of something like 84 millijoules per
18 millimeter. The red curves are all brittle materials,
19 and they typically get fracture energies less than 50
20 millijoules per millimeter, and with a maximum of
21 something on the order of about 48. And you can see
22 here that they typically all kind of break fracture
23 here within fairly small displacements.

24 Now how do you use this material is shown
25 on this slide, where we have these oxidized samples

NEAL R. GROSS

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

1 that have been ring compression tested plotted here on
2 a long scale of time at oxidization versus one over
3 the temperature here for the oxidation temperature,
4 and this is kind of a classical way to look at some of
5 this data. This was the approach that was used by
6 Hobson and some people back in the original criteria
7 development days for the LOCA embrittlement criteria.
8 And we see for zirc-4 that they have defined the
9 material here using a fracture energy where we have
10 the solid symbols represent ductile material, and the
11 open symbols represent failed or brittle material.
12 Those less than 50 millijoules per millimeter, and
13 these would be greater than 50 millijoules per
14 millimeter. And we draw lines on -- typically lines
15 are drawn and we find an empirical correlation that
16 represents the transition between ductile material and
17 brittle material.

18 And I've indicated on here one line I've
19 added here. This is the old Baker-Just correlation
20 giving you a 17 percent correlation, and this was all
21 as-received material. And you can see that it
22 represents fairly well the transition zone between the
23 brittle material and the ductile material as a
24 function of the temperature and the time. That's kind
25 of an example of how some of the data is put together.

NEAL R. GROSS

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

1 I apologize for the quality of this graph
2 but what I'm showing here is some data from the Czech
3 Republic where we have residual ductility plotted here
4 versus either ECR, and this would be calculated ECR,
5 and then R as a function of hydrogen content. And I
6 realize this is a fairly busy graph, and what you see
7 here, they have run tests between 800 degrees C, all
8 the way up to 1200 degrees C. The solid symbols
9 represent as-received material, and the open symbols
10 represent material that has been pre-oxidized, and
11 hence, prehydrided in some fashion. The hydrogen
12 contents range anywhere from the as-received would be
13 near zero, out to as high as 1500 ppm, or over 1000
14 ppm of hydrogen for some of these samples.

15 And what we see, if you kind of boil it
16 down, is that for samples above 1000 degrees which are
17 represented here in green, so that would be the
18 oranges and the reddish colored samples, they
19 typically have fairly low residual ductilities, with
20 any amount of oxidation above zero. And with hydrogen
21 contents typically above 300 ppm or so, you begin to
22 see a fairly significant impact on the residual
23 ductility. So these early data sets that were
24 available, I would say a couple of years ago, a year
25 and a half ago, are already indicating that hydrogen

NEAL R. GROSS

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

1 has a pretty dominant role on the residual ductility
2 capability as defined by these data here.

3 So that's kind of my quick summary of
4 what's been done elsewhere. Now what I'd like to do,
5 and this slide kind of goes through that summary, but
6 what I'd like to do now is give a little bit more
7 detail in comparing the Argonne results with some of
8 the CEA data, the more current data that's been
9 generated. But before I do that, I'd just like to
10 point out that several countries are using ring
11 compression tests to evaluate post LOCA cladding
12 ductility. They're using different mechanical
13 parameters. Some are using offset strain, fracture
14 energy, total strain. But in some way or another,
15 these all can be related back to material ductility,
16 and we do see that there is some consistency between
17 the different material properties, mechanical
18 properties. I didn't show a slide, but there have
19 been -- and we've done some work to compare fracture
20 energy versus offset strain, and see if you get the
21 same conclusion, that the material would be brittle
22 using those two different parameters for the same data
23 set, and you do.

24 The data tends to show conclusions
25 consistent with what Argonne has produced, and that is

NEAL R. GROSS

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

1 that the oxygen uptake in the beta layer is one of the
2 key factors affecting residual ductility. And also,
3 that the pre-transient hydrogen content and the
4 distribution in the beta layer are also influencing
5 the residual ductility.

6 And finally, as I said in the last slide,
7 that some of the data coming out of the Czech Republic
8 indicates that for ECRs of about 4 or 5 percent, and
9 hydrogen contents greater than 300 ppm, you get very
10 low or zero residual ductility at oxidation
11 temperatures above 1000 C.

12 So the next couple of slides, I think Mike
13 has already shown these, maybe I'll go through these
14 quickly, are kind of a brief summary of the Argonne
15 program, and then I'll get to the results. But what
16 I wanted to point out here is a couple of key points.
17 First, is that the oxidation times that -- there were
18 a number of tests run on the irradiated H.B. Robinson
19 fuel. F07 was derived that the samples were removed
20 from. The targets were something like 3 percent, 5
21 percent, 7 percent, 8 percent, and 10 percent ECR
22 calculated using the Cathcart-Pawel model. And these
23 were run without quench. I think that's important, as
24 we just heard previously, to note. But also, it
25 should be important to note that the target ECRs 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 the times are calculated based on a temperature
2 history from a benchmark test on archive material.
3 There's no direct temperature measurement, so the
4 temperatures for the samples that were evaluated are
5 not really known. They're just estimated.

6 Because of some difficulties in the
7 Argonne program in testing as irradiated material, the
8 direct weight gain measurements were not possible.
9 There was some flaking of the oxide so that was kind
10 of difficult to do. And then primarily at this time
11 when this slide was prepared a few months ago, we were
12 waiting for metallography on the measured weight gain,
13 and that's really the method that will be used in the
14 Argonne program to determine the actual ECR values for
15 the samples, will be the metallographic image analysis
16 that Mike talked about earlier today.

17 I think he already went over that the ring
18 samples are 8 millimeters long, and that he typically
19 stops the loading after the first major load drop. He
20 showed this slide already. What I wanted to point out
21 was that this slide is a thermal benchmark, this is
22 the temperature history used to calculate the times,
23 and hence, the calculated ECR values for the samples.
24 But in actuality, the sample saw an importantly
25 different, I think, temperature history than what was

NEAL R. GROSS

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

1 used to design the experiment and calculate the ECR
2 values for these specimens, and I'll come back to that
3 in a minute.

4 Now these are a comparison of the load
5 displacement curves for the various samples. These
6 are the 3 percent calculated ECR values, 5 percent, so
7 on and so forth. We also have the as-received
8 material tested under ring compression test of 135 C,
9 so you can kind of see the effect, the softening
10 effect due to the high temperature annealing process,
11 removing some of the irradiation damage. And then you
12 then see the effects of the oxygen embrittlement, and
13 possibly the hydrogen embrittlement as you move to the
14 higher and higher oxygen contents or ECR values. So
15 the highest ECR of 10 percent gives us the lowest load
16 and strain or displacement.

17 Now you saw this previous presentation.
18 The CA data on prehydrided zirc-4 material, and that
19 was at about 600 ppm. I'm comparing here again
20 offset strain versus predicted or Cathcart-Pawel ECR
21 values for the Argonne data in blue and red, and the
22 CA data in green. These are all tested at 135 C ring
23 compression tests. And I should also point out that
24 the CA data are the data that were direct quenched,
25 not cooled and quenched, or slow cooled. Whereas, the

NEAL R. GROSS

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

1 Argonne data are all slow cooled, except for one, and
2 that's the red data point here, which was quenched.
3 And what we see is that there is some difference
4 between the data sets and the first thing we want to
5 look at is the pre-corrosion effect having any
6 problem, any effect here in influencing the offset
7 strain, so what we want to do is look at the actual
8 ECR value for the Argonne samples so we'll plot this
9 reprocess data. Now in terms of the actual transient
10 ECR - this is the ECR that was built up in the
11 specimen, not calculated by Cathcart-Pawel, but
12 actually determined from the metallographic image
13 analysis, which tells us more about the actual weight
14 gain that happened in the specimen, and the oxygen
15 build-up in the specimen. And we see here that the
16 data tended to shift from this region over here to the
17 left, or I'll call it to the right in a minute, but
18 the data are shifted to the right when you look at
19 Cathcart-Pawel, but when you compare it to the actual
20 -- using the actual ECR, there's a bit of a shift.
21 And you get a little bit better agreement with the CA
22 data.

23 Now I should note that the CA data did not
24 move, because the Cathcart-Pawel calculated values for
25 those samples and the actual samples are the same,

1 because they don't have any pre-corrosion, they don't
2 have any effect of the pre-corrosion on the oxidation
3 process.

4 Now lastly, let's look at another
5 difference between these two data sets as was pointed
6 out, is that we have the CA data are direct quench,
7 and these are slow cooled without quench, so let's
8 compare the Argonne H.B. Robinson results to the most
9 recent results that we just saw a few minutes ago. I
10 put this slide together last night that compares all
11 these different types of tests that CA has run with
12 direct quench, slow cooling, different ring test
13 temperatures, slow cooling plus quench, and then just
14 slow cooling, so we have a variety of different ring
15 test test temperatures, and a variety of cooling
16 rates. And the most representative samples or the
17 samples that most represent the Argonne test samples
18 are these diamonds here, which are only slow cooled,
19 and then ring compression test at 135 C, which is the
20 similar protocol as was -- uses the word "protocol"
21 from the last presentation, same protocol as the
22 Argonne specimens, which are slow cooled at 135 C ring
23 compression test. And you can see very good agreement
24 between these data sets here.

25 This point here is the one point that Mike

NEAL R. GROSS

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

1 said maybe could be a little higher because it was a
2 test that he stopped a little early, so this point
3 actually could go up a little bit, and then would even
4 probably be a better agreement in terms of the data
5 comparison there. And then we see that if we look at
6 the CA data a little bit more closely, if we add a
7 quench, which would be the slow cooling here, plus
8 quench at 135 C, that's these plus or Xs, X symbols
9 here, and then we have the slow cooling plus quench of
10 room temperatures. It's a little bit lower down here.
11 I think that is a pink circle, I believe, if we look
12 closely. And then we have slow cooling at room
13 temperature, which are the blue diamonds here, so you
14 can see the effect of just testing the blue diamonds
15 which are without quench, but testing at room
16 temperature versus 135 C, you see an improvement, and
17 Jean-Paul pointed that out in his previous
18 presentation.

19 And then finally, we have the direct
20 quench samples, which are the samples that I was
21 showing in the previous slides, and those are shown
22 here, either the 135 C, or the open pink circles, or
23 the open pink triangles. I can't tell exactly which,
24 and then the direct quench of room temperature are the
25 solid pink triangles there. And these have all been

NEAL R. GROSS

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

1 plotted -- I should point out, very important point,
2 I should point out that the CA data are plotted as ECR
3 Cathcart-Pawel, but as I pointed out just a few
4 minutes ago, the ECR Cathcart-Pawel and the actual ECR
5 in the sample are the same for the CA data, so those
6 don't shift.

7 In terms of the Argonne data, these have
8 been plotted at the actual ECR space, determined from
9 metallographic or estimated, I should say, from the
10 metallographic image analysis that Mike at Argonne has
11 done. If we were to plot them in Cathcart-Pawel
12 space, they would actually move to the right by about
13 2 percent ECR, so all of these data points and blue
14 circles would move to the right about 2 percent ECR,
15 so instead of plotting at 5 and 5-1/2, these are
16 plotted more at 7 and 7-1/2. This would plot more at
17 about 10, and this would plot more at about 5, so they
18 would all be shifted, and you wouldn't see as quite a
19 good correlation between the slow cooled data sets,
20 the diamonds, and the circles, as you would in terms
21 of when you plot the data in terms of actual ECR, and
22 that's one point I'll bring up a little bit later.

23 Just to compare low deflection curves
24 between the two data sets, I've pulled together one of
25 the Argonne samples. The actual ECR is about 5

NEAL R. GROSS

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

1 percent, so this would be one of the Cathcart-Pawel
2 samples of about 7 percent ECR. Again, it's a ring
3 compression test at 135 C. We see the elastic
4 portion, the non-linear portion. Here's the offset
5 strain measurement, the fracture point. A similar
6 curve for one of the CA specimens, again the layered
7 portion. Unfortunately, I didn't have the ability to
8 change the scale on this, so the X scale, the
9 displacement scale in this sample goes out to 3
10 millimeters, whereas this one only goes to 1
11 millimeter, so can't do a direct comparison,
12 unfortunately. But they go up to almost the same
13 load. I should point out that the sample sizes aren't
14 quite the same, so the maximum loads may not be
15 exactly the same. You see a major load drop in this
16 sample very similar to this sample, and these both
17 showed rather low ductility.

18 All right. Kind of a summary then. The
19 ANL data exhibits more post-quench ductility than
20 other tests on prehydrided cladding material. That
21 would be both CA and the Czech Republic data. One
22 reason particularly with the Argonne samples is the
23 difference between the calculated ECR value and the
24 actual ECR value, and the effect of the protectiveness
25 that Mike referred to. That tends to shift the data

NEAL R. GROSS

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

1 to the right, if you will, to the more ductile region
2 by about 2 percent is that difference, maybe a little
3 bit less, 1.7, 1.8 percent.

4 Another effect is the effect of slow
5 cooling. The slow down without quench, that tends to
6 shift the data up, add more ductility coming from
7 primarily the impact of the beta layer on the micro
8 structure, and you saw a little bit about that from
9 Jean-Paul's presentation, some new data coming out
10 that says that you get some partitioning of the oxygen
11 and the hydrogen into localized regions, and the
12 depleted zones, and these depleted zones tend to have
13 a bit more ductility, or lower micro hardness at least
14 at this point we know, and allow the material to have
15 a bit more macroscopic ductility.

16 The direct quench or the material that's
17 quenched did not have a partitioning effect. ANL post
18 quench ductility data seems to show less impact of
19 hydrogen than some of the other data sets that are out
20 there. The example we selected is that you see a
21 pretty significant recovery of ductility going from
22 room temperature to 135 C in the post oxidation test,
23 which have not been really observed in the CA quench
24 test. As I've showed, the direct quench test, or even
25 the direct quench with cooled, there's not a big

NEAL R. GROSS

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

1 difference between the room temperature and the 135
2 degree C specimens. This more than likely is related
3 to the ductility recovery coming from the cooling rate
4 effects.

5 MR. SHACK: Rob, did you mention what the
6 cooling rate was in the Hungarian tests?

7 MR. MONTGOMERY: No, I did not. I
8 apologize. I don't know the real details of their
9 test. We're working to try to get some of that
10 information.

11 MR. SHACK: That's the same with the Czech
12 test then, too.

13 MR. MONTGOMERY: That's right. Just a
14 brief summary of kind of the differences between the
15 methodologies, the protocol between the two labs,
16 where the most current data is coming from. First is
17 the temperature ramp up to the target temperature. As
18 we've seen today, ANL has a fast initial ramp, and
19 then a slowdown where they go to about 1 to 2 degrees
20 C per second, to the final oxidation temperature.
21 This tends to accumulate some corrosion, I'm sorry,
22 some oxidation at temperatures below the target
23 temperature for the test specimens.

24 In addition, Mike talked about this a
25 little bit, is that the outer surface corrosion layer,

1 the pre-existing corrosion layer on there, also tends
2 to delay the sample heat-up a little bit. You saw
3 that, and that, again, forces more oxidation to occur
4 below the target temperature, and delays the time it
5 takes to reach the target temperature. That's this
6 bullet here. Whereas, the CA data tends to have a
7 more direct ramp to the temperature without an over-
8 shoot, so they get to their target temperature quite
9 a bit sooner and quicker, and that means most of the
10 oxidation or a higher fraction of the oxidation
11 process is at the target temperature.

12 What's important about that is that the
13 diffusion kinetics, the oxygen diffusion kinetic
14 parameters are strongly temperature-dependent, and
15 could be influenced by the fact that the diffusion
16 process either occurring at a lower temperature over
17 a longer period of time in these samples than in the
18 other samples.

19 We also have seen today that the cool down
20 from oxidation temperature, there's quite a bit of
21 difference between the different labs. Argonne tends
22 to furnace cool their irradiated specimens at this
23 point. CA mostly quenches directly from the oxidation
24 temperature, but newer data they're working, they've
25 looked at the effect of slow cooling and then quench,

NEAL R. GROSS

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

1 or just slow cooling.

2 What we've learned so far and what we've
3 seen is that quench may be impacting the prior beta
4 phase morphology, either the hydrogen content in that
5 phase or the partitioning, or how the hydrogen and
6 oxygen are distributed. That, again, is influencing
7 the results.

8 One point that really didn't get brought
9 up today, I have it on this slide and the next slide,
10 is that Argonne is primarily using double-sided
11 oxidation tests. Their initial attempt at running a
12 single-sided oxidation test had some problems that
13 needed to be resolved. They had some end-effect
14 problems, and primarily the biggest one is they lost
15 hydrogen in the flowing gas. Whereas, CA primarily
16 uses single-side oxidation tests, with a few tests
17 that they've conducted with two-sided oxidation.

18 What we did see, though, which was
19 interesting in the Argonne test, was that when the
20 single-sided tests were loaded, they still cracked at
21 the ID, and they still cracked at the top and the
22 bottom, or the 12 and 6 o'clock positions; whereas,
23 the one-sided oxidation just said that all the
24 embrittlement would have been on the outside of the
25 specimen, and the specimen should have cracked at the

NEAL R. GROSS

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

1 3 and 6 degree position, so that's 3 o'clock and 6
2 o'clock position, or 90 and 270. I'm going to be in
3 degrees.

4 CHAIRMAN POWERS: Let me ask you a
5 question, and this is not considered a fair question.
6 Okay? But you know about these things, and so I'll
7 ask you. You know, when we run the abacus
8 calculations on any kind of structure, and then
9 compare that to a test, sometimes the code calculates
10 it'll break at a different place than is actually
11 observed in a test. But oftentimes, the difference
12 between those is delta pressure, or whatever thing
13 like that it is. I mean, if it hadn't broken where it
14 actually did because of some flaw or something like
15 that, it would have broken at the predicted location
16 within a little bit. Is that the case here? I mean,
17 they observed a 6 and 12 o'clock break, but if they
18 had not, it would have broken at the, what is that, 3
19 and 9 --

20 MR. MONTGOMERY: Yes.

21 CHAIRMAN POWERS: With delta displacement
22 --

23 MR. MONTGOMERY: Yes. In fact, Joe
24 pointed out a little bit earlier, you do have the
25 highest stresses at the top and bottom. That's where

NEAL R. GROSS

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

1 you get discontinuities because of the loading platen,
2 the shape of the loading platens.

3 CHAIRMAN POWERS: Right. Right.

4 MR. MONTGOMERY: The next highest place
5 where the highest stresses are at the 3 o'clock and
6 the 9 o'clock position. Those are the next highest
7 locations if you look at your abacus calculation. But
8 the stresses are highest at the OD; whereas, they're
9 a bit compressive, or less high at the ID.

10 CHAIRMAN POWERS: Yes.

11 MR. MONTGOMERY: Whereas, at the 12 and 6
12 o'clock positions, the high stresses are on the ID.
13 The question here we have is that that ID material in
14 the Argonne test should have been fairly robust
15 because it didn't have much oxidation. It should have
16 been primarily beta material, and all of the oxidation
17 was from the outside, so the alpha layer and the oxide
18 thickness were all on the outside, so that's the
19 question.

20 In the CA program, they tend to see that
21 on one-sided tests they get cracks starting from the
22 OD, because that's where the most embrittled material
23 is. And then when they have two-sided oxidation, they
24 get the crack starting on the ID, which is where the
25 most brittle material is.

1 Our question is, when we look at these
2 data - and I'll come to a slide on that - is there
3 something inherent in irradiated material that should
4 cause crack initiation on the ID, even though that's
5 not where the ECR parameter is that we're looking at,
6 is the largest? That's kind of a question; or is that
7 a test artifact, or the way they're loading the
8 specimens?

9 DR. BILLONE: I sort of put those results
10 aside because we lost hydrogen, but you're ignoring
11 the fact that you started out with a 10 micron fuel
12 cladding bond layer and it disappeared, so where did
13 the oxygen go? It went into the metal, so you do have
14 some embrittlement at the ID, not from the steam, in
15 those tests. But I don't like those test results, so
16 I'm not trying to justify them. You do see cracks at
17 -- let me get this right now - the 3 and 9 o'clock
18 position. You see that kind of cracking on as-
19 irradiated cladding coming out of a pool where you
20 have the brittle hydride rim, and you have the brittle
21 oxide rim. And that's where we definitely see it, and
22 whatever we saw in the one-sided test, I really would
23 like to complete the test of the long fuel sample
24 where you have an oxygen source from the fuel, the
25 fuel cladding bond. That still may break at the ID.

NEAL R. GROSS

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

1 I don't know, but at least it's a valid test.

2 MR. MONTGOMERY: Right. Yeah, I think
3 that's what our point is, too, is that we need some
4 more data to evaluate if the ID cracking that was seen
5 in your first run, the one-sided oxidation test is a
6 valid assessment or not. I think that's the point.
7 Should we just ignore that data totally and wait for
8 you to do more tests?

9 DR. BILLONE: Yes.

10 MR. MONTGOMERY: Okay. So we won't have
11 to talk about this point then. We've basically hit
12 this point on this slide, but it's our opinion that
13 there still needs to be areas of research that are
14 remaining to be explored, and I've kind of listed some
15 of those here. We really need to understand a bit
16 better the impact of cooling rate and quench
17 temperature on the embrittlement process, both from
18 the fact that we now have seen it, that it can
19 influence the results, and the second point is, we
20 need to identify what we're doing in the labs, how
21 relevant that is to what the actual LOCA events are.

22 One point that Mike just went over rather
23 quickly, he's noted it, but in other test programs
24 they have not seen that effect, and that is the
25 hydrogen redistribution that does not occur greater

NEAL R. GROSS

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

1 than 1000 degrees C. Argonne observed that, but in
2 other labs they have not seen that. They typically do
3 see hydrogen redistribution going on, so the question
4 is, is that, again, some artifact in their test
5 program, or is that real, and how do we understand it?

6 I won't talk about the ID alpha layer and
7 the one -- we just talked about that. And then
8 finally, this effect of pre-transient corrosion layer
9 on oxidation kinetics, that needs to be resolved. We
10 need to talk about how to -- need to decide how to
11 differentiate between Cathcart-Pawel value and the
12 actually measured value, which one should be used in
13 defining, evaluating the data and then using the data
14 later on in terms of criteria development.

15 CHAIRMAN POWERS: Let me ask a question
16 about your redistribution results, or it's really just
17 a question about diffusion. I just don't know how to
18 do diffusion calculations in this circumstance.
19 You've got two things diffusing around you. You've
20 got oxygen and hydrogen, and I assume they're both
21 interstitial. Is that true?

22 DR. BILLONE: The oxygen solution, the
23 hydrogen solution.

24 CHAIRMAN POWERS: Yes, interstitially.

25 DR. BILLONE: They're supposed to treat --

NEAL R. GROSS

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

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25

CHAIRMAN POWERS: So you can't -- so you have to be very careful when you do diffusion calculations here. You've got two things moving; therefore, the solute has to move, so you have a multi-component diffusion problem here. And so because one of the diffusants has a really high mobility, things can move contragradient? I mean, that happens in ordinary diffusion problems all the time, something has to move against the gradient. So this is --

DR. BILLONE: But I'm not sure Rob is -- you might be mixing apples and oranges. If CEA and JAERI did a good job of homogenizing the hydrogen, for example, in the axle direction of the circumferential erection, what they're seeing is movement across the radius, we agree with. We did such a crappy job in hydriding, we had huge concentration gradients, and they were pretty much frozen in the samples, so what I specifically was referring to is during the time of the test, there isn't much redistribution of hydrogen in the axial direction.

MR. MONTGOMERY: Or circumferential.

DR. BILLONE: And the circumferential.

MR. MONTGOMERY: Right.

NEAL R. GROSS

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

1 DR. BILLONE: Now that's because we
2 started with non-uniform distribution, we can make
3 that statement. To the extent that they started with
4 good stuff, which is homogenized, there is no
5 contradiction in the results, though.

6 MR. MONTGOMERY: Well, it's an issue that
7 needs to be raised, I think, or at least answered. We
8 need to answer it. You've seen --

9 DR. BILLONE: You said not consistent, and
10 I'm not sure that they looked -- they'd have to start
11 with the same samples we started with, and then take
12 hydrogen measurements.

13 MR. MONTGOMERY: Yes. Currently, they're
14 not consistent between the two data sets. And we just
15 need to answer --

16 DR. BILLONE: To me, they're not
17 inconsistent, because we're starting with different
18 samples. We started with very, very different
19 samples, and I thought they only looked for
20 redistribution across the radius. I thought that was
21 the primary point, that hydrogen very quickly -- if
22 you start with a hydride rim or something like that,
23 it very quickly --

24 MR. WAECKEL: I have a comment, just a
25 short comment. I think --

1 DR. BILLONE: Or did you do a bad job
2 hydriding it?

3 MR. WAECKEL: In both CA and JAERI tests,
4 they use some sample with hydride rims.

5 DR. BILLONE: Okay. But then all you can
6 look at --

7 MR. WAECKEL: And we got everything
8 homogenized very quickly.

9 DR. BILLONE: Across the radius.

10 MR. WAECKEL: Across the radius, yes.

11 DR. BILLONE: Yes, well that doesn't
12 contradict what we did. We didn't look across the
13 radius. We looked in the long direction. The radius
14 is .6 millimeters. We looked over the 25 millimeters
15 and over the 30 millimeters of the circumference.
16 There's a huge difference in length of diffusion
17 pattern, so that's why I don't like --

18 MR. MONTGOMERY: Yeah, but I can't speak
19 too much to the CA data, because I haven't seen it all
20 yet, but I can speak to the JAERI data, and they see
21 the redistribution happening in a second or two. And
22 you're up at oxidation times of 3000 seconds or 2000
23 seconds, or even 1800 seconds, so you're much longer
24 time, so you allow for some diffusion to go on. So
25 that's what I'm --

1 DR. BILLONE: We're more like 1200 degrees
2 C, we're more like 60 seconds to 150 seconds or
3 something like that for the prehydrided stuff. Those
4 were low ECR samples.

5 MR. MONTGOMERY: Right. But you've seen
6 this even in higher ECR samples.

7 DR. BILLONE: But JAERI has also seen it
8 in high ECR samples in their secondary hydriding
9 peaks.

10 MR. MONTGOMERY: You see the peaks, right.

11 DR. BILLONE: So how could you possibly
12 sustain a huge --

13 MR. MONTGOMERY: Yeah, but that's a
14 different process. That's a hydrogen absorption
15 process from a gas on the inside of the fuel rod or
16 the cladding.

17 DR. BILLONE: But why didn't it diffuse?
18 Why didn't that --

19 MR. MONTGOMERY: It's being absorbed the
20 whole time that the diffusion process is going on.

21 DR. BILLONE: Okay. I don't see the
22 inconsistency.

23 MR. MONTGOMERY: Okay.

24 DR. BILLONE: They were totally different
25 studies with materials.

NEAL R. GROSS

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

1 MR. MONTGOMERY: My job today is just to
2 raise some questions.

3 DR. BILLONE: No, that's a specific
4 statement. There was no question there.

5 MR. MONTGOMERY: All right. Did we answer
6 your question, Dana?

7 CHAIRMAN POWERS: No, but it's
8 illuminating, nevertheless.

9 MR. MONTGOMERY: All right. One slide
10 here on the effect of the pre-transient corrosion.
11 There really isn't much data that indicates that the
12 pre-transient corrosion would remain protected for
13 fuel rods experiencing an actual LOCA event, that
14 includes the ballooning and burst process. JAERI has
15 presented some data that shows that the pre-transient
16 corrosion protectiveness is lost once you get any kind
17 of cladding deformations going on.

18 In addition, as we saw today, there are
19 some thoughts that the pre-transient corrosion
20 protectiveness is really more exacerbated by the slow
21 temperature ramp, and that if the temperature ramps
22 the pre-transient corrosion tends to add to the oxygen
23 absorption and diffusion process, and doesn't really
24 affect the -- or goes ahead and affects the ductility
25 the same way as if the material was not pre-corroded.

NEAL R. GROSS

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

1 CHAIRMAN POWERS: Let me make sure I
2 understand this. Now I'm operating a little bit from
3 memory here, but my memory is that the experiments
4 were done with a very rapid, very rapid heat-up to
5 like 800 degrees Centigrade, and then a slower kind of
6 ramp-up into the 1200 degree Centigrade region.

7 MR. MONTGOMERY: Which program?

8 CHAIRMAN POWERS: This is the Argonne
9 test.

10 MR. MONTGOMERY: Okay.

11 CHAIRMAN POWERS: And so that initial
12 heat-up to temperatures where the ballooning would
13 occur, it's very rapid. I mean, so you can't complain
14 about -- that can't be the slow one. It has to be the
15 post-ballooning heat-up.

16 MR. MONTGOMERY: Yes.

17 CHAIRMAN POWERS: And is that post-
18 ballooning heat-up slow relative to the heat-up that
19 the clad would experience in an accident?

20 DR. BILLONE: No, relative to other
21 experiments.

22 MR. MONTGOMERY: Yeah. You mean you're
23 talking about the Argonne test program.

24 CHAIRMAN POWERS: Yes. Yes.

25 MR. MONTGOMERY: The 1 to 2 degrees C per

NEAL R. GROSS

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

1 second, I think that's about what you're shooting at.
2 Right, Mike? You're shooting for 5, but you're
3 actually getting something like 1 or 2. It's a little
4 lower. Typical heat-up rates are on the order of
5 about 5 to 10 degrees C per second, depends on, again,
6 there are many LOCA events, LOCA scenarios out there.

7 CHAIRMAN POWERS: I understand that.

8 MR. MONTGOMERY: So we try to do an
9 evaluation, and 5 degrees C, somewhere between 5 and
10 10 degrees C would be a representative heat up rate.

11 CHAIRMAN POWERS: Your statement could be
12 entirely correct. I'm not sure it's a critique of the
13 experiment.

14 MR. MONTGOMERY: Yes, maybe I didn't word
15 it exactly correctly in terms of it's one factor that
16 is a --

17 CHAIRMAN POWERS: I mean, you could be
18 entirely correct. Yes, this affects the results we
19 see, but it seems to me that once I've gone through
20 the ballooning, not much happens prior to the
21 ballooning.

22 MR. MONTGOMERY: Right.

23 CHAIRMAN POWERS: And once I go through
24 that ballooning, then I want to be on a ramp that's
25 reasonable, if that ramp is important. If that ramp

NEAL R. GROSS

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

1 is not important, then I don't care. But if that
2 ramp, in fact, is influential, then I want to be on a
3 ramp that's -- I mean, I'm not sure I can tell the
4 difference between 2 and 5 degrees C per second. I
5 certainly don't want to be at 100. If that ramp ridge
6 is important, and from what Mike was saying in his
7 presentation, that ramp is important. You've got a
8 substantial amount of oxidation in that 800 to 1200
9 temperature regime.

10 DR. BILLONE: Well, like 1000 to 1200,
11 yes.

12 CHAIRMAN POWERS: A thousand to 1200,
13 okay.

14 MR. MONTGOMERY: Yeah. And some of his
15 sample is 100 percent of his oxidation occurred in
16 that period of time depending when ECR --

17 DR. BILLONE: It's still a more reasonable
18 rate than 20 degrees C per second or 50 degrees C per
19 second. And, Dana, there's still data that can be
20 used along with other data if you know what
21 mechanistically is going on. You get off the ECR into
22 embrittlement phenomenon.

23 MR. MONTGOMERY: That goes to the last
24 point here, is that the as-measured, the actual ECR
25 where we all it, as-measured is kind of a difficult

NEAL R. GROSS

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

1 term because I know in some tests it's difficult to
2 measure the ECR value, but using the actual ECR is
3 more representative of what's happened in the sample,
4 as opposed to the square root of time Cathcart-Pawel-
5 type parameter that was tried to use to normalize the
6 specimen. We think that, as I showed earlier, if we
7 try to compare two data sets from two different labs,
8 using the Cathcart-Pawel parameter works as long as
9 the Cathcart-Pawel parameter represents the actual
10 ECR. Once it does no longer represent the actual ECR,
11 but there's a deviation, then you can't use that
12 parameter. You can't use Cathcart-Pawel ECR to
13 prepare data sets. You have to use the actual
14 measured values.

15 DR. BILLONE: Or you can reword it and say
16 it's conservative to use the Cathcart-Pawel for
17 corroded cladding.

18 MR. MONTGOMERY: I don't think it's
19 conservative. I think it's non-conservative, to be
20 quite honest with you, but that's a personal opinion.
21 That may not represent everybody's opinion in this
22 room.

23 DR. MEYER: It depends whether you're
24 talking about for calculating the amount of oxidation,
25 or for calculating the embrittlement, because I think

1 we have concluded, and have confirm from Jean-Paul,
2 that we really are talking about the time required for
3 the oxygen to diffuse into the metal for the
4 embrittlement phenomenon. And in that case, we want
5 to use a time parameter, which we're doing indirectly
6 using Cathcart-Pawel. And we would not want to use
7 measured values for the embrittlement correlation.

8 MR. MONTGOMERY: Well, I deliberately
9 tried not to get into this subject, but maybe I'll
10 just leave it at that, because I believe -- our
11 position at this point, or at least my position at
12 this point is, is that in evaluating the data in terms
13 of defining ductile brittle transitions and things of
14 that nature, the actual ECR is a better parameter to
15 use than the Cathcart-Pawel, if there is a
16 protectiveness effect.

17 Since we didn't really go over an
18 embrittlement correlation, I won't go through these
19 slides. They're there. I'll just skip to the
20 conclusion slides. The pre-transient corrosion we've
21 seen today, been demonstrated pretty well that it does
22 have an impact, and does reduce residual ductility.
23 The real question remains is how much to the extent
24 does the pre-transient hydrogen content impact the
25 residual ductility. That's still a question mark.

NEAL R. GROSS

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

1 Comparison of the Argonne data to other
2 data sets raises many questions about the post-quench
3 ductility of irradiated material. We talked about
4 most of these, the effect of cooling rate and quench
5 temperature. That needs to be further evaluated with
6 prehydrided material or irradiated material.

7 Effect of pre-test corrosion layer - is it
8 protectiveness or not under all conditions? The
9 mechanisms for hydrogen embrittlement needs further
10 research. We've seen today that the hydrogen and
11 oxygen diffusion redistributions and the synergisms
12 between those two components have a very important
13 impact on the residual ductility.

14 The embrittlement correlation we didn't
15 really talk about, but if this is an approach that's
16 going to continue to be pursued, we clearly need more
17 data to really develop a model that incorporates all
18 the key factors that are influencing residual
19 ductility.

20 MR. CARUSO: Is this embrittlement
21 correlation part of this proposal?

22 DR. BILLONE: No, Ralph didn't make it
23 part of this proposal.

24 MR. CARUSO: Okay.

25 DR. BILLONE: It's our attempt to compare

1 data sets from different labs. It's an analytical
2 tool to take into account different heating rates and
3 different experiments, try to get at what's
4 fundamentally embrittling material, and get away from
5 ECR.

6 MR. CARUSO: So it doesn't form any part
7 of the --

8 DR. BILLONE: It's a correlation, not a
9 criteria, at this point.

10 DR. MEYER: Yes. Last winter we
11 considered using it directly and during the spring
12 changed our mind.

13 MR. CARUSO: So it doesn't form any part
14 of the technical basis for the rulemaking.

15 DR. MEYER: It forms part of the technical
16 basis, because it describes the understanding, and
17 it's only after we get a clear picture of the effect
18 of hydrogen on the solubility in the beta phase for
19 oxygen can we then go and use some simplistic-type
20 empirical correlation with a little more confidence.
21 And I think that's what we've tried to do.

22 MR. MONTGOMERY: So the last bullet here,
23 although we feel that Argonne has made a lot of good
24 progress, Odelli summarized a lot of their progress
25 made to-date, and they really have pushed the

NEAL R. GROSS

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

1 boundaries of our knowledge quite a bit forward, we
2 still believe that there's some work that needs to be
3 done, and that the technical basis at this point for
4 initiating the rulemaking process is not quite
5 complete, and we need more information. And
6 basically, the bottom line is that the results that
7 are coming out look very good, but we still need to
8 consider them to be preliminary at this point, and
9 that we need additional data to answer all these
10 questions that have been raised by all the good work
11 that they've done. I think that's it for me.

12 CHAIRMAN POWERS: Are there any questions
13 for Mr. Montgomery? I think you've been interrogated
14 enough.

15 MR. MONTGOMERY: Thank you for the time.

16 CHAIRMAN POWERS: One question I did have
17 for you. One of your slides mentioned Japanese
18 presented data on non-protectiveness of the oxide.
19 Can you elaborate just a little bit about that? Have
20 I seen these data, or can I see these data?

21 MR. MONTGOMERY: I believe you can.
22 They've fairly recently been published in the open
23 literature, and they found that cracking of the oxide,
24 once cracking of the outer surface corrosion layer
25 occurs, and this can occur by straining, that once

NEAL R. GROSS

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

1 that cracking occurs, protectiveness goes away, that
2 the oxygen can get into and get direct access to the
3 metal. And the oxidation rate begins to increase back
4 to the rate that you would expect for bare metal
5 material as opposed to pre-oxidized --

6 CHAIRMAN POWERS: Do you have a citation
7 for that?

8 MR. MONTGOMERY: I don't have it handy,
9 but I can get it for you.

10 CHAIRMAN POWERS: Yes, I appreciate that.
11 I'd just like to look at it. Okay. At this point on
12 my agenda, Bert, you're going to give us a
13 perspective. About time we got some perspective here,
14 right?

15 MR. DUNN: Thank you for letting me say a
16 few words. I promise this will be very short.

17 CHAIRMAN POWERS: It doesn't have to be
18 short, it has to be informative.

19 MR. DUNN: Well, I wanted to put forward
20 our opinion, Framatome's opinion, on the status, and
21 in particular, relative to the rulemaking that may or
22 may not proceed here in the future.

23 I am the lead contact between Framatome
24 and the Argonne program, and have been responsible for
25 facilitating some of the assistance that we've

NEAL R. GROSS

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

1 provided the Argonne program. I want to say that this
2 program has been open to us. We've had the
3 availability of working within it, through it. We've
4 been listened to, we've learned an awful lot,
5 particularly with Mike, and so that's been quite an
6 enjoyable opinion.

7 Now I'm going to show the next slide. All
8 I want you to look at now, because it's going to be
9 redundant, you'll see it a bit later, we're basically
10 in agreement with some of the stuff that EPRI and the
11 industry has come out. I may very well be speaking
12 for industry, as well as Framatome here; that the
13 initiation of rulemaking at this time is premature.
14 We want to understand the rule, not the rule - excuse
15 me - the data, and how it comes together. We want to
16 get the theories right. We want enough peer review so
17 that we know we're going in the right direction. We
18 don't want to be back here five years from now.

19 CHAIRMAN POWERS: Let me ask you this
20 question.

21 MR. DUNN: Okay. Do you want me to go
22 back?

23 CHAIRMAN POWERS: Yes, please, go back to
24 the other slide. I think we're confronting a dilemma
25 here. We're on a pathway to do something with 50.46.

NEAL R. GROSS

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

1 I'm not sure what exactly is going to happen there.

2 MR. DUNN: Are you talking about the other
3 rule?

4 CHAIRMAN POWERS: Yes. Your third bullet
5 is in the works, something is going to happen there.
6 But part of 50.46 includes these cladding criteria,
7 and we have a problem. I mean, it's just a continuous
8 problem. It's expensive for the industry, it's
9 expensive for the staff, and that is that that rule is
10 written probably inadvertently for Zircaloy and ZIRLO.

11 MR. DUNN: That's correct.

12 CHAIRMAN POWERS: Okay. So every time
13 anybody uses any slightly different clad, it doesn't
14 have to be very different, they have to come in for an
15 exemption.

16 MR. DUNN: I'm one of them.

17 CHAIRMAN POWERS: And so we have an
18 opportunity here, since the train is in motion here,
19 to go ahead and fix that, so you guys don't have to
20 get an exemption every time you turn around. And this
21 is every core load.

22 MR. DUNN: True.

23 CHAIRMAN POWERS: I mean, this is not I
24 get it once, and then I go away and forget about it.
25 It's every time you reload the core, you have to get

NEAL R. GROSS

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

1 an exemption.

2 MR. DUNN: Once you get the first one then
3 the --

4 CHAIRMAN POWERS: It's easier, yes, I
5 know, but still somebody has to process some
6 paperwork, and I am always told by the industry
7 processing a piece of paperwork is more expensive than
8 I'd like to think it would be.

9 Okay. It seems to me that the choices are
10 go ahead and live with it, make an interim change that
11 we may not be as comprehensive as we like, or wait and
12 make a change in five years or something like that.
13 And you're voting for making the change in five years.

14 MR. DUNN: I'm not sure I'm voting for
15 making the change in five years. I think I may be
16 voting for starting the change process in six months
17 to a year from now. We've thought about this, and as
18 a company, I'll speak for Framatome here, we've
19 decided that it's more important to be sure we capture
20 the right type of criteria and the right effect, as
21 best we can do it. We can never be perfect.

22 CHAIRMAN POWERS: Sure.

23 MR. DUNN: Than it is for Framatome to no
24 longer have to make its exception for the M5 material.
25 We didn't actually connect these two up. They kind of

NEAL R. GROSS

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

1 got connected up by happenstance and I think maybe
2 Ralph or Farouk can tell you how they got connected
3 up. We submitted a recommendation through NEI, I
4 think it was Working Group 2 that helped us submit it
5 two or three years ago, and gotten it on the docket to
6 try and change to Zircaloy-based alloys that were
7 approved by the staff. And we would have liked that
8 to have gone ahead. It got derailed a little bit
9 because of some internal workings in the staff, I
10 believe, or between the commissioners. But still, my
11 answer to you is, I'd rather do it right, and know
12 that it'll last a while, than to do it wrong and have
13 to come back to this.

14 CHAIRMAN POWERS: Let me ask you this
15 question then. When you say "do it right", are we
16 looking for a rule that accommodates M5, and maybe
17 E110, I don't know, but certainly accommodates M5, or
18 should we be looking for a rule that accommodates - I
19 don't know - M6, Zircaloy-10, whatever is coming down
20 the pike that I don't know anything about right now.

21 MR. DUNN: Well, that is of interest to
22 us, is to have the formulation be at a nature and
23 follow or suggest procedures for the establishment of
24 whatever the criteria might be. It could be
25 responsive. I think I would cut it at Zircaloy-based,

NEAL R. GROSS

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

1 Zirconium-based alloys. I'm not sure the -- I came up
2 with at lunch time --

3 CHAIRMAN POWERS: Silicon carbide
4 reinforced.

5 MR. DUNN: Silicon carbide clad we need to
6 worry about now, but the --

7 CHAIRMAN POWERS: It's very interesting
8 stuff.

9 MR. DUNN: It is very interesting. It's
10 a wonder how axial offset is going to live with that
11 stuff, but --

12 CHAIRMAN POWERS: If you've ever looked at
13 the mysteries of making silicon carbide, you would not
14 be so enthusiastic.

15 MR. DUNN: Actually, I think they're all
16 BMW people that are involved in that. Okay. Should
17 I go ahead?

18 DR. DENNING: Well, no. Let's follow that
19 just a little bit further, because I'm kind of curious
20 in terms of what your concern is about the future. I
21 mean, is it your concern that there will be a rule
22 that will turn out to be too restrictive later, that
23 you'll come in with some new clad material that isn't
24 going to pass the test?

25 MR. DUNN: Actually, I think it's both.

1 It could be that, or it could be --

2 DR. DENNING: And is it the other way?

3 MR. DUNN: It could be the other way, as
4 well.

5 DR. DENNING: Now what kind of benefit
6 could you see from a less restrictive -- I mean, if
7 you came up with something that's less restrictive
8 than what RES is kind of proposing here, what kind of
9 benefit would that provide to you? What kind of
10 advantage could you take with that in either a safety
11 domain, or an economic domain? I'm kind of missing
12 why this particular thing is of such a level of
13 concern to you.

14 MR. DUNN: Well, if it were -- actually,
15 what Ralph has proposed today on the surface looks
16 fairly decent in terms of its consequences to the
17 industry. Okay? When we came in this morning, we
18 were thinking that something unknown was going to be
19 coming out, and it was going to somehow relate to the
20 embrittlement correlation. And the details involved
21 in embrittlement correlation need to be established
22 and validated within the community of manufacturers,
23 if you will. And we need to look at whether that
24 correlation would be responsive to future alloys.
25 What could we expect to have happen; it goes away

NEAL R. GROSS

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

1 completely and is totally inappropriate when we come
2 in with a clotinary alloy or something like that.

3 The proposal that we heard today, we don't
4 know where the regulatory side of the organization is
5 going to go. If they were to go like that, my thought
6 is that that's probably going to be pretty good,
7 provided it works. It provides the protection that we
8 want to provide.

9 The other side of it is, I don't -- I
10 mean, five years ago I got called into the staff here
11 on the 1 percent niobium question, and literally
12 people were standing us up on our heads and shaking us
13 because of some inappropriate testing that had been
14 done in East Germany, the Bohmert issue. Okay? And
15 one of the reasons that we got called in is no one
16 understood why E110 and M5 were behaving differently.
17 We want to try and avoid that kind of a situation
18 developing, as well, because that's always bad for the
19 industry.

20 DR. DENNING: I understand, I think, where
21 you are.

22 MR. DUNN: Okay. So if I didn't say it,
23 I want the correlation to do the job of the
24 correlation, the criteria, the procedures we come up
25 with to do the job that they should do, because I

1 think that's the best thing for nuclear power and my
2 company.

3 To face that a little bit, when we
4 licensed our new alloy, we recognized the need to
5 qualify the criteria for the new alloy. Now we didn't
6 do that according to the ring compression test,
7 because at the time what we felt out of the literature
8 we looked at, and what we were familiar with, was that
9 surviving quench during an accident was the basis for
10 the criteria.

11 We still have arguments between Ralph and
12 not so much myself but one of my compatriots in the
13 company who likes to argue all the time about whether
14 ductility is the appropriate metric, or whether it's
15 necessary, or whether, in fact, the staff threw it
16 away in 1985 when they approved best estimate LOCA.
17 So those arguments still go around, but we did look at
18 each one of the five criteria. And we established a
19 reason why those criteria still apply to our alloy, so
20 being interested in this is not new to Framatome.

21 It's not new that we've participated in a
22 program. And I want to remind the committee that
23 industry has contributed a great deal to the program.
24 It's not our program. We haven't contributed the
25 majority to it, but we've contributed quite a bit.

NEAL R. GROSS

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

1 And in speaking of strictly the Argonne program and
2 the non-irradiated, we've gone through and worked out
3 a memorandum of understanding so that we could share
4 research. We've provided a substantial amount of M5
5 and Zircaloy cladding. We've shared test procedures
6 and information, and guidance with Argonne directly to
7 make sure that they knew what we were doing in other
8 locations in the world, and this is not just us, this
9 is EDF and CEA. It is primarily French, but it's been
10 there, so we've -- and some of the particulars there
11 are the first tests on prehydrated Zircaloy cladding,
12 which indicated that things got pretty brittle at 600
13 ppm hydrogen, sharing test procedures. And finally,
14 today you saw some information on cool down and
15 corrosion layer effects.

16 Now the cool down information actually was
17 provided informally about four or five months ago, but
18 it wasn't provided to the extent that you saw from
19 Jean-Paul today. And we've just now completed the
20 corrosion studies. So in the irradiated program,
21 we're working on a cooperative memo. We have worked
22 out and assisted in supplying the fuel cladding
23 samples for M5 to Argonne. The industry,
24 Westinghouse, has worked out supply de-fueled samples
25 of Zirlo. Our M5 samples will be at 63 megawatt days

NEAL R. GROSS

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

1 per metric ton. That's a fairly high exposure. It's
2 not up to 70 or something. We worked our supplying
3 and actually have now moved the rods into the spent
4 fuel canal in a special basket ready to be shipped.
5 At least two full-length rods, there may be little
6 parts of those rods that are going to be used in a hot
7 cell examination, but there'll be 70 megawatt day per
8 metric ton rods provided to Argonne, M5 for their
9 program. Those will contain fuel, and those will be
10 used in integral tests, and maybe in long section
11 single-sided oxidation tests.

12 We're going to continue the formal and
13 informal briefings between CEA, and EDF, and Argonne.
14 And we're working to try and keep the program, you
15 might say going, and on the best track we think we
16 can. So enough patting myself on the back. I just
17 wanted to be sure people knew we were there, or at
18 least remind you of what we were doing.

19 Going back to the first slide I showed, we
20 think it's premature. We think the cladding
21 embrittlement database is immature at this time. It
22 does have holes in it. It hasn't been cross-
23 connected, cross-tested enough from lab to lab, et
24 cetera. We haven't got as much cross-checking as we'd
25 like to do. Testing continues. We continue to be on

NEAL R. GROSS

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

1 a fairly steep learning curve with this one.

2 CHAIRMAN POWERS: That seems, for your
3 point earlier about cross-testing of specimens, that
4 seems to be a fairly crucial step in any kind of
5 mechanical properties testing, isn't it? I mean, it
6 seems we never understand anything, that we do one of
7 these round-robin tests. Is that roughly correct?

8 MR. DUNN: I'm not sure we understand it
9 after we do the round-robin tests. The ring expansion
10 program that tried to look at the Oak Ridge test,
11 which I happen to like a lot versus the gauge tests,
12 et cetera, I don't know what happened with that. It
13 just kind of did something, and then evaporated. I
14 think it leaves quite a bit, as well as we can do it,
15 it should be done, because then we -- you always are
16 going to learn something.

17 I know I'm not on your subject. I'm not
18 a metallurgist and stuff like that, so I get a little
19 difficult. We stepped into this one. My biggest
20 concern on getting rid of large break LOCA is that we
21 will lose the opportunity to learn something. By
22 doing large break LOCA for 35 years, we actually have
23 uncovered problems, and addressed them. Now it's been
24 an expensive way to do it, but we throw them away
25 completely, where will that discovery come from?

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 Okay? And that's one thing that happens with
2 processing.

3 In peer review we get discovery, as well.
4 Okay? And maybe peer review is more important when we
5 were talking about the correlation as a basis. Okay?
6 I still think that correlation needs to be peer
7 reviewed. I would love to have a good correlation on
8 embrittlement, because I really don't know that we
9 have it today.

10 Okay. Then you come down here to the
11 potential change in the rule. I had a note for myself
12 that I was supposed to say something earlier. Oh, one
13 example of something - we heard a lot about oxygen,
14 how important oxygen is, as it diffuses into the prior
15 beta region, or into the beta region at the time.
16 Anybody show us an oxygen map today? Did we see a
17 radial survey of what the oxygen content of a sample
18 was post transient? I don't remember one.

19 DR. BILLONE: I've got a calculated one
20 and I've got micro hardness. That's all --

21 MR. DUNN: We've got calculations, we've
22 got micro hardness. We haven't taken the step to go
23 do a micro probe where we can actually measure it, but
24 that could be done. I don't know. It would be nice
25 to have that. Okay.

1 We talked a little bit about heat uprate.
2 If, in fact, we make this transition, the important
3 zone for heat uprate is going to switch back to 1
4 degree C per second, or maybe even less than that, a
5 half a degree C per second, depends a little bit upon
6 how the transient goes. But in your small breaks,
7 your critical small break is going to heat up on
8 curves and be very slow. Now they're all on curves,
9 but with the small break you can almost come close to
10 reaching quasi-equilibrium sometimes against the boil-
11 off rate, and come on down. I'd like to make sure
12 we've got that type of an influence in our knowledge-
13 base, in our consideration-space before moving
14 forward.

15 Finally, some of the other reasons is when
16 we go forward with rulemaking, we're going to
17 establish plans, we're going to establish
18 expectations, we're going to establish schedules.
19 Okay? Even though we're going to continue to do
20 testing and understand this thing over the coming
21 year, I'm afraid those plans and schedules may put a
22 little artificial constraint, an artificial pressure
23 to come up with a set of criteria that just work. We
24 agreed earlier so I won't read that, but there's no
25 safety issue identified.

NEAL R. GROSS

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

1 It could very well be in terms of
2 something that would be easier, is the quench survival
3 would be appropriate, perhaps restrained quench
4 survival test, similar to what the Japanese are doing.
5 At least at Framatome, we're not convinced that the
6 ductility is the necessary metric.

7 CHAIRMAN POWERS: It seems to me when we
8 started the discussions this morning we hit this
9 general area going back to we don't really know how
10 the core responds to a reflood that you get from a
11 stress strain relationship sort of thing. Is that
12 what you're talking about there?

13 MR. DUNN: Well, yes. I mean, people say
14 that. I think if you were to take a look at the
15 reflooding test, for example, you can get some idea of
16 what some of the reflood-related phenomena were.
17 Perhaps, asking Larry Hochreitter to give us some
18 information from his current test rate, which is
19 sitting there and there's at least partially a bundle,
20 and can tell us some information. And then we go with
21 the current Japanese position, which was to -- I think
22 you looked at the grids and they put a restraint on it
23 that was enough to bend a grid or something on that
24 order, and so you would have some relief after you
25 pass that. And maybe that's what provides you with

NEAL R. GROSS

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

1 your margin to knowing what happens.

2 We, I think, do know a fair amount about
3 the process and how we'll proceed. In 1970 we hadn't
4 done very -- we'd only done the FLECHT test. We
5 hadn't done LOFT, we hadn't done a lot of these tests.
6 We've done a lot more. Whether that answers all the
7 questions, I guess I'm not prepared to tell you today,
8 but I do know one thing, is that the cladding survives
9 this easier than it does the ductility, so the
10 ductility does provide some margin. I would agree
11 with that, when that was said this morning.

12 CHAIRMAN POWERS: There's no question that
13 the ductility criteria was intended to bound.

14 MR. DUNN: Yes. Okay. So what am I
15 asking, and that's the bottom line. I'm just asking
16 that there be no rush to go into the rulemaking. And
17 I guess I'm talking not to Ralph now, and who's at the
18 table over there. I'm talking to the back row, and to
19 the subcommittee, because the subcommittee can
20 influence all sides of this question. We do think
21 that there should be some substantial more review
22 data, peer review available.

23 CHAIRMAN POWERS: Any questions to the
24 speaker?

25 MR. ELTAWILA: Can I make a clarification

NEAL R. GROSS

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

1 and ask Bert a question. I just want to be sure that
2 it's understood here that 10 CFR 50.46, Part A and
3 Part B, can proceed separately. They are not linked
4 together. So your discussion here talk about Part B
5 only, or you're also addressing the 50.46 changes in
6 general?

7 MR. DUNN: I brought the 50.46 changes up,
8 but I understand it's not going to be forced on
9 people, that it will go in as an option, so we may
10 still have plants for a number of years that are doing
11 large break LOCA with the old criteria. But again, we
12 have said that large break LOCA is so risk-insensitive
13 that we're willing to go license plants without it.
14 We should be able to say maybe those current criteria
15 are all right for that period of time.

16 MR. ELTAWILA: So to understand it myself,
17 so you are -- what you are asking for delay right now
18 is for the fuel criteria in 50.46, and not for the
19 break size definition in 50.46. Or you're asking for
20 both of them?

21 MR. DUNN: No, no. I am supportive of the
22 removal of large break LOCA from the design-basis. In
23 1978, I remember people saying - or in 1979, I
24 remember people saying that one of the reasons -- that
25 we thought large break LOCA bounded everything. Well,

NEAL R. GROSS

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

1 in '79, and I found out very personally, because I had
2 to testify on it quite a bit of time. I was in the
3 wrong place at the wrong time with a little bit of
4 information. We should have recognized that we did
5 not have a certain human aspect tied down well enough,
6 and we should have done something about it.

7 Now we had that information here, we had
8 that information -- well, I'll just -- I'm on my
9 soapbox now. I'm sorry. Large break LOCA doesn't
10 bound everything. We do that other one, and we can
11 concentrate on what will really happen.

12 CHAIRMAN POWERS: Any other points?
13 Thanks, Bert.

14 MR. DUNN: You're welcome.

15 CHAIRMAN POWERS: At this time, I'm going
16 to ask if Mr. Shadis from the New England Coalition
17 can make his comments.

18 MR. SHADIS: Thank you. Do you want me at
19 this microphone over here?

20 CHAIRMAN POWERS: Oh, why don't you come
21 up and sit up front. And we're going to put you in
22 the spotlight here.

23 MR. SHADIS: How is this from here? I
24 think people can hear me without --

25 CHAIRMAN POWERS: No, it's not us hearing

1 you, it's the keeper of the record that has to hear
2 you.

3 MR. SHADIS: Oh, thank you. First off, my
4 name is Raymond Shadis. I work for a group called the
5 New England Coalition. My job with them is to
6 identify and track safety and environmental issues at
7 New England's nine nuclear power stations, five
8 operating stations, four in decommissioning. And I
9 really appreciate the very focused, professional
10 presentations done today on all sides. It was totally
11 informative.

12 A couple of things - first, I heard both
13 NRC staff, the Chairman of this subcommittee, and
14 folks on the industry side say there is no safety
15 issue to be dealt with here. But if you read the
16 second slide in the first presentation from NRC staff,
17 we're talking about the goals in 50.46. And if the
18 goals are to maintain a coolable geometry, keep the
19 fuel pellets inside the cladding, don't let the
20 cladding fragment and so on, if those are the goals,
21 and there is a challenge to those goals, or if we're
22 not doing enough to make sure that those goals can be
23 met, then I take exception, there is a safety issue.
24 From the public point of view, we have been promised
25 over and over that there exists something called

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 defense-in-depth, that there are multiple fission
2 barriers, and I think one of those is the cladding.
3 We're talking now about the integrity of the cladding,
4 whether or not embrittlement of the cladding
5 automatically signifies failure in an accident. I
6 don't think so, but it could, and so from that
7 perspective, we see it as a safety issue.

8 I was very glad to hear Framatome say that
9 they were going to be providing some samples taken
10 from a reactor to be examined by Argonne. We were a
11 little taken aback that before that presentation all
12 that we heard about that was that there were samples
13 taken from Robinson. And really, for what it's worth,
14 layman's point of view, the issue is not fresh
15 samples, or samples that have been irradiated, it is
16 samples that are taken from a reactor environment.

17 You have your one, two, three phenomenon
18 that you're considering, irradiation, the presence of
19 oxygen, the presence of hydrogen, but I'd offer that
20 in the reactor environment there are other phenomenon
21 that may predispose the fuel to embrittlement, and may
22 predispose the fuel to fail under the effects of
23 embrittlement. And just the only few things that came
24 to mind, and they may be such small contributors as to
25 be negligible when they're squared off against these

NEAL R. GROSS

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

1 big three phenomenon. But if they are, then I think
2 in your deliberations or somewhere it ought to be
3 stated that they are negligible, just to give a little
4 comfort to the laity.

5 I look at, for example, water chemistry,
6 Noble metals treatment or hydrogen treatment, pH
7 content, cooling water, not all of it is completely
8 demineralized, maybe copper content. If you're
9 looking at incipient cracking, microfissures, the
10 stress corrosion cracking, intergranular stress
11 corrosion cracking as it begins as a setup, as a nodal
12 point for fuel to fail. You're only testing and
13 examining what are they, 8 millimeter or so, segments
14 of fuel, then you're not really dealing with the
15 mechanics of fuel being stressed over time, not a 12-
16 foot segment, whatever that is in meters, two and a
17 half meters, whatever it is. Fine.

18 There are questions of low-end thermal
19 cycling for the fuel. I would presume that if you
20 heat the fuel up to 1200 degrees Centigrade that you
21 will, in effect, anneal it, remove all those stresses,
22 but I think it may be important to examine whether or
23 not there are some residual effects, whether or not
24 you're starting with a fuel that is bowed, or bent, or
25 deformed in some other way. So I'd ask you to, in

NEAL R. GROSS

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

1 your consideration of this, to just reach back and
2 take in some of those what may be minor phenomenon.
3 And that's all I have to offer. I really -- once
4 again, I totally appreciate the focused comments that
5 we heard today. Questions?

6 CHAIRMAN POWERS: A couple. First of all,
7 I appreciate your comments here. I want to come back
8 to your first comments on the goals that have been set
9 down, which include maintain coolability and assure
10 the fuel doesn't -- are you comfortable with those as
11 being goals? Does that look like the adequate
12 description of this element of defense-in-depth,
13 recognize the clad is an element of our defense-in-
14 depth?

15 MR. SHADIS: I think under the specific
16 criteria that are referenced, sure. It's a reasonable
17 articulation.

18 CHAIRMAN POWERS: Okay.

19 MR. SHADIS: May I just mention, also, in
20 terms of real-life plant experience, that we're now
21 dealing with a lot of plants that have gone for
22 extended power uprate, including one in my territory.
23 And the record so far is not perfect by any means.
24 There are problems surfacing in particular with flow
25 induced vibration, so where fuel can be predisposed to

NEAL R. GROSS

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

1 fail or other reactor internals predisposed to fail,
2 it becomes all the more important to make sure that
3 that cladding integrity is preserved. I just offer
4 you that.

5 CHAIRMAN POWERS: And there really are
6 lots of chemical phenomenon on surfaces that I
7 certainly don't understand. You mentioned noble
8 metals also, boric acid deposition, things like that.
9 That's a good point.

10 MR. SHADIS: Yes. Well, when you're
11 dealing with little segments --

12 CHAIRMAN POWERS: Well, we don't have much
13 choice but to deal with --

14 MR. SHADIS: Oh, I understand that, but
15 you have a certain symmetry that is there, and that
16 affects the way that you measure. But corrosion, and
17 I have a phenomenon with control elements called
18 shadow corrosion. Corrosion doesn't always fall
19 uniformly on the fuel either, I would guess, or the
20 accumulation of crud or whatever other kinds of
21 phenomenon may play on the way that heat is
22 distributed through fuel or stresses. Somehow those
23 are -- just on first glance, they don't appear to be
24 addressed in this narrowly focused discussion, and I'm
25 suggesting they should be.

NEAL R. GROSS

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

1 CHAIRMAN POWERS: You've got more
2 comprehensive -- right now you're seeing a work in
3 progress, and I assume that with more comprehensive
4 documentation, lots of things would flow in the
5 description and cover things more completely. And
6 you've certainly given us a nice list of things to
7 make sure they cover.

8 MR. SHADIS: And I would qualify this,
9 too. And again, on a layman's perception, in reading
10 the list for the modifications for 50.46, it does not
11 appear that there are any great show-stoppers there.
12 There doesn't seem to be, in reading them, that
13 there's any reason that that rulemaking could not go
14 forward and still have the exploratory process for
15 improvement go on. That's the best I can tell you.

16 CHAIRMAN POWERS: Any other questions for
17 the speaker?

18 MR. SHADIS: I'm good at doubling recipes.

19 MR. OZER: I have a question, Mr.
20 Chairman.

21 CHAIRMAN POWERS: Sure.

22 MR. OZER: Odelli Ozer, EPRI. I was
23 surprised by your discarding the Robinson data in
24 favor of the other material that we'll be getting.
25 You must realize that this is 12 rods that were

1 exposed in a reactor to rather high exposures, well
2 beyond the currently licensed limit. So they did
3 experience boron cycling, whatever, and just because
4 we consider that they were limiting, they were exposed
5 to this very high exposure.

6 Similarly, the Limerick rods were from the
7 Limerick reactor. Again, they were exposed to the
8 limits, currently licensed limit, and they're a part
9 of our characterization program that we're holding for
10 normal in-reactor operation, and some of these rods
11 were also made available for LOCA testing. So why are
12 you unhappy with the --

13 MR. SHADIS: I'm not unhappy with it.
14 It's my fault, and I'm sorry that I was unclear about
15 it. And I neglected to mention the Limerick donation
16 also. What I was saying was up to the point that we
17 heard that Framatome was coming in with yet more rods
18 to be examined that came from a reactor. I thought it
19 was a very limited sample, nothing wrong with the
20 sample, probably a wonderful sample, and it may
21 actually, if miracles happen, it might actually be
22 representative of all the plants. But when you take
23 a look at the operating experience of the different
24 plants, the different physical characteristics of
25 these plants, my take on it, and again a layman's

NEAL R. GROSS

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

1 take, was that a larger sample would be worthwhile.

2 MR. OZER: Your reference then was just to
3 the M5 samples that were received up to now by ANL.
4 Is that correct?

5 MR. SHADIS: Well, yes. What I was saying
6 was that's a welcome addition, and the larger the
7 sample that you take from operating reactors with all
8 the variations, all the inputs varied, the better.
9 That was my comment on that. I'm sorry I wasn't clear
10 about it. Does that answer your question?

11 MR. OZER: Thank you.

12 MR. SHADIS: Thank you.

13 CHAIRMAN POWERS: Thank you very much.

14 MR. SHADIS: Thank you, sir.

15 CHAIRMAN POWERS: At this point, Ralph you
16 and I suppose Farouk are on the hook to offer any
17 responses that you have.

18 MR. ELTAWILA: Yes. I would like to make
19 some comment, Mr. Chairman. I don't have a prepared
20 speech or anything, so I might go all over the place,
21 but I hope you bear with me. But before I start, I
22 really want to thank all the presenters. They have
23 done a fantastic job, and the presentation was very
24 clear and very informative.

25 CHAIRMAN POWERS: You need to come to our

NEAL R. GROSS

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

1 fuel subcommittee meetings. This is the standard.

2 MR. ELTAWILA: Absolutely. You were
3 speaking of the standard. It's very hard --

4 CHAIRMAN POWERS: It has nothing to do
5 with the membership of the committee. It has to do
6 with the participants, and the man to your right, and
7 the woman to your left are largely responsible for
8 this high technical level.

9 MR. ELTAWILA: Absolutely. And they are
10 congratulated for the working they are doing. At the
11 beginning, I mentioned this is a cooperative program
12 and we are going to hear some difference in
13 interpretation. I don't know if it's me only, but I
14 really got the feeling that until Bert Dunn started
15 speaking, that the industry is distancing itself from
16 the Argonne program as if they have not participated
17 in that program. And that came as a surprise to me.
18 The Argonne program is not a matter of interpretation
19 of the data, it's criticizing the underlying of the
20 whole test program. And that came as a surprise to
21 me, so I really hope that the industry -- I think I
22 appreciate Bert at the end say that we were involved.
23 There was a tech committee. That was a lot of
24 interaction with the industry about the formulation of
25 the tests, so there were ample opportunity to express

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 their views about some of these tests, and at any time
2 if there was a need to change direction, that would
3 have been done, but at this stage, raising substantial
4 issue that's going to cost us millions and millions of
5 dollars, I find myself, that's expressing my opinion,
6 we're going to finish our program if the industry
7 wants to pursue additional tests, provide data to
8 support the rulemaking - that will be their
9 prerogative to do that. But we feel that we have
10 enough data to support a rulemaking.

11 The other things that I'm surprised at,
12 they are coming here saying we don't want to see a
13 rulemaking. We don't know even what's the rulemaking
14 going to read. An example, a rulemaking can be say,
15 maintain coolability by maintaining the temperature at
16 2400 degree and oxidation calculated by Cathcart-
17 Pawel, and then provide a sample, as an example of
18 doing that see Reg Guide. A Reg Guide can have a
19 specific issue.

20 As an example, the industry can always
21 come back and say we are going to have our own
22 justification for different bases for a performance-
23 based regulation. But right now, the rationale for
24 saying do no go with the rulemaking because there are
25 not sufficient data, I wonder who is going to produce

NEAL R. GROSS

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

1 the data? I don't think it's going to be NRC, because
2 we have a program. If there is a fatal flaw in this
3 program, I would like to know about it. But at this
4 stage, we have enough work that we are ready to
5 proceed, and I think we have to let the rulemaking
6 process identify -- you know, you issue it, you look
7 at the language and see if the language is going to
8 provide the assurance that we want, the safety of the
9 nuclear power plants. I think I'll stop at that and
10 see if Ralph wants to --

11 DR. MEYER: Thank you. I had just four
12 more specific comments than that, that I wanted to
13 make. And the first is to acknowledge that this was
14 the first time that we've spoken in public and to the
15 industry about the specific direction for the proposed
16 criteria, so there was an element of surprise that I
17 acknowledge here. And I was pleased to see that
18 Odelli pointed out that some of the criticism that was
19 contained in the slides was based on an assumption of
20 a different direction that we might have taken. And
21 the assumption wasn't a bad assumption, because we had
22 six months ago talked about the correlation at some
23 length, as if we might adopt it. But those
24 discussions subsequently took place internally, and we
25 brought them here for their first public outing, so I

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 wanted to acknowledge that.

2 Now I wanted to make a couple of other
3 points. In another one of the comments on Odelli
4 Ozer's slide was a lament about the integral test with
5 the Robinson rod not having been performed yet. They
6 will be performed very soon, but I would like to point
7 out that the integral test will not produce, nor
8 directly affect the embrittlement criteria themselves,
9 because they come from a mechanical test. They
10 certainly will have an impact on supporting
11 information and other discussions that take place
12 should we go forward with the rulemaking, but the
13 absence of those tests do not handicap our efforts, at
14 the moment, to try and formulate embrittlement
15 criteria.

16 The third comment that I would like to
17 make has to do with prehydrated material. It's
18 obvious that there's considerable value to taking
19 unirradiated cladding, charging it with hydrogen, and
20 then testing it as if it were a substitute for the
21 real irradiated thing. And we're doing some of that
22 ourselves, we're doing it primarily to calibrate test
23 plans for tests on the real irradiated cladding.

24 We have had discussions with the industry
25 in public meetings about the desirability of trying to

1 validate some prehydrided surrogate for irradiated
2 material, such that in the future one wouldn't have to
3 go to hot cell with expensive programs to make some
4 tests of this sort. And I simply want to emphasize
5 that such a validation has not taken place, may take
6 place in the future, but it requires testing on
7 irradiated fuel rods in comparison with prehydrided
8 rods to show that the equivalence or similarity is
9 there. So I just want to sort of blunt any thinking
10 that might jump too quickly to the use of prehydrided
11 unirradiated cladding, as if it were irradiated fuel
12 cladding.

13 And finally, the fourth comment that I
14 want to make is - and I won't belabor this point, but
15 it's about Bert's comment about the quench survival
16 versus ductility, which is the true basis for the
17 regulation. And we have, indeed, had many interesting
18 and friendly discussions about this subject. And I
19 simply, for the record, would mention a letter from
20 Farouk Eltawila to Rosa Yang dated February 25, 2004,
21 that discusses this subject, and records our opinion
22 that the basis remains ductility. It doesn't mean we
23 couldn't change it, but such a change would, indeed,
24 be a fairly radical change from the current rule and
25 its basis. And we have, as I said before, have

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 attempted to make the course correction as gentle as
2 possible. Thank you.

3 CHAIRMAN POWERS: Thanks, Ralph. Rosa.

4 MS. YANG: Is it okay I respond to some of

5 --

6 CHAIRMAN POWERS: Rosa, go ahead.

7 MS. YANG: Okay.

8 CHAIRMAN POWERS: Just pull up a chair and
9 sit down, Rosa.

10 MS. YANG: Okay. All right. This is Rosa
11 Yang from EPRI. First, I'd like to respond to
12 Farouk's surprise about our presentation. I think
13 just like Bert said, and I think in Odelli's
14 presentation, Robbie's presentation, we're part of the
15 program, and we strongly supported the program from
16 the beginning until now. I think as you said, and
17 many of us said, that the interpretation is different.
18 We have different interpretation. I think it is
19 understandable that the reason we've come up with the
20 presentation we have, because as recently as two
21 months ago, we were all meeting in Argonne looking at
22 the program results, and we were very excited about
23 the results. That's probably one of our best
24 meetings. I couldn't say best, better meetings. It
25 was just really insightful, and on one hand you're

NEAL R. GROSS

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

1 very excited about results, on the other you recognize
2 you're on a very steep learning curve, because the
3 results are so different from different labs. And
4 that's not a criticism. I think that's a normal
5 process of any scientific research. And I think it's
6 important we recognize that. And maybe even more --
7 maybe that's why we were misled or whatever, is the
8 embrittlement correlation, which was part of the
9 handout I see, but Mike did not address. That
10 particular correlation was discussed in great detail.

11 In fact, we went ahead and mapped out the
12 plan on how to implement that correlation, with all
13 due respect. I'm sorry, but we had -- and since that
14 meeting, we have followed through with experiments in
15 CEA trying to understand it. And I think the
16 presentation that Jean-Paul Mardon did, a lot of it
17 are very, very recent results, really trying to
18 understand the differences. And I think, Farouk, I'd
19 like you to see that as our very, very positive
20 contribution. And that's what -- I guess, I feel a
21 little bit wronged, and we're doing our best trying to
22 understand it. So we are an active member, and we're
23 very proud of Argonne achievement.

24 And I also want to say, many of us in this
25 room have write very, very strong letter that

1 contribute to Mike's being the award winning
2 metallurgist and scientist. I want to go on record
3 for that.

4 So having said that, that's maybe kind of
5 where we are coming from. So, indeed, we're a little
6 bit surprised by what Ralph presented this morning.
7 I would say pleasantly surprised, but I just want to
8 add my own personal opinion. I don't quite see how
9 that's performance-based, but I'll learn that later.

10 CHAIRMAN POWERS: You're not the first to
11 struggle with what is and is not performance-based.

12 MS. YANG: Okay. But overall, I want to
13 say why --

14 MR. ELTAWILA: It will be performance --
15 Rosa, it would be performance-based if provided as an
16 example, but not as a requirement. As I indicated,
17 you can have a general criteria, maintain coolability
18 by such and such, and such, and you provide example in
19 the Reg Guide. And always, you can have the option,
20 technology change, new information comes, you update
21 the Reg Guide rather than the regulation itself.

22 MS. YANG: Okay.

23 MR. ELTAWILA: That's an approach that you
24 can go.

25 MS. YANG: Let me just finish with one

NEAL R. GROSS

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

1 thing about the if we are ready or not. I think there
2 are a lot of data being presented, but it's clear to
3 see their inconsistencies. And I forgot, either Dana
4 or Bill said very eloquently, none of these tests are
5 the real test, but we need to figure out, we don't
6 want any of the artifact to bias what we're trying to
7 protect, so there is -- I think it's premature. I
8 mean, the whole embrittlement criteria is not a linear
9 relationship, and it's wonderful to use an empiric,
10 something simple and empirical, but until we
11 understand it, I just don't see how we can be ready.
12 And I'm even more puzzled when Ralph said we're going
13 to continue to look at the empirical embrittlement
14 correlation, and that would kind of form the basis for
15 the rulemaking criteria. That suggests to me that
16 there's some work to do. Thank you.

17 CHAIRMAN POWERS: Any further comments?
18 Then I'll turn to the committee. Now -- oh, I'm
19 sorry.

20 DR. BILLONE: My comment was really going
21 to be I'm hungry, so I'd rather turn it over --

22 CHAIRMAN POWERS: You're hungry. At this
23 point, I turn to the members of the committee. What
24 were, as I understand, what the RES wants feedback on
25 is what is expressed on pages 28 and 29 in the slides

NEAL R. GROSS

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

1 Dr. Meyer used at the opening, which he presented some
2 possible criteria. It's challenging, I know, to
3 separate the technical information from the criteria,
4 but I think in the end we're going to have to write a
5 letter that addresses those criteria, so to the extent
6 that you can address those in your comments, I would
7 appreciate your doing so. And I'll begin with you,
8 Mr. Denning. Professor Denning.

9 DR. DENNING: Since I'm the least
10 experienced here.

11 CHAIRMAN POWERS: No, I didn't say that.
12 I said the shortest tenure on the committee, not the
13 least experienced.

14 DR. DENNING: Well, in this area I
15 certainly am, but based upon what I've heard today,
16 certainly there is the normal amount of ambivalence
17 that we seem to often have here, in that the question
18 of are we ready to go forward, I think in one respect
19 it's clear that we are, and that is that we're
20 operating plants, and we've been operating for quite
21 a period of time with a great deal of confidence that
22 they're being operated safely under criteria that are
23 pretty similar to those that RES is talking about
24 here.

25 With regards to is there really adequate

NEAL R. GROSS

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

1 technical basis for the three general criteria there,
2 I did have some concern based upon what I heard today,
3 as to whether this time-related criterion has been
4 fully supported by the experimental work that is going
5 on, and is still going on.

6 And then let me raise just one other
7 issue, and that is the question of whether we should
8 go forward with part of 50.46 and not with all of it
9 together. And I do see some relationship here between
10 the two. I haven't given much thought to that, and
11 it's apparent that the NRC has decided that one can go
12 forward with the two independently, but there
13 certainly is some overlap between the two, and it does
14 seem rather strange to me that we would go forward on
15 part of it, and not the other, when there is as much
16 close relationship as there is. So I guess that I
17 think that certainly we need a lot of discussion
18 before the ACRS is going to be ready to support the
19 RES proposal here, particularly in light of the fact
20 that industry has kind of taken the other position,
21 and if the industry is saying we shouldn't go forward
22 yet, then it's a little bit hard to say we ought to
23 proceed forward, because I think that the whole 50.46
24 activity is really in response to the industry's
25 feeling that by changing those regulations, there

NEAL R. GROSS

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

1 might be room for safety improvement or financial
2 improvement.

3 I also suspect that if the industry had
4 known what RES was going to say today, that their
5 presentations might have been a little different. I
6 don't know, but I did have a feeling that they might
7 have been at least a little bit different. And I
8 think there was a little bit changing in midstream
9 even of the positions they took, so that's kind of
10 where I stand at the moment.

11 CHAIRMAN POWERS: Dr. Kress.

12 DR. KRESS: First off, I think the
13 database and the experiments have been well-conceived,
14 and well done, and I'm really pleased to see this
15 being developed. I originally thought I might see
16 some sort of correlation of embrittlement versus the
17 uptake of hydrogen and oxygen effects on the phases,
18 but I'm very doubtful that such a correlation would be
19 very useful, frankly. I don't think we can do that.
20 I really like the empirical approach. Let's do a
21 correlation with this time and temperature, and the
22 time and temperature is, I think, a one-to-one
23 correlation with the Cathcart-Pawel. By the way, the
24 pronunciation is Pawel. And I believe there is a one-
25 to-one correlation with temperature and time. I mean,

NEAL R. GROSS

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

1 time and temperature is the parameter that we judge.
2 And I like the thought that one sees the square root
3 of that as related to the various changes in phases,
4 and the various movement of the material, so I think
5 it's a good approach. And I think it's supportable by
6 the data we have.

7 Now I do think that the cool-down effect
8 needs to be tied down just a little bit better, and
9 related to the actual LOCA conditions we may have.
10 That's the one place I think needs to be tied down
11 just a little bit more before we go to rulemaking, but
12 I think that's something that can be done rather
13 quickly. So given that, I'm in favor of going forward
14 with the rulemaking. I think we also need to -- I
15 understand the tests that you do with the clad with
16 the fuel and everything else removed was an
17 expeditious way of doing it. I do think you need this
18 confirmatory test with the actual fuel. But I'm like
19 Ralph, I think that's just going to be a confirmatory
20 test, and it's not going to change your criteria. I
21 think the way you've developed the criteria based on
22 the actual use of the clad and the Cathcart-Pawel
23 relationship is good, so I'm encouraged that you've
24 captured the ductility requirements by this, which
25 that's a very nice way to do it, because to me, it is

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 least painful way, and it does capture it. And so
2 I'd say go ahead with the rulemaking, and you've
3 pretty well got the right idea. That's basically my
4 reaction to it.

5 CHAIRMAN POWERS: Dr. Shack, I can't ask
6 you to comment.

7 DR. SHACK: I'm sorely tempted.

8 CHAIRMAN POWERS: The cat can keep your
9 tongue. We eschew your counsel with this.

10 DR. KRESS: One thing I did want to say,
11 though, about the slides on 28 and 29. Even though I
12 think you have the right idea, I think they're phrased
13 wrong. I think I would re-look at those, and I think
14 the guidance on asking the people to do the testing
15 needs to include more protocol on how the testing
16 ought to be done.

17 DR. MEYER: Yeah. I don't know that I
18 mentioned that in connection with this, we fully
19 expect to develop a regulatory guide, because there
20 are a lot of details involved.

21 DR. KRESS: And that would include the --

22 DR. MEYER: Oh, yes. But the regulatory
23 guide would, of course, not be unreal.

24 DR. KRESS: That's probably the way --

25 DR. MEYER: The rule itself would be

1 stated simply, and NRR will --

2 DR. KRESS: Yes. I don't think that the
3 rule stands alone by itself without a regulatory
4 guide.

5 DR. MEYER: Right. I agree.

6 DR. KRESS: Okay.

7 DR. SHACK: Just it's not quite a comment,
8 but I would like to see a lot more of the data
9 expressed in the way the criteria is set up. I see
10 weight gain, actual ECR, Cathcart-Pawel ECR. I mean,
11 I would tell my contractor to shape up and go off and
12 analyze all that data that's out there, and express it
13 in a way that you can compare it against these
14 criteria and find out when I draw the lines, I color
15 all the dots that are more than 45 minutes orange,
16 does everything that sits above the limit in the color
17 orange. There seems to be a whole lot of data out
18 there. I can't tell whether it's consistent with
19 these criteria or not. There may be a scrap of paper
20 sitting on Ralph's desk somewhere that shows all this,
21 but I haven't seen it.

22 DR. KRESS: Well, I particularly liked
23 that, I forgot, was it Mr. Ozer that presented the
24 integral value of the energy and showed the line that
25 Cathcart-Pawel separated the flow -- I thought 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 was a good approach at showing that. And I think he
2 also mentioned you could get a one-to-one correlation
3 between the energy and the Cathcart-Pawel time.

4 CHAIRMAN POWERS: Maybe in deference to
5 Oak Ridge, I point out the bounding line was actually
6 Baker-Just.

7 DR. KRESS: Well, okay.

8 CHAIRMAN POWERS: We didn't even know what
9 that other line was.

10 DR. KRESS: The line was --

11 (Simultaneous speech.)

12 DR. KRESS: But I was impressed that that
13 made a good line to separate the two. That's one of
14 the reasons I thought they were on the right track.

15 MR. ELTAWILA: Can I make one comment?

16 CHAIRMAN POWERS: Please.

17 MR. ELTAWILA: I think for the industry,
18 you have to understand the process of when we go out
19 for a notice for rulemaking, that starts focusing the
20 discussion. Right now we are just trying to test the
21 program, so proceeding with the rulemaking itself will
22 focus the discussion, will identify what's needed,
23 industry can provide its views, NRC can provide its
24 view, and we'll start interacting with each other on
25 the rule itself rather than on what kind of tests

NEAL R. GROSS

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

1 we're going to run. So just think about it in that
2 regard, that the earliest we can issue a notice for a
3 rule will be March of next year.

4 DR. MEYER: And that's even -- the best
5 thinking now is that would be an advance notice of a
6 proposed rulemaking, not even a notice.

7 MR. ELTAWILA: That will help us just
8 achieve the goal that we want achieved. Right now
9 just test the program without an end in sight, and
10 that's what I'm concerned about.

11 CHAIRMAN POWERS: Well, there's no
12 question that a tremendous amount has been
13 accomplished. I, myself, believe that I have shared
14 agonizing over this issue of what to do about the non-
15 Zircaloy clads for the last eight years or something
16 like that, so this is not a precipitant program by any
17 means, but rather a rather deliberate program. And I
18 presume the understanding has expanded enormously here
19 in the presentations. What I noticed, and I think
20 this was reflected in many of the speakers, is nothing
21 that we've seen here changed the goals that we have
22 for this particular aspect of the rules; that is, the
23 coolability, keep to criteria and things like that
24 seem to be a constant that's not going to be changed,
25 and we're comfortable with that.

NEAL R. GROSS

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

1 Some have questioned whether ductility is
2 the bound to take for that, but we don't have really
3 any warm alternatives on this immediately in the
4 offering. Now that may change because I think Dr.
5 Eltawila said that what happens when you have a notice
6 of rulemaking is we go from a joint program where we
7 are free to make independent interpretations, to a
8 program where we try to unify those interpretations.
9 And quite frankly, my experience with that process is
10 just about everything becomes fair game in that
11 discussion.

12 We have a question before us as to whether
13 the proposed criteria are the ones that can at least
14 start that process, and it seems to me in thinking
15 about things, they have a certain attraction to them,
16 but they run rough against the more explicit
17 quantitative criteria that appear in the current rule,
18 so they're a little bit jarring when you look at them.

19 One issue that had seemed to be absolutely
20 universal agreement on was that this hydrogen
21 synergism and its effect on the data was a recognized
22 phenomenon, that even the quantification of it I
23 didn't see radical differences in the data and
24 whatnot. And the question that I think we need to
25 confront the rest of the committee with is do we treat

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 more explicitly in the rule, or do we address it
2 via this corrosion layer subtraction process at the
3 end?

4 The break away avoidance step in the
5 criteria is an interesting one, and I don't know that
6 we explored it too thoroughly, but I got the
7 impression that that was an area that there was also
8 broad agreement, that you want to avoid this break
9 away and the excessive amounts of oxidation, plus the
10 possibility of additional hydrogen uptake in that, and
11 so I didn't -- the really thorny question that comes
12 up here is whether this minimalist approach is
13 appropriate, and it's pretty clear why you would want
14 to undertake this kind of a minimalist approach.
15 There's an opportunity open to us presented by
16 changing 50.46 to couple these things together and do
17 that, and you can do it and get rid of a problem that
18 exists even if you don't accommodate anything that
19 comes down in the future; that is, I can almost
20 guarantee you there's going to be another kind of clad
21 that's going to come down within the next 10 years
22 that will have even better properties and more
23 wonderful features to it, cheaper to make and
24 everything else, and it will run orthogonal to
25 anything we set up in the short term. And that may be

NEAL R. GROSS

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

1 a cost that we endure versus setting up a far more
2 generalized rule. And I think that's one issue that
3 the Full ACRS is going to have to confront. And in
4 advising the staff on what they might choose to
5 present to the full committee, I think it's that
6 strategy aspect of your proposal. It's much less of
7 the technical details, the things that will show up
8 largely in a Reg Guide, how you do the experiments --
9 you're going to have to show something about the
10 technical foundations for this approach, but I think
11 that's a supportive and not a major thrust. I think
12 you need to say here's why I came up with these
13 criteria, and why I'm taking the approach I am,
14 because I think that's what the full -- we're going to
15 need the wisdom of the full committee to formulate a
16 response in that effort, because I think that's one of
17 the questions that we're confronted, not just these
18 three criteria that you've laid down here. So in
19 developing your strategy, that's what I would think
20 you would want to present.

21 I don't know, are we planning to get
22 presentations, Rosa, from the industry at our full
23 committee meeting?

24 MS. YANG: We haven't been informed.

25 CHAIRMAN POWERS: Okay. Before the

NEAL R. GROSS

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

1 committee can write a letter, the full committee has
2 to hear something. And in some cases it can be done
3 by the members summarizing. This is not an area that
4 I would like to summarize and whatnot, and so there
5 will be a presentation, and my recommendation is that
6 you did a pretty good job here in Odelli's
7 presentation and Mr. Dunn's presentation in
8 addressing this strategy issue. I don't think we've
9 got -- I have a feeling the technical details are
10 going to get worked. The technical details that upset
11 the apple cart, they're important to bring up. The
12 technical details over things that -- how you do ring
13 compression tests and stuff like that, those get
14 worked in the Reg Guide, and strategy is the issue
15 here. And from your presentation, is that strategy
16 now or is it strategy later? And I think Odelli and
17 Mr. Dunn did a pretty good job in articulating their
18 position. Some of the stuff that Robbie presented
19 where he looked at here are the kinds of things that
20 you guys need to question, the supporting database can
21 again be supportive of those positions, and I think
22 they're well articulated. That's my advice.

23 MS. YANG: Thanks. What kind of schedule
24 are you looking at?

25 CHAIRMAN POWERS: This is scheduled for

NEAL R. GROSS

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

1 September, and I think we put two and a half hours on
2 the agenda. And I think we will absorb it all, so
3 you're looking at something like maybe a 45 minute
4 presentation, something like that.

5 One of the issues I think we're going to
6 need clarification on at some time is the coupling
7 between this change to the 50.46 rule and the thermal
8 hydraulic change, particularly the temperature
9 transients that can be expected in there. I don't
10 know that it's essential to have that for this
11 discussion in September, but if we go forward by any
12 path, that coupling is going to be -- we're going to
13 have to really understand that a lot better than I do
14 right now.

15 DR. DENNING: In that regard, Dana, should
16 we be asking -- I had not realized before it was said
17 here that they could be separated, and I think the NRC
18 is recognizing them as being separated. I'm kind of
19 curious as to what the logic is, and whether we ought
20 to have a brief presentation on how - I don't know, is
21 it NRR - how they see the two being coordinated, and
22 how they think that they can separate them.

23 CHAIRMAN POWERS: My impression is, and
24 I'm going to let Farouk talk in answer to your
25 question in a second, but my impression is the thermal

1 hydraulics can proceed independently of the fuel
2 criteria. It's not entirely clear to me that the fuel
3 criteria can proceed independently of the thermal
4 hydraulics. With that, did you have a comment,
5 Farouk?

6 MR. ELTAWILA: I think that's exactly --
7 and just from a practical point of view, the
8 Commission will be issuing SRM on the Part A of the
9 rule very shortly, so we are way ahead in the thermal
10 hydraulic part than the large break LOCA, or the LOCA
11 break definition. We're way ahead in that area than
12 in the fuel area. They might be coupled together at
13 the end or something like that, but we are proceeding
14 right now, and we are here at the beginning of the
15 process.

16 CHAIRMAN POWERS: Almost assuredly, no
17 matter what decision the ACRS makes, I can assure you
18 this is an issue that we're going to get to discuss
19 face-to-face with the Commission. And it's the
20 strategy issue that they're going to be interested in
21 and whatnot, and so we're going to have to spend close
22 attention to that because what view -- the collective
23 view presented to us is what we're going to be
24 presenting to the Commission, and so don't send us up
25 there naked, please. I really get embarrassed when I

NEAL R. GROSS

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

1 have to stand up there and tell them I don't
2 understand what the strategy is, so help us out to any
3 extent that you can there.

4 Again, let me say that I like coming to
5 these subcommittee meetings. Mr. Atherton is back,
6 and he asked if he could say a few words, and I
7 certainly want to accommodate him.

8 MR. ATHERTON: I'm not sure that this
9 would be an appropriate time, perhaps tomorrow would
10 be --

11 CHAIRMAN POWERS: If it deals with RIAs
12 it's fine for tomorrow. If it deals with LOCA, it's
13 fine for today. If you can't tell, then go ahead.

14 MR. ATHERTON: Okay. Is it okay if I --

15 CHAIRMAN POWERS: Yes, please sit down.

16 MR. ATHERTON: I'll try to be brief. Some
17 of what I planned to cover has already been covered,
18 and so I don't wish to go over that again. My name is
19 Peter James Atherton. I work part-time as a Nuclear
20 Safety Consultant, and in doing so, I provide
21 technical advice and guidance to people in and around
22 various nuclear power plants.

23 The basic concern that these people
24 express to me is not an interest in what's happening
25 within the nuclear power plant generating station, but

NEAL R. GROSS

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

1 the radiation releases that come out of the plant, and
2 so for the last several years I've been involved in
3 the environmental aspects of radiation releases
4 working my way backwards to the plant, which is the
5 source of the radiation releases, and this is the
6 first opportunity I've had to get involved and listen
7 to what's happening within the reactor pressure vessel
8 itself, so I have a few comments I'd like to; and that
9 is, one, the public is concerned about radiation
10 releases. The brunt of the radiation releases are a
11 result of what's happening within the reactor pressure
12 vessel. And what I haven't perceived is a
13 relationship between what you're doing here in the
14 rulemaking, which is my first involvement with this,
15 and ultimately what the people outside the plant and
16 in and around the plant are concerned with, and that
17 is the radiation that is released by the power plant
18 into the environment.

19 And the comment I have is, is there any
20 way to -- since the public as a general rule is
21 probably not going to get involved with the technical
22 details of this rulemaking, some sort of a statement
23 or a paragraph, or something that addresses the
24 relationship of what you're doing to the radiation
25 release or the lack of it, that would ultimately

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 prevail if this rulemaking takes effect, I think would
2 be very helpful to them.

3 In doing that, I would also suggest, and
4 I didn't hear anything about this at this meeting, and
5 perhaps it's addressed in a different way, I used to
6 work -- I was hired by the Atomic Energy Commission.
7 I used to work for the Nuclear Regulatory Commission
8 in the 1970s, and common mode failures was a big item
9 back then. And I don't see that language being used
10 today; that is, if you have a causal factor for one
11 fuel rod to fail, what's to prevent other fuel rods
12 from failing simultaneously with that same causal
13 factor? That was not addressed, and from what I saw,
14 it does not appear to be a subject matter at this
15 time, but it is something that would ultimately effect
16 the public should you have multiple failures within
17 the reactor pressure vessel.

18 I'd like to say something that's very
19 positive for me, and I happen to be a real-time
20 advocate that is if you use computer codes to do this,
21 that, and the other, I'd like some sort of
22 verification that they're accurate, and they're going
23 to work. And I have problems from an environmental
24 perspective with the use of computer codes without any
25 kind of testing to verify that the dispersion model

NEAL R. GROSS

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

1 for the radiation releases at the stack are what the
2 model says they are. And what I was really very happy
3 to see is that you've gone through at least some
4 semblance of destructive testing. I guess you all
5 realize that fuel failures are not something you want
6 to deal with. You'd like to keep the fuel in-tact,
7 and you seem to be going in a direction which I would
8 like to say I agree with concerning empirically
9 testing these fuel rods to make sure that they will
10 endure or withstand, or perhaps they won't and you've
11 got to do something about it. So I'd like to raise
12 that as something that I'm very thankful to see.

13 And I just want to from a perhaps -- I've
14 been criticized for being naive or idealistic, but the
15 NRC's basic mission to the public is protecting the
16 public health and safety, and generally that has to do
17 with radiation releases. And whatever you do here and
18 the technical details of how you do it, that
19 impression seems to be lost as a basic mission of NRC.
20 And I would be interested personally in seeing that
21 incorporated in what you're doing in some way, shape,
22 or form.

23 And I have one question that I'd like to
24 ask of the French, and it has nothing to do with
25 anything that's happening here, but it's something

NEAL R. GROSS

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

1 that I've been curious about personally, and was
2 wondering if I'd be permitted to ask that.

3 CHAIRMAN POWERS: Well, I guess you'll
4 have to ask and I'll tell you if you're out of order.

5 MR. ATHERTON: It's very simple. Why do
6 the French only have pressurized water reactors for
7 nuclear power generating stations?

8 CHAIRMAN POWERS: I think that's outside
9 of our scope. You might get to them privately on
10 that.

11 MR. ATHERTON: I just wondered if they
12 knew something we didn't.

13 CHAIRMAN POWERS: Let me just comment that
14 the issue that you are most concerned with, that is
15 the radiation release, is what's embodied in the goals
16 of this activity. And Dr. Meyer listed them down, I
17 think other speakers listed them down. This is the
18 coolability, whatnot. There is some radiation
19 releases of course associated with rupturing the rod,
20 but you want to stop it at that. And it's the
21 coolability and maintaining of coolability, and those
22 are the issues that you want to look at. And that's
23 why I was so curious of a previous speaker, are you
24 comfortable with those goals? Because that's why they
25 were -- that's why those goals came about, is to stem

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 radiation release at this barrier and our defense-in-
2 depth strategy fails.

3 MR. ATHERTON: Well, the defense-in-depth
4 back in the 1970s was the fuel cladding, the primary
5 if it's a pressurized water reactor, the primary
6 coolant system, boundary, and then lastly, the
7 containment.

8 CHAIRMAN POWERS: It hasn't changed much.

9 MR. ATHERTON: The problem with say
10 pressurized water reactors which I'm most familiar
11 with, is that perhaps under the high pressure and
12 temperature that they operate at, there's been a
13 tendency in the past to have the steam generators
14 fail, so any problems with the fuel is not necessarily
15 contained within the primary system as long as it
16 leaks passed the steam generators into the secondary
17 system.

18 CHAIRMAN POWERS: That's another issue
19 that we're not really dealing with today.

20 MR. ATHERTON: Okay.

21 CHAIRMAN POWERS: Stay tuned. It's on our
22 agenda.

23 MR. ATHERTON: That's how the radiation
24 essentially gets released to the environment, and that
25 would be something I would be interested in.

NEAL R. GROSS

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

1 CHAIRMAN POWERS: We're trying to stop it
2 before it gets to that stage. Okay. Thank you very
3 much. Well, let me conclude by again saying how much
4 I enjoy these meetings, and the high quality of the
5 technical work here - I mean, it's really excellent
6 technical work, both in the experimental side and in
7 the interpretation, analysis, and critique side. I
8 think those are just really excellent contributions to
9 my understanding, these help me a lot. I'm not giving
10 you part of my salary for that, but I did appreciate
11 it very much. We will recess for the day and tomorrow
12 we will turn to the RIA issue, which itself is an
13 interesting, though not quite as pivotal an issue in
14 reactor safety.

15 (Whereupon, the proceedings in the above-
16 entitled matter went off the record at 6:28 p.m.)
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 Meeting

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.



Eric Mollen
Official Reporter
Neal R. Gross & Co., Inc.

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



ANL LOCA-Relevant Research Results

*M. Billone, Y. Yan, T. Burtseva and H. Chung
Energy Technology Division*

*ACRS Meeting
NRC Headquarters
July 27-29, 2005*

Argonne National Laboratory



A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago



Technical Purpose of ANL Research

- **Generate Steam Oxidation Kinetics and Post-Quench Ductility Data for Cladding**
 - As-fabricated cladding alloys: Zry-2, Zry-4, ZIRLO and M5
 - Pre-hydrided cladding alloys: Zry-4 (ZIRLO and M5 on as-need basis)
 - High-Burnup Zry-2, Zry-4, ZIRLO and M5
- **Develop Mechanistic Understanding of Cladding Behavior with Emphasis on Effects of High Burnup and Fuel**
- **Develop Rate Correlation for Ductile-to-Brittle Transition as Function of H-content and $T = T(t)$ in Steam**
- **Document & Distribute ALL Data & Correlations to NRC, EPRI, Industry & TAG for Their Independent Assessment**
 - Letter reports, PowerPoint present., Journal articles, NUREG reports

2



Scope of ANL Research

- **Steam Oxidation Kinetics and Post-Quench Ductility (PQD)**
 - 1000°C, 1100°C, 1200°C oxidation of 25-mm-long rings; quench at 800°C
 - RT, 100°C, 135°C ring-compression tests to determine PQD
 - LOCA integral tests of 300-mm-long fueled samples; 4-point-bend tests
- **Advanced Cladding Alloys**
 - As-fabricated 17×17 ZIRLO & M5 vs. 17×17 Zry-4 & 10×10 Zry-2; E110
 - Pre-hydrated 17×17 Zry-4 (rings)
 - High-burnup defueled ZIRLO & M5 at ANL: ring tests
 - LOCA integral tests: fueled M5 (NA→INL→ANL); ZIRLO (TBD)
- **High-Burnup Zry-2 and Zry-4**
 - Limerick BWR Zry-2 (9×9): LOCA integral tests with fresh & high-burnup
 - Robinson PWR Zry-4 (15×15): short rings and fueled LOCA integral tests
As-fabricated, prehydrated (5-800 wppm) & high-burnup (400-800 wppm H)

3



As-Fabricated Zr-Alloy Tubing and Cladding

Material	Do, mm	h, mm	Oxygen wt. %	Outer Surface Finish & Roughness
Zry-4				
15×15 (HBR)	10.82	0.79	0.14	Tubing, 0.36 μm
15×15 (low-Sn)	10.77	0.76	0.14	Cladding, 0.31 μm
15×15 (low-Sn)	10.91	0.67	0.14	Cladding, 0.10 μm
17×17 (low-Sn)	9.50	0.57	0.12	Cladding, 0.14 μm
17×17 ZIRLO	9.50	0.57	0.12	Cladding, 0.11 μm
17×17 M5	9.50	0.61	0.145	Cladding, 0.12 μm
17×17 M5	9.50	0.57	0.145	Cladding, 0.12 μm
15×15 M5	10.91	0.64	0.145	Cladding, 0.11 μm
E110	9.17	0.71	0.050	Tubing, 0.35 μm
9×9 Zry-2	11.18	0.71	0.11	Cladding, 0.14 μm
10×10 Zry-2	10.3	0.66	TBD	Cladding, 0.11 μm



Parameters for Irradiated Cladding Test Specimens

Reactor (Design)	Burnup GWd/MTU	Clad.	Fast Fluence 10^{25} n/m ²	Oxide μ m	H wppm
Robinson 15×15 PWR 1.4 wt.% Sn	67	Zry-4	14	≤100	≤800
Limerick 9×9 BWR	57	Zry-2 Lined	11	≈10 + ≈10 crud	≈70
TMI-1 15×15 PWR	49	Zry-4 Low-Sn	9	≤30	<270
Surry 15×15 PWR	36	Zry-4	7	≤40	≤300

5



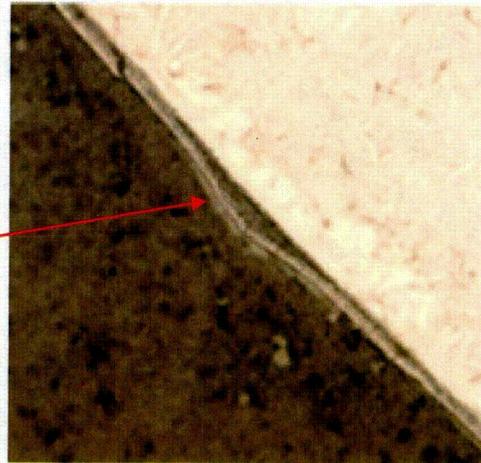
Background Information

- **ANL LOCA Program: Focused on Post-Quench Ductility**
 - Embrittlement \uparrow as oxygen content \uparrow in metal (prior-beta layer)
As-fabricated Zry-4: 0.12-0.14 wt.% O (similar for ZIRLO and M5)
RT-embrittlement occurs at \approx 0.4 wt.% oxygen for Zry-4
135°C-embrittlement occurs at \approx 0.6 wt.% oxygen for Zry-4
 - Solubility of oxygen in prior-beta layer of as-fabricated cladding (low H)
0.24 wt.% at 1000°C, 0.38 wt.% at 1100°C, **0.58 wt.% at 1204°C**
 - Solubility of oxygen in prior beta vs. hydrogen (300-600 wppm)
>0.24 wt.% at 1000°C
>0.38 wt.% at 1100°C, \approx 1 wt.% at 1200°C & 300-600 wppm-H
- **Must Move Beyond “ECR” as Metric for Embrittlement**
 - ECR depends on weight gain, which is independent of H-content
 - Embrittlement is **HIGHLY** dependent on hydrogen content

6



*E110 after 300 s and 1400 s at 1000°C
Ductile or Brittle at RT?*



Delaminated
Oxide Layer
after 300 s

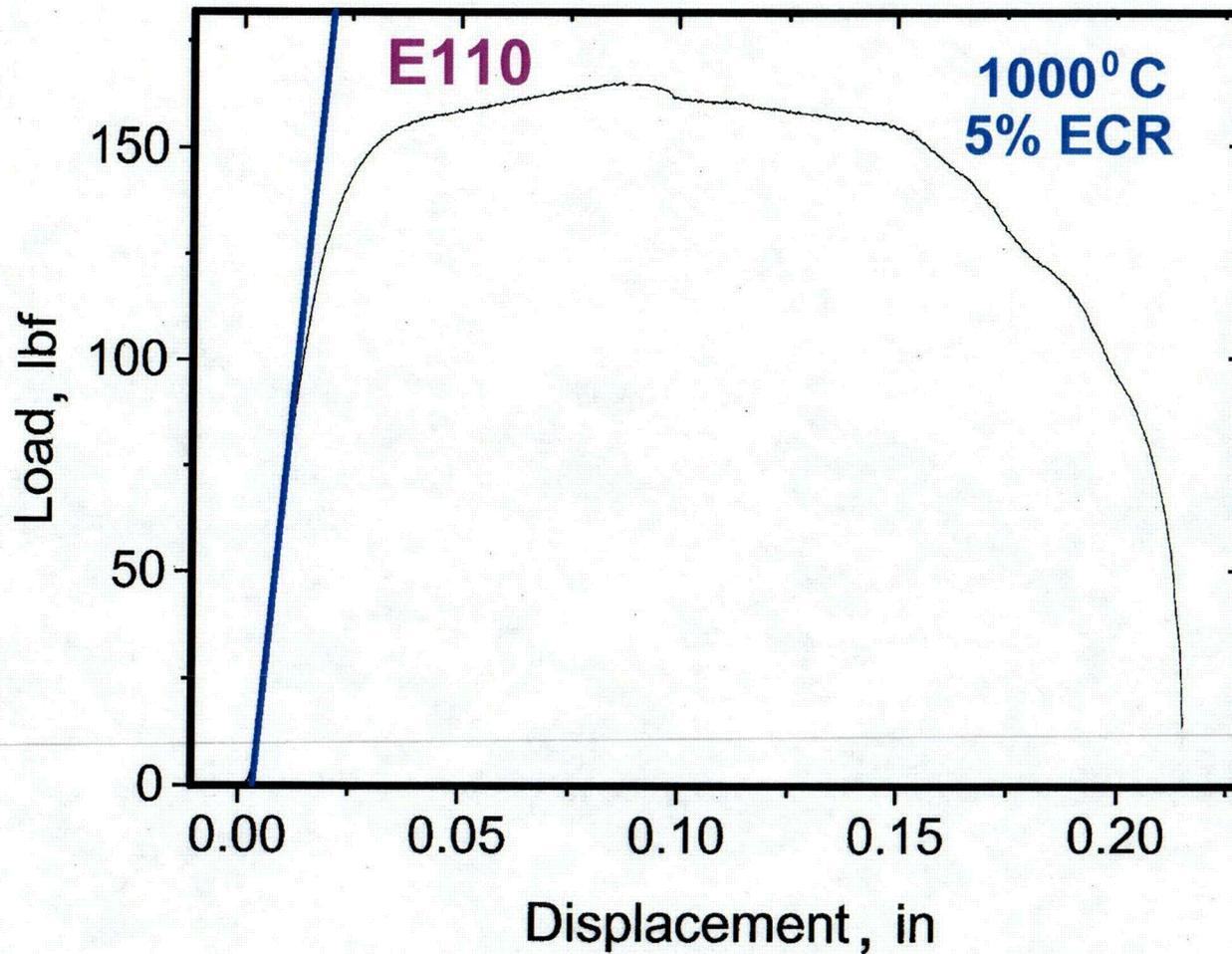


5% ECR
≈300 s at 1000°C
120±50 wppm H

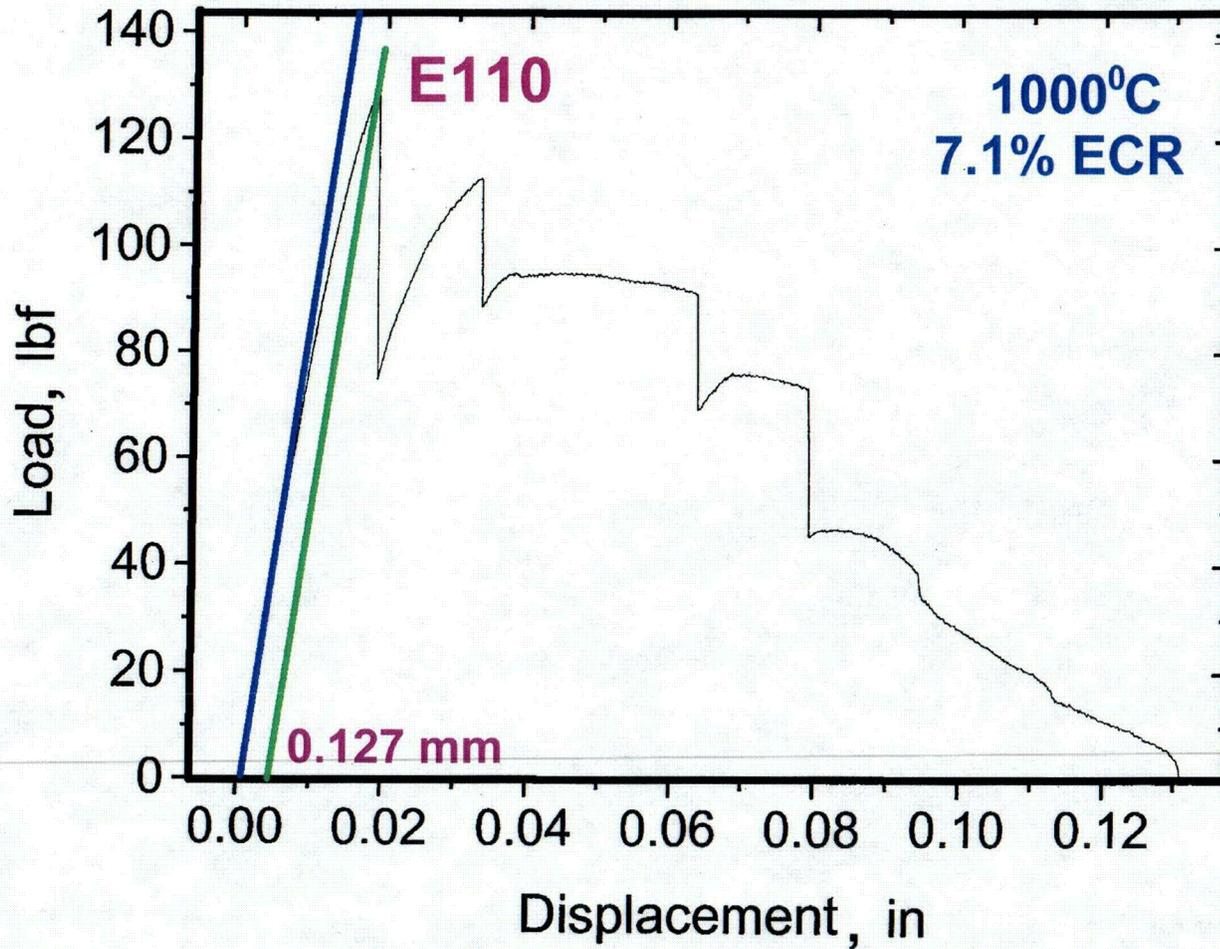
10% ECR
≈1400 s at 1000°C
>4000 wppm H

7

Very High RT Ductility of E110 after 300 s at 1000°C



RT Embrittlement of E110 after 625 s at 1000°C

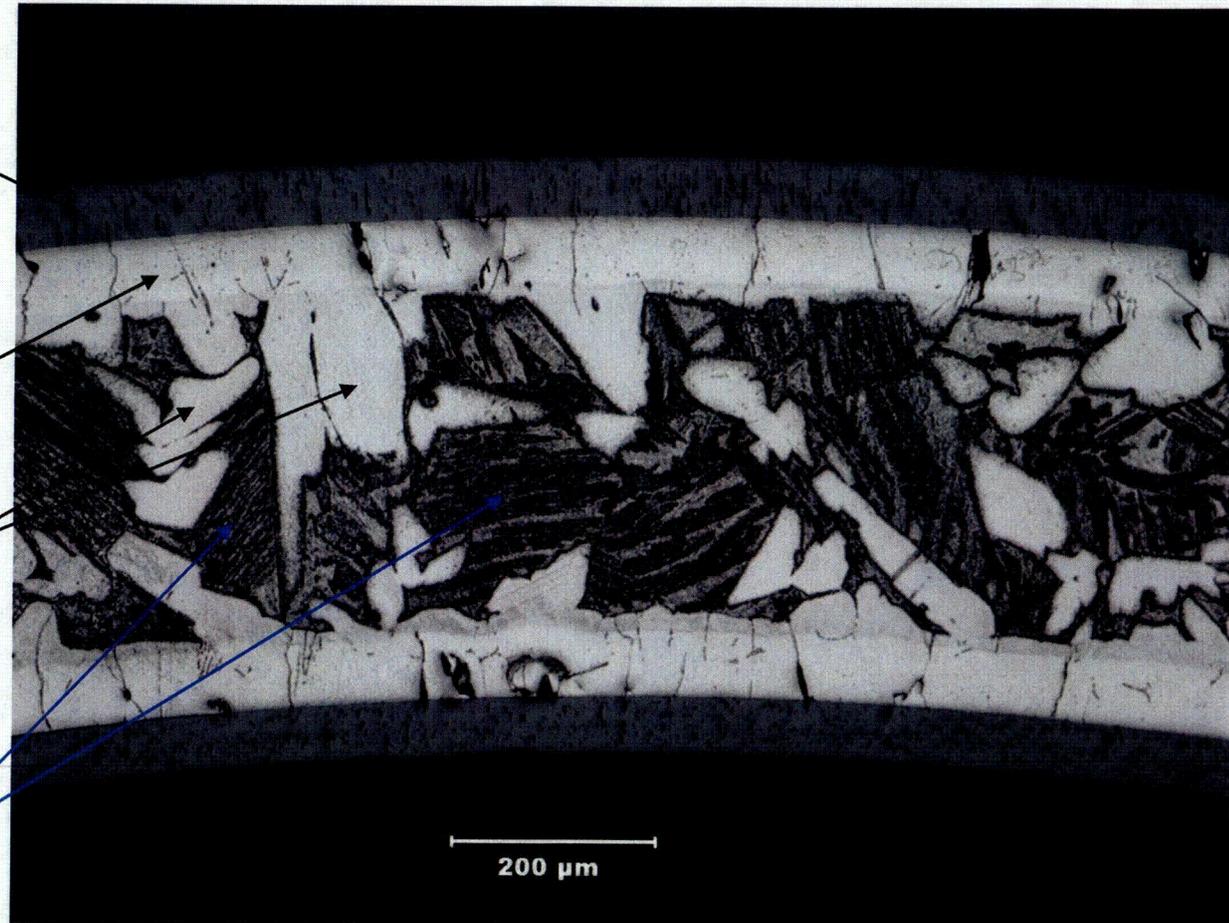


9

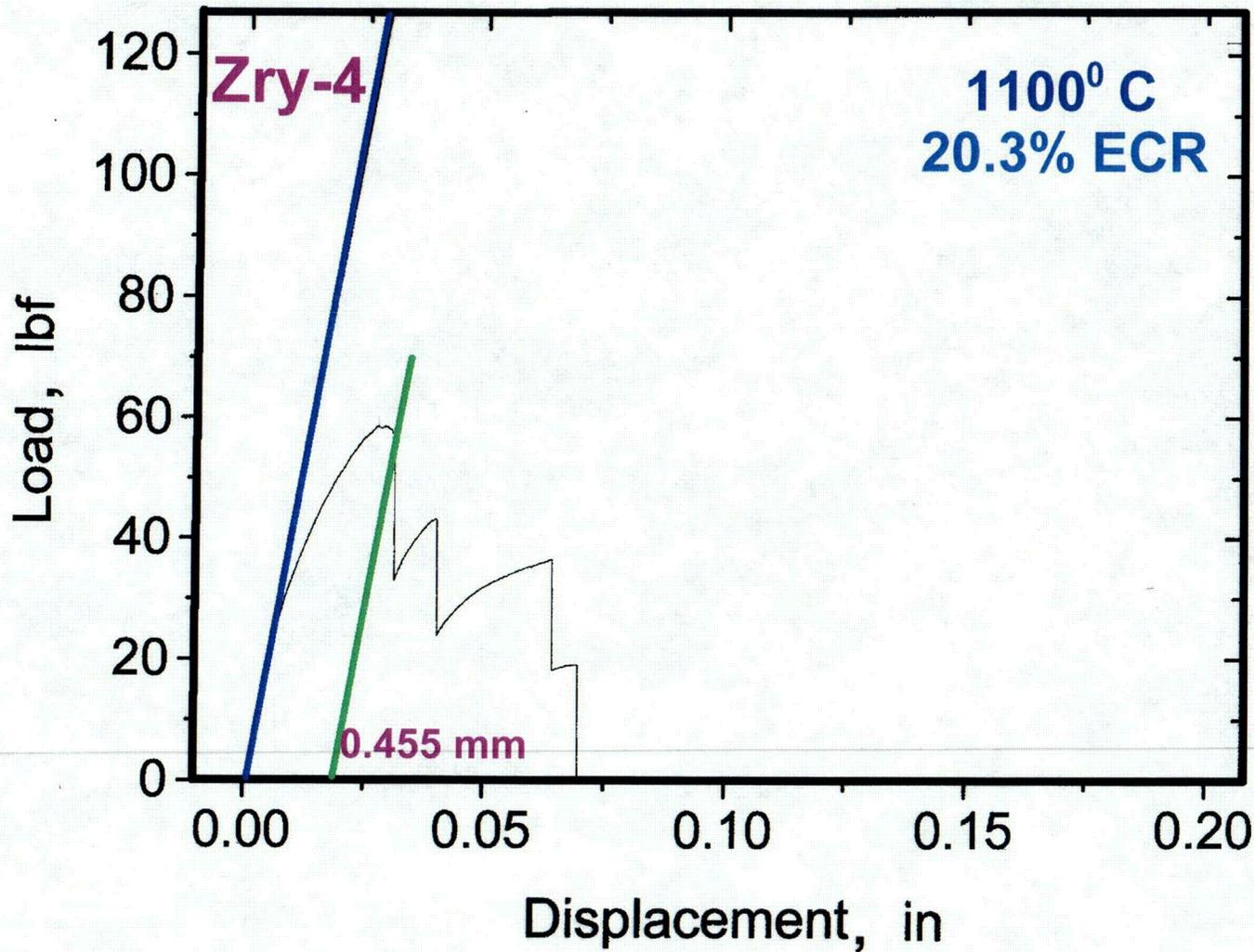
Post-Quench Zry-4: 20% ECR at 1100°C

Ductile or Brittle at RT?

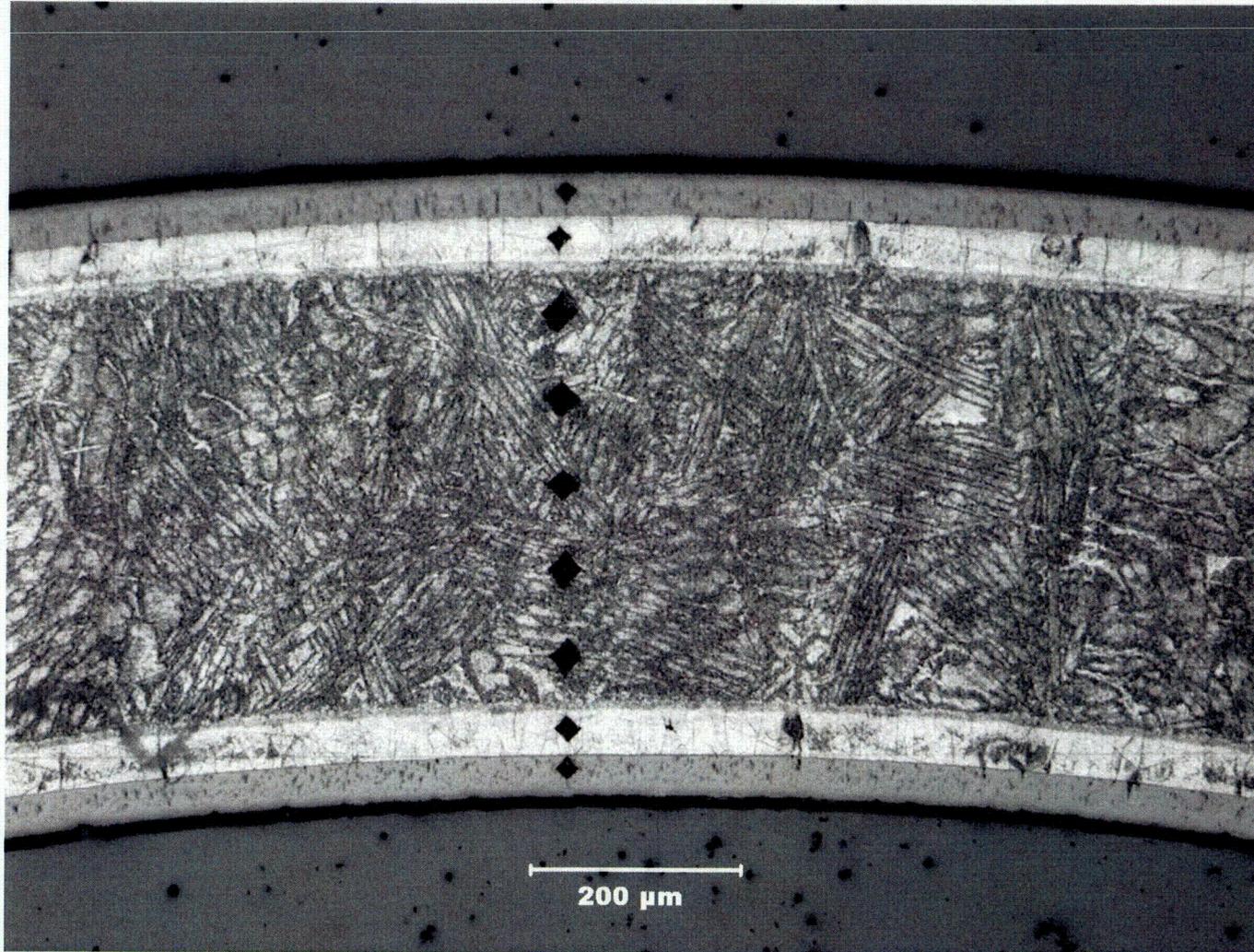
- Brittle Oxide
- Very Brittle Metal
≈2-3 wt.% O
≈1000 DPH
- Brittle Metal
≈0.6-2 wt.% O
≈500 DPH
- Ductile Metal**
<0.3 wt.% O
<300 DPH



RT Post-Quench Ductility (5%) of 17×17 Zry-4 following 20% CP-ECR at 1100°C

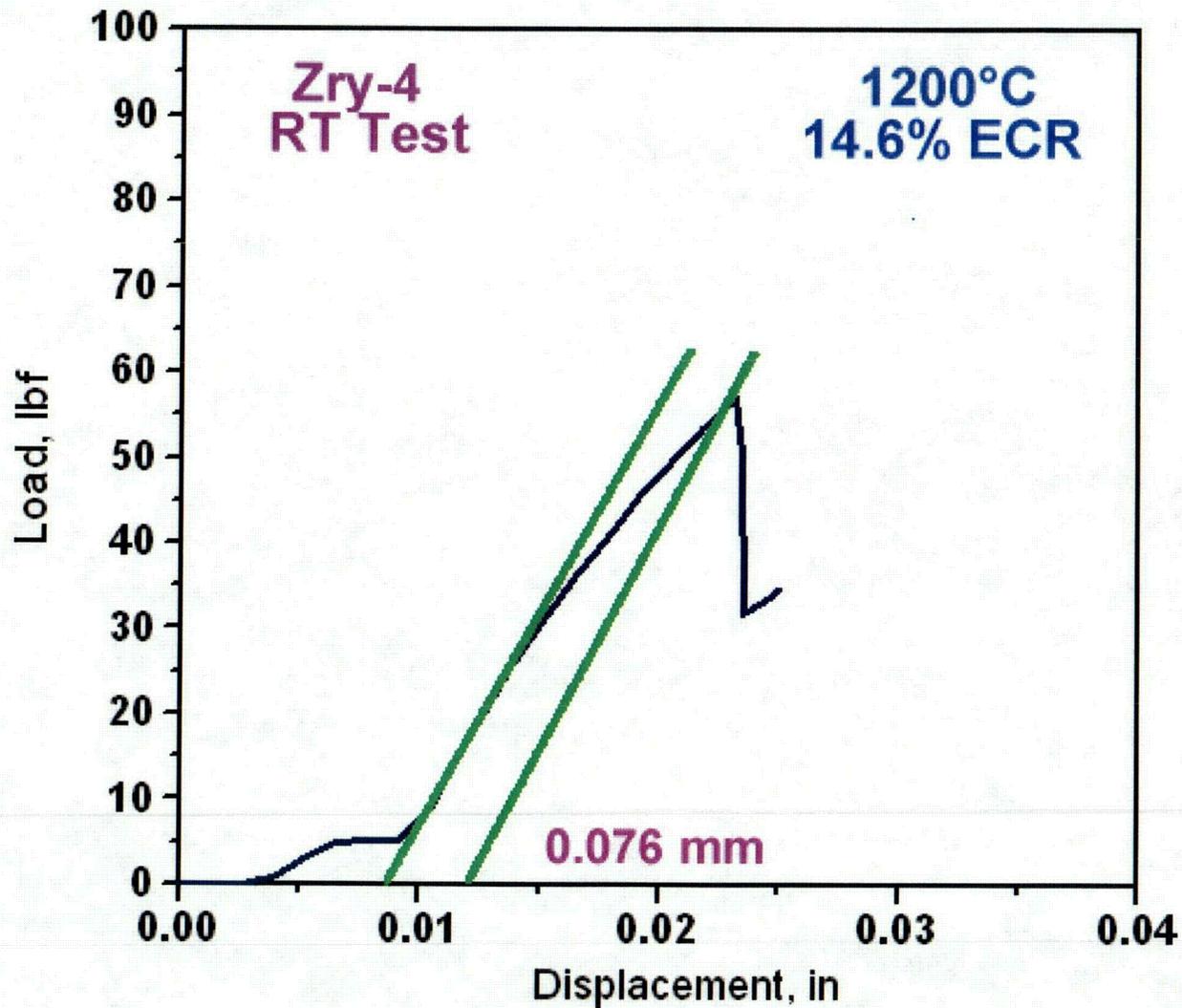


*Post-Quench 17×17 Zry-4: 13% ECR at 1200°C
Ductile or Brittle at RT? At 135°C?*

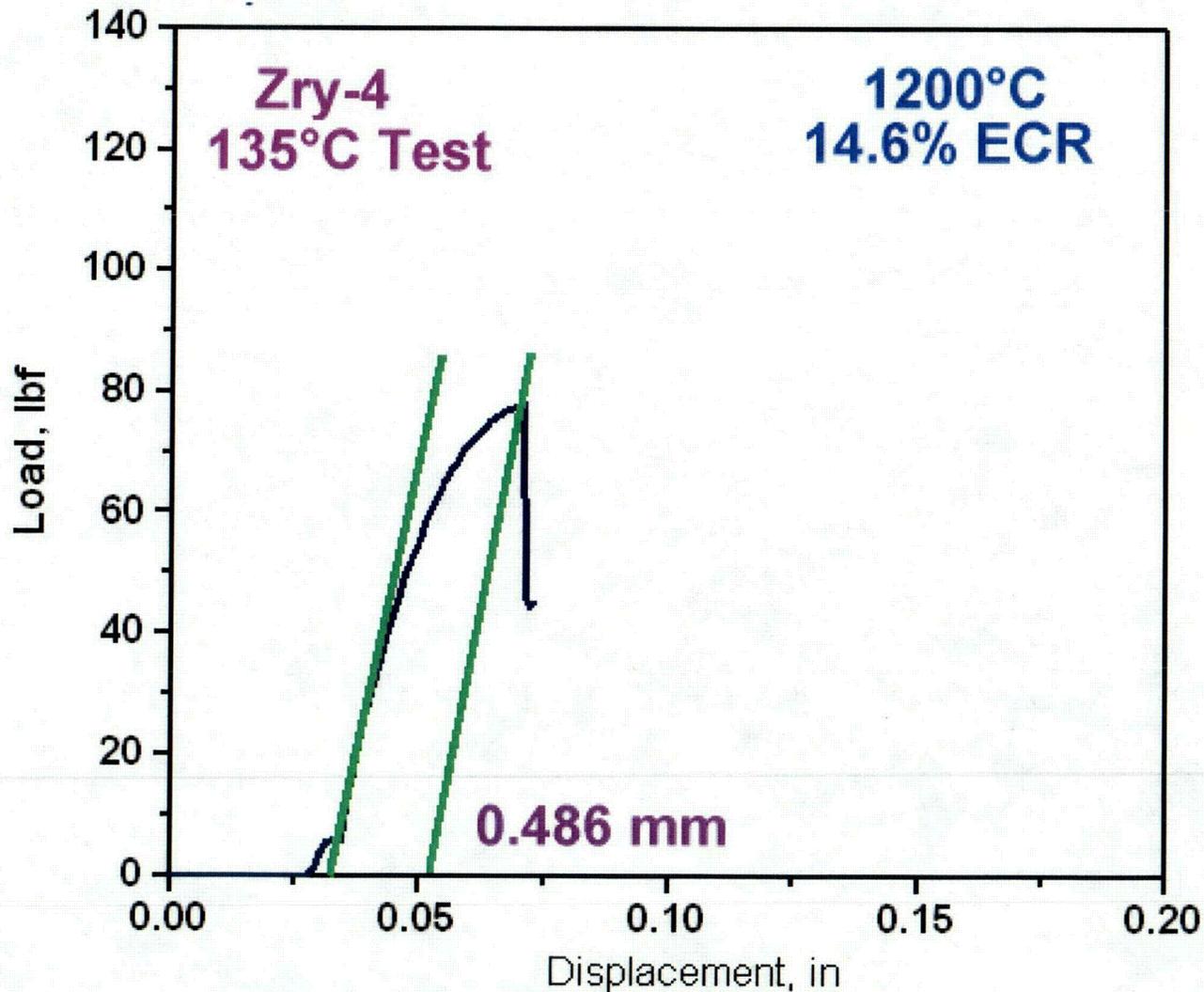


12

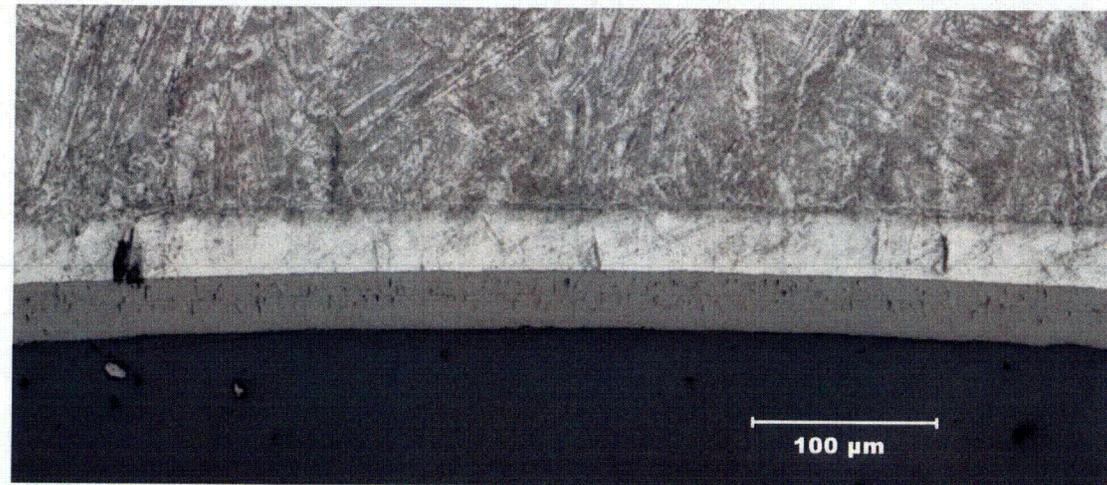
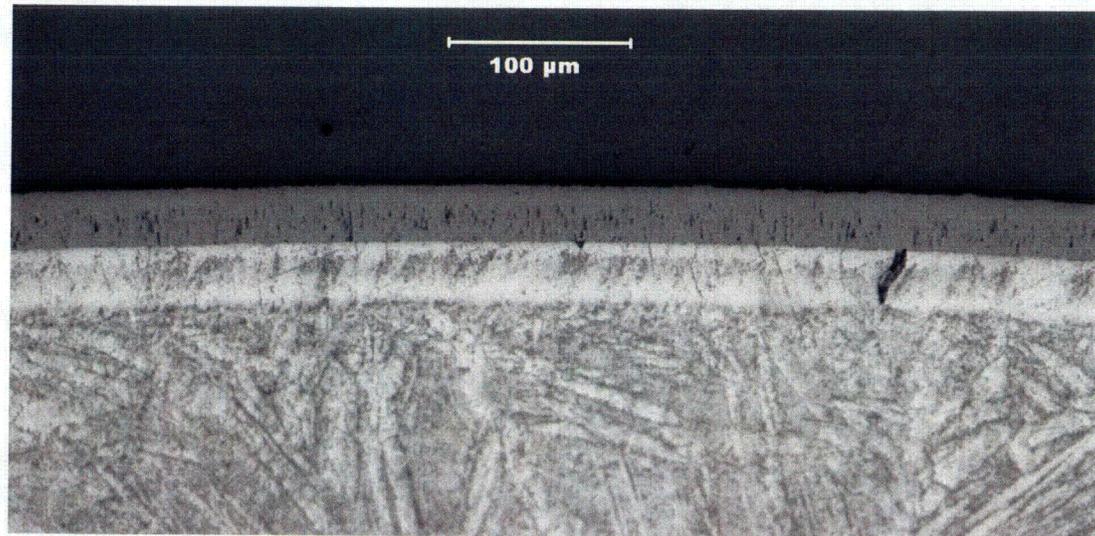
RT Post-Quench Embrittlement for 17×17 Zry-4 following 13% CP-ECR at 1200°C



135°C Post-Quench Ductility (5%) for 17×17 Zry-4 following 13% CP-ECR at 1200°C

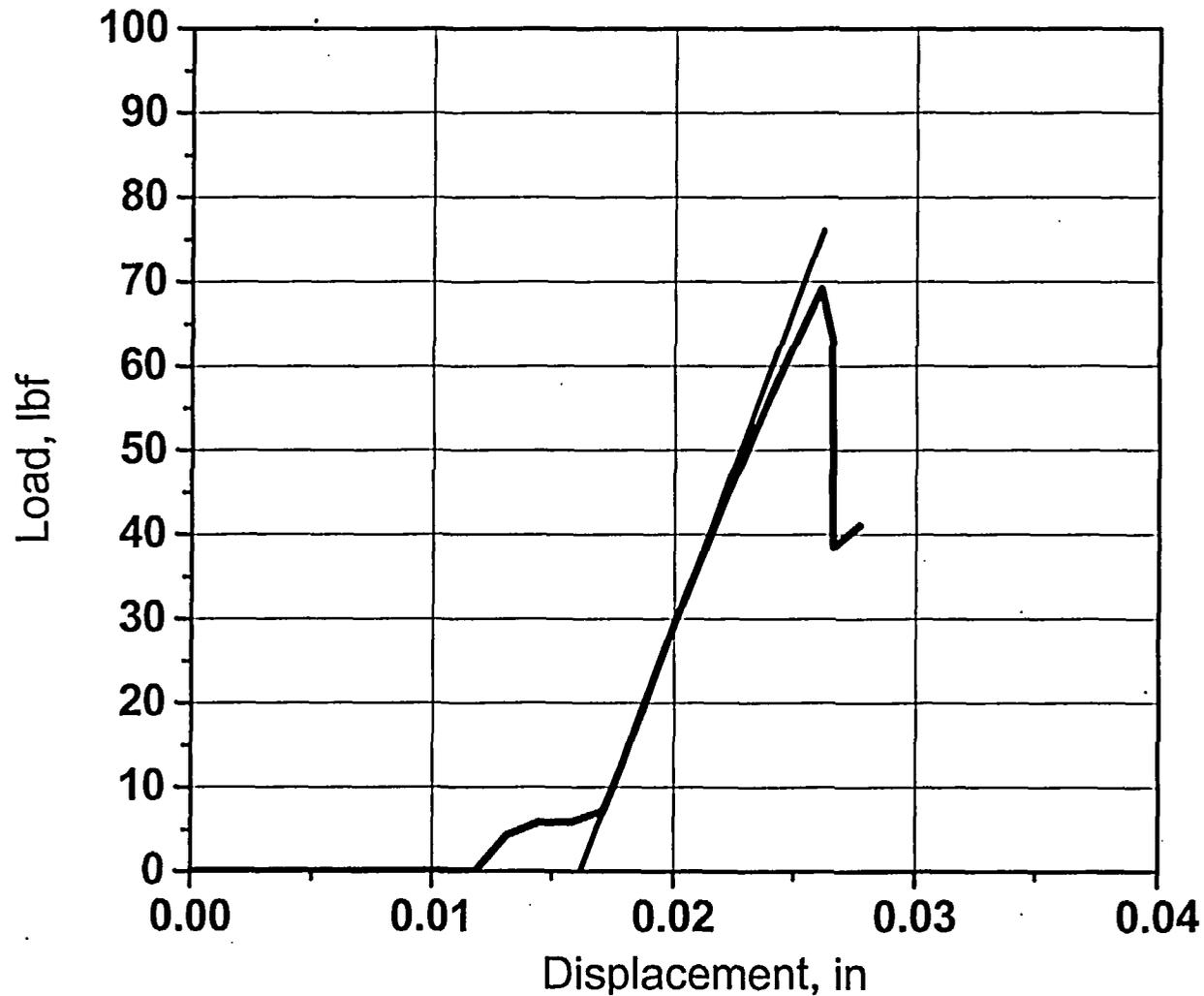


*Post-Quench 15×15 Zry-4 (600-wppm-H): 7.5% CP-ECR
at 1204°C; Ductile or Brittle at RT? At 135°C?*



15

135°C Post-Quench Embrittlement of 600-wppm-H 15×15 Zry-4 following 7.5% ECR at 1204°C



Data Quality and Data Comparison

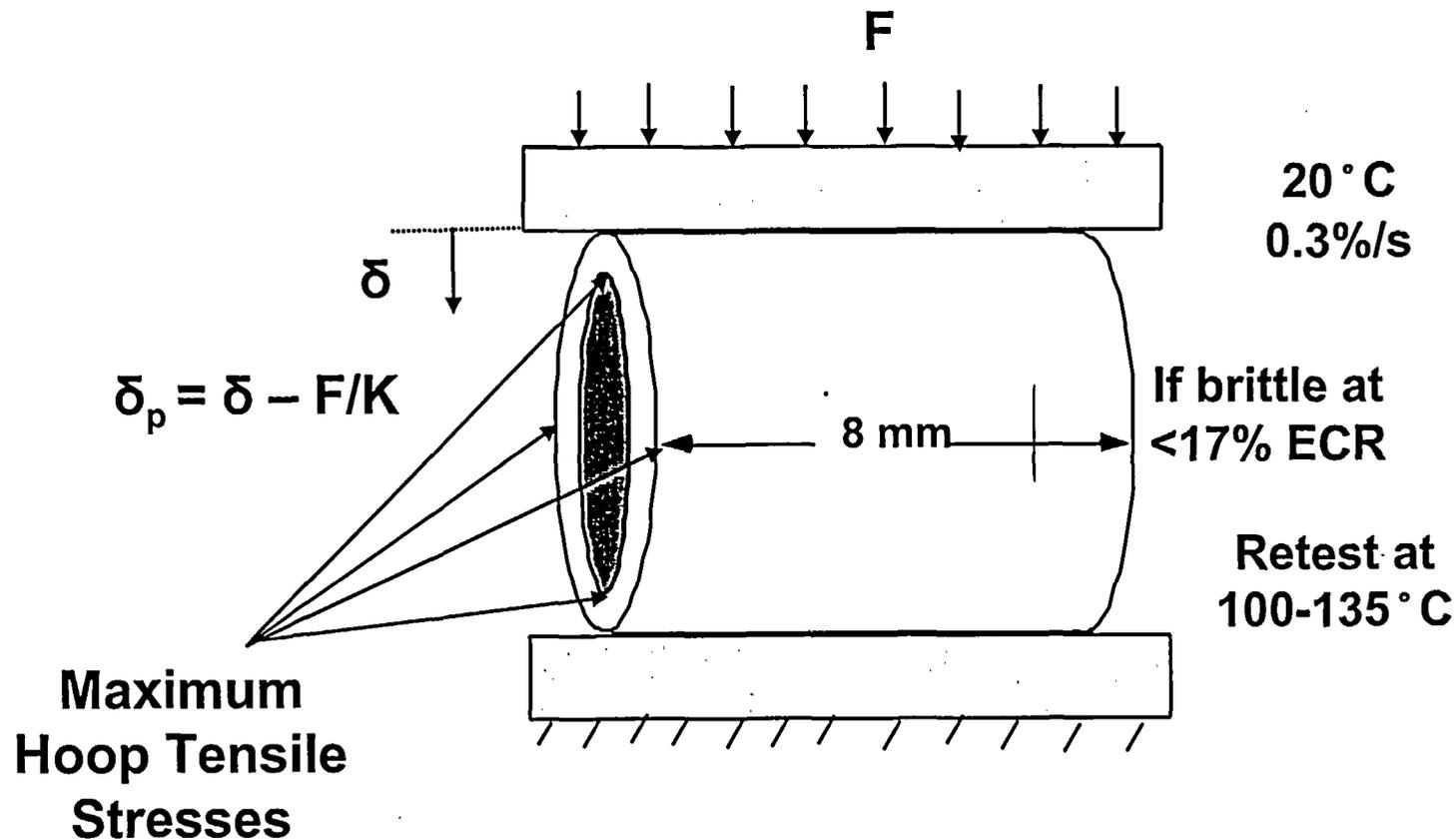
- **ANL Sample Oxidation and Quench**
 - All cladding alloys are oxidized in the same apparatus with similar heating rates, same hold temperatures, similar cooling rates (3-10°C/s), and same quench temperature (800°C)
 - Test-train and sample carefully benchmarked
 - Cladding outer-surface temperatures measured directly
 - Cross-checked with weight gain, oxide-alpha-beta layer thicknesses
 - Programmed heating rate chosen to eliminate temperature overshoot
- **ANL Ring Compression Tests**
 - Benchmarked to determine uncertainty (<0.2 mm) in offset displacement
 - Tests interrupted after first significant (40-100%) load drop to determine if failure (through-wall crack along sample length) has occurred and to determine directly the permanent change in diameter
 - Tests are repeated at 135°C for samples exhibiting RT embrittlement

17

Data Quality and Data Comparison (Cont'd)

- **Range of Sample Oxidation and Quench Conditions**
 - Double- vs. single-sided oxidation (may not be significant)
 - Range of heating rates: 0.5 to >20°C/s (important if ECR is metric)
 - Heating in steam vs. introduction of steam at high temperature
 - Temperature overshoot: 0 to 100°C for several seconds
 - Uncertainty in hold temperature
 - Cooling rates: direct quench from oxidation temperature; cooling rate to quench temperature (0.5 to 10°C/s); quench T; slow cooling to RT
- **Range of Ring Compression Test Conditions and Data**
 - Most tests conducted at RT and run to complete failure (3-4 cracks)
 - Uncertainty in interpretation of load-displacement curve
 - Reported displacement (δ): total δ to zero load (3-4 cracks)
 - total δ to first load drop
 - offset displacement δ_p to first load drop

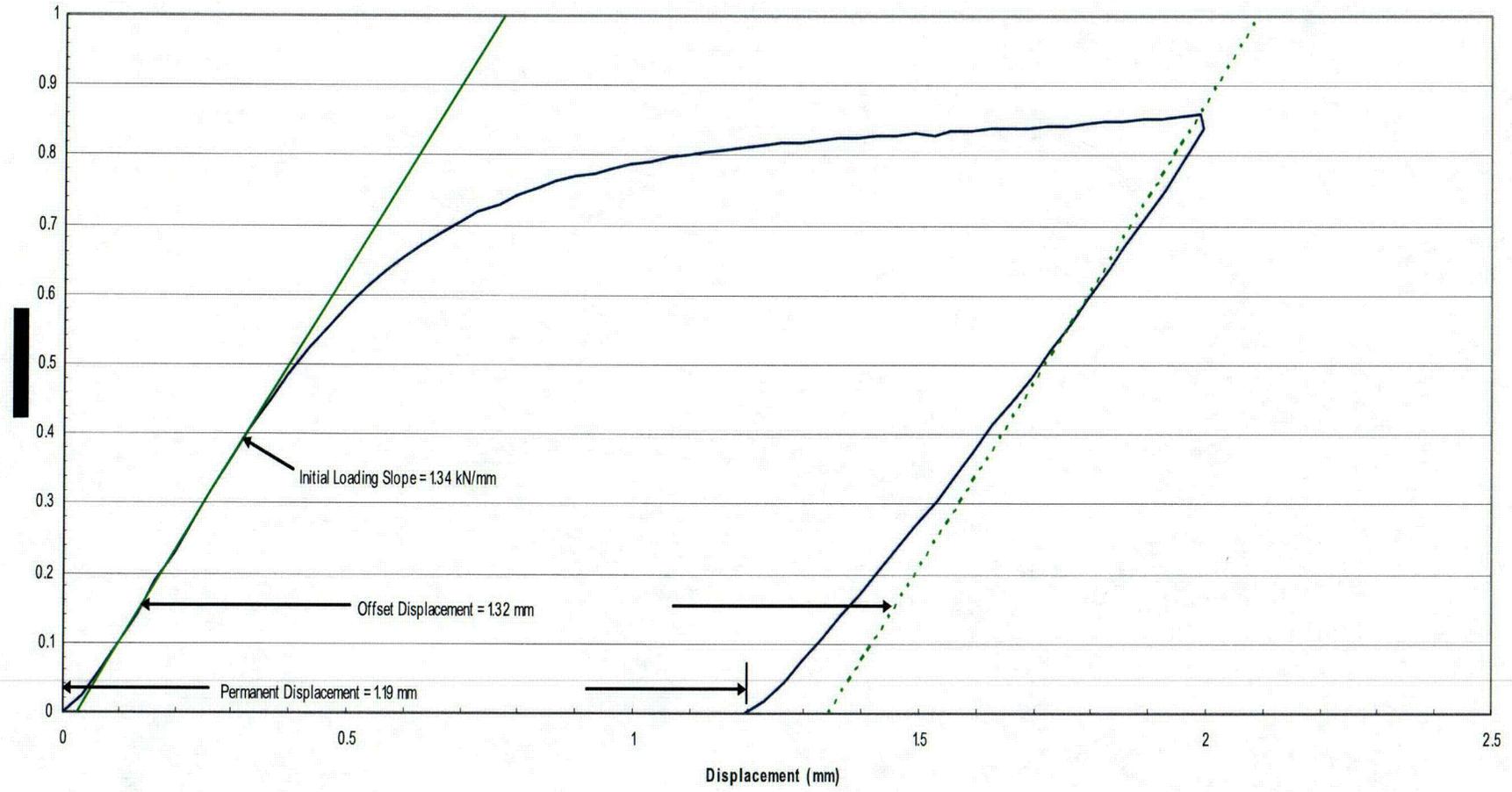
Diametral (Ring) Compression Screening Test for Post-LOCA-Quench Ductility (PQD)



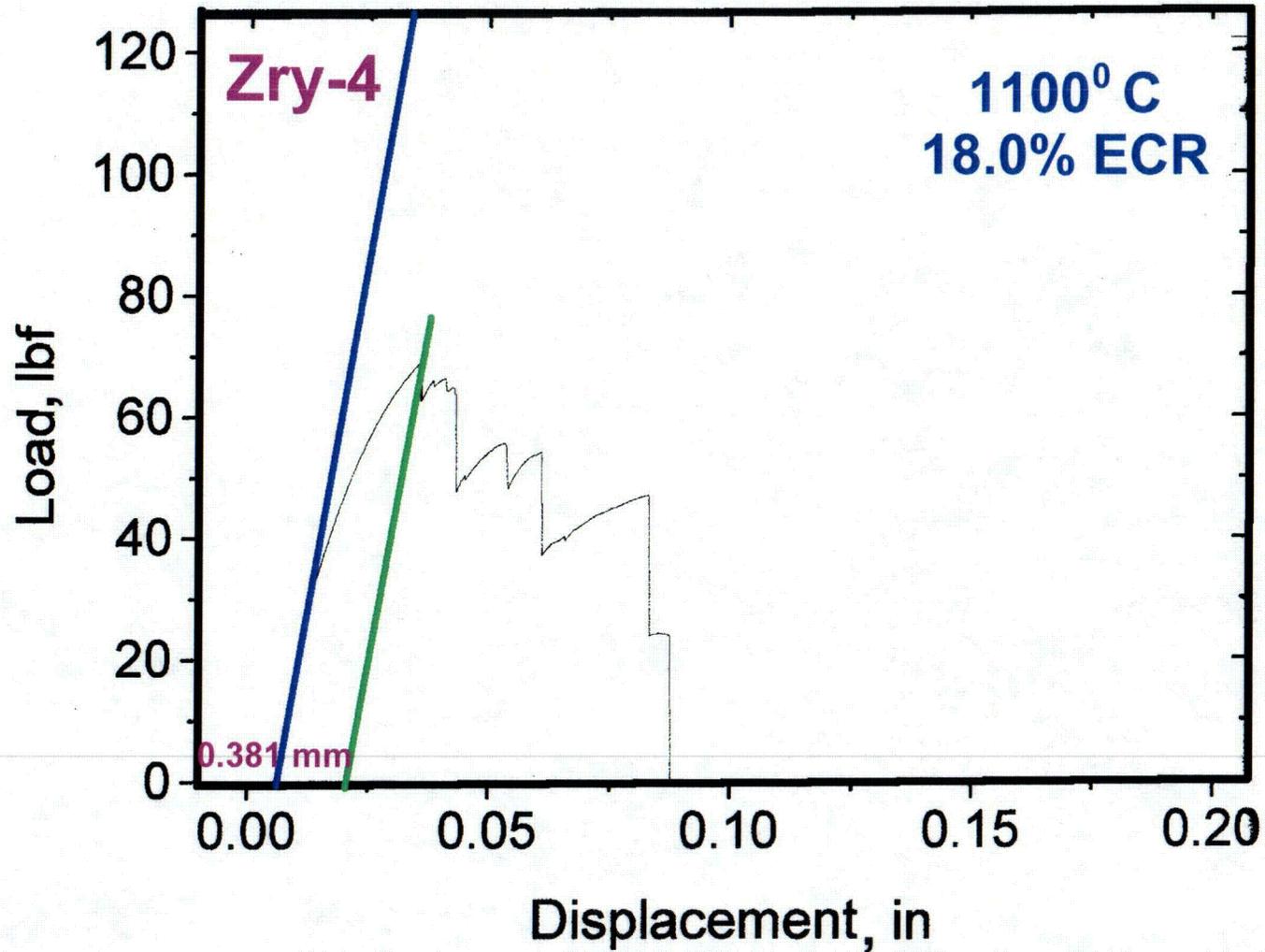
Note: some tests conducted with curved support and/or load plate

19

Definitions of Offset and Permanent Displacements and Strains for As-Fabricated 15×15 Zry-4



Methods and Uncertainties in Interpreting Load-Displacement Curves to Determine Failure Displacement



Summary of ANL Results

- **Advanced Alloy Program (Two-Sided Oxidation)**

- 1000 & 1100°C oxidation, slow-cooled to 800°C & quenched

Good RT ductility to >17% Cathcart-Pawel (CP)-ECR (Zry-4, ZIRLO, M5)

- 1200°C-oxidized, slow-cooled to 800°C & quenched (Zry-4, ZIRLO, M5)

RT embrittlement at $\approx 9\%$ ECR (Zry-4) & $\approx 12\%$ ECR (ZIRLO & M5)

Significant ductility improvement at 135°C (embrittlement ECR > 17%)

Severe embrittlement (135°C) at < 10% ECR for > 300 wppm H (pre-H)

- High-burnup ZIRLO and M5: oxidize at 1200°C, 1000°C and 1100°C

- **LOCA Integral Test Results at 1204°C**

- High-burnup BWR Zry-2 (significant embrittlement in balloon region)

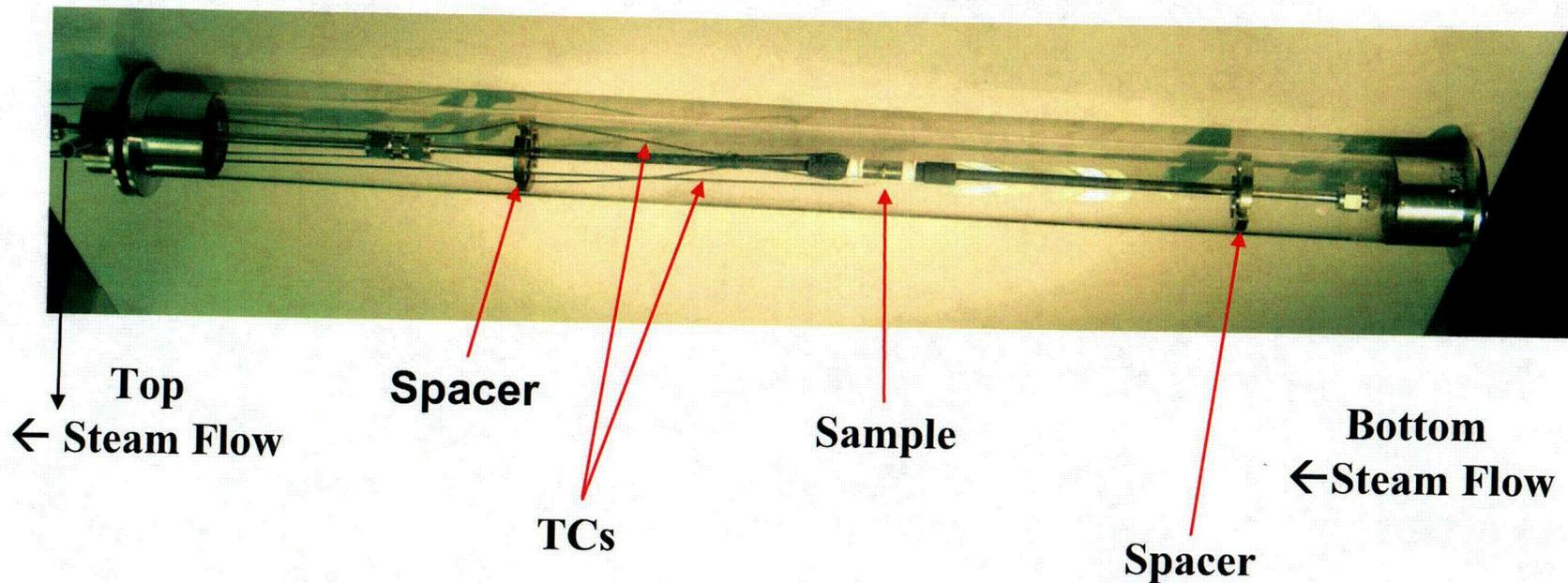
Non-uniform wall-thinning, 2-sided oxidation, high secondary H pickup

- High-burnup PWR Zry-4 (test details to be determined from data below)

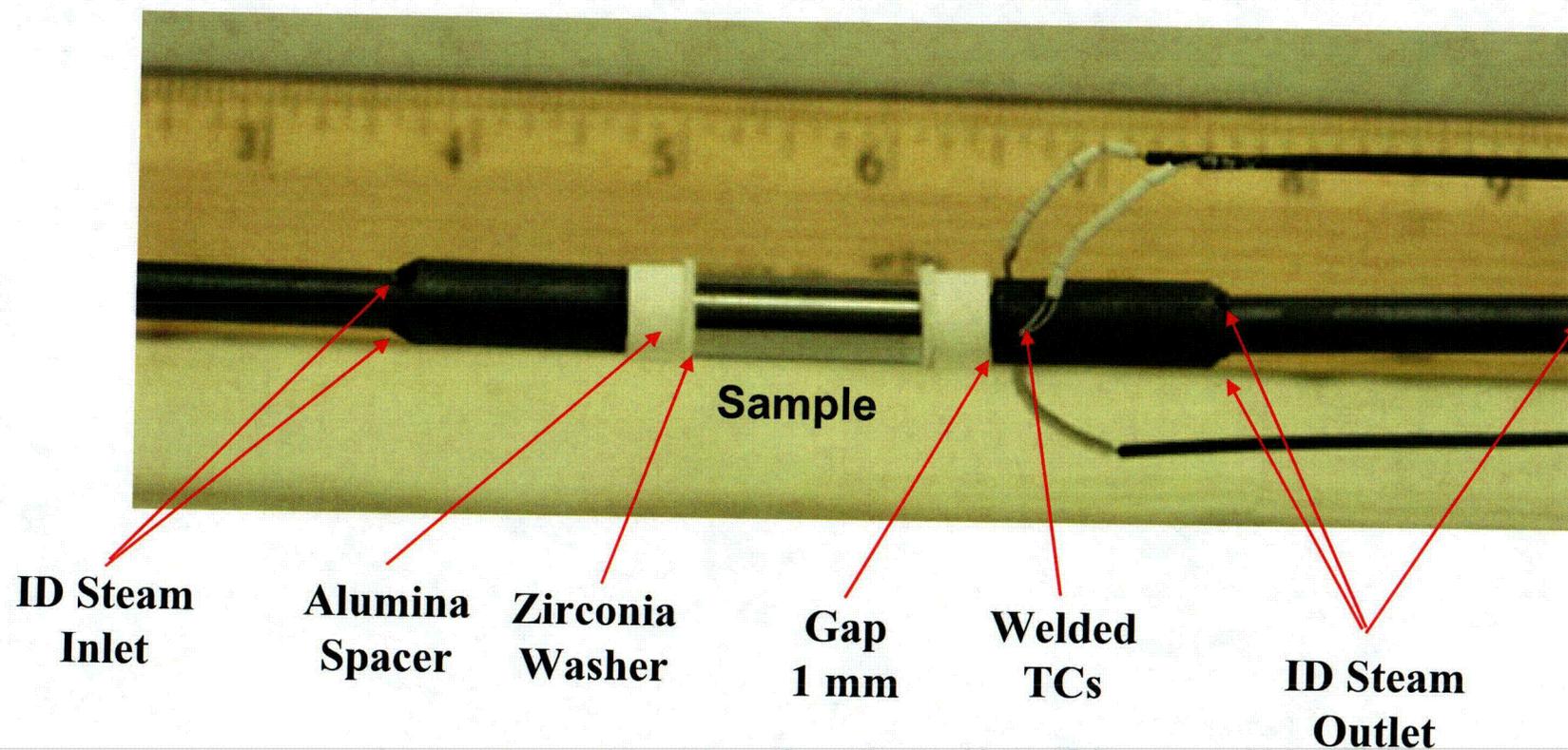
Baseline ductility data for as-fabricated & prehydrided 15×15 Zry-4 rings

High-burnup Zry-4 data: rings oxidized at $\leq 1200^\circ\text{C}$ to 3-9% CP-ECR

Steam Oxidation Test Train with Quartz Tube

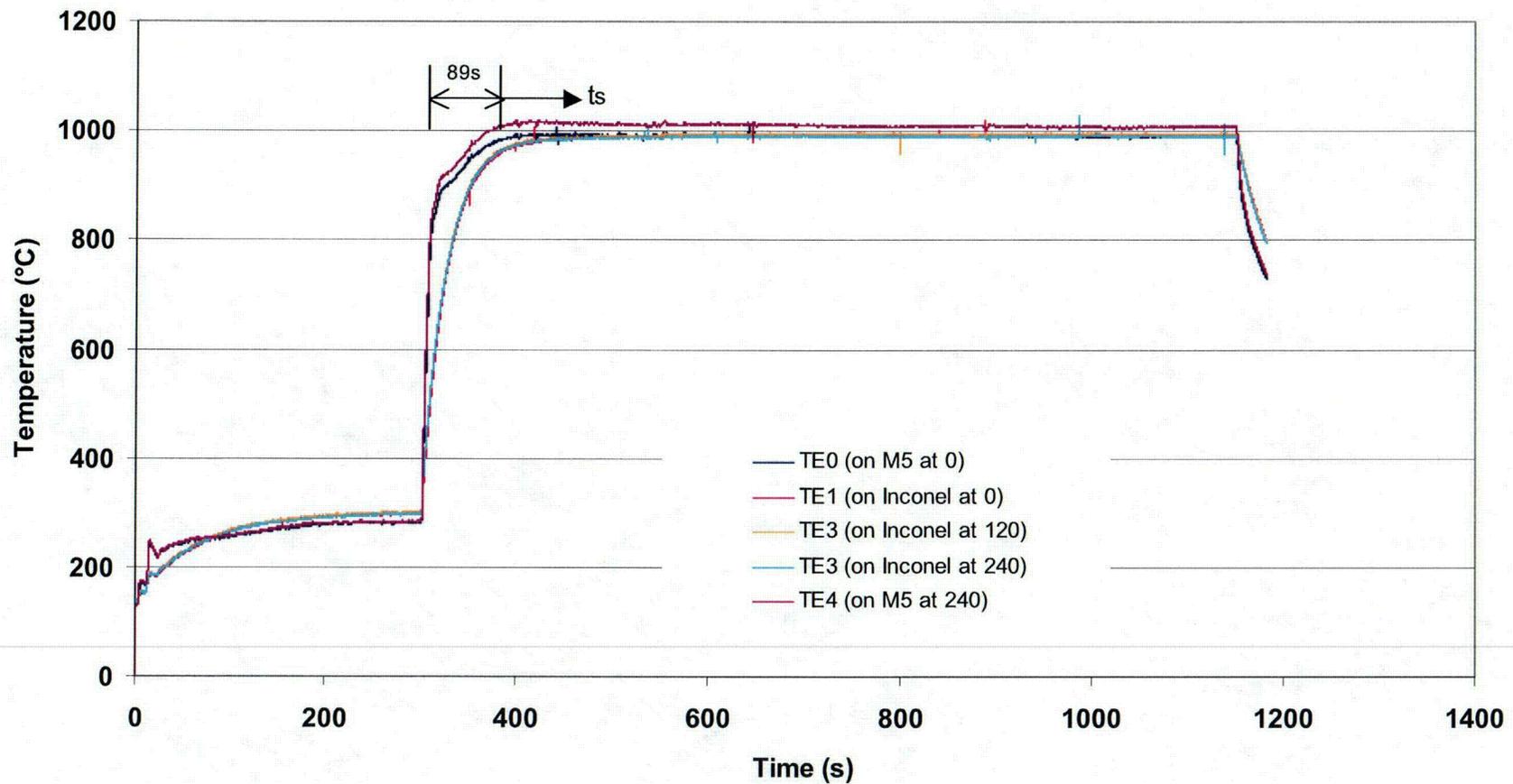


Two-Sided Steam Oxidation Test Train

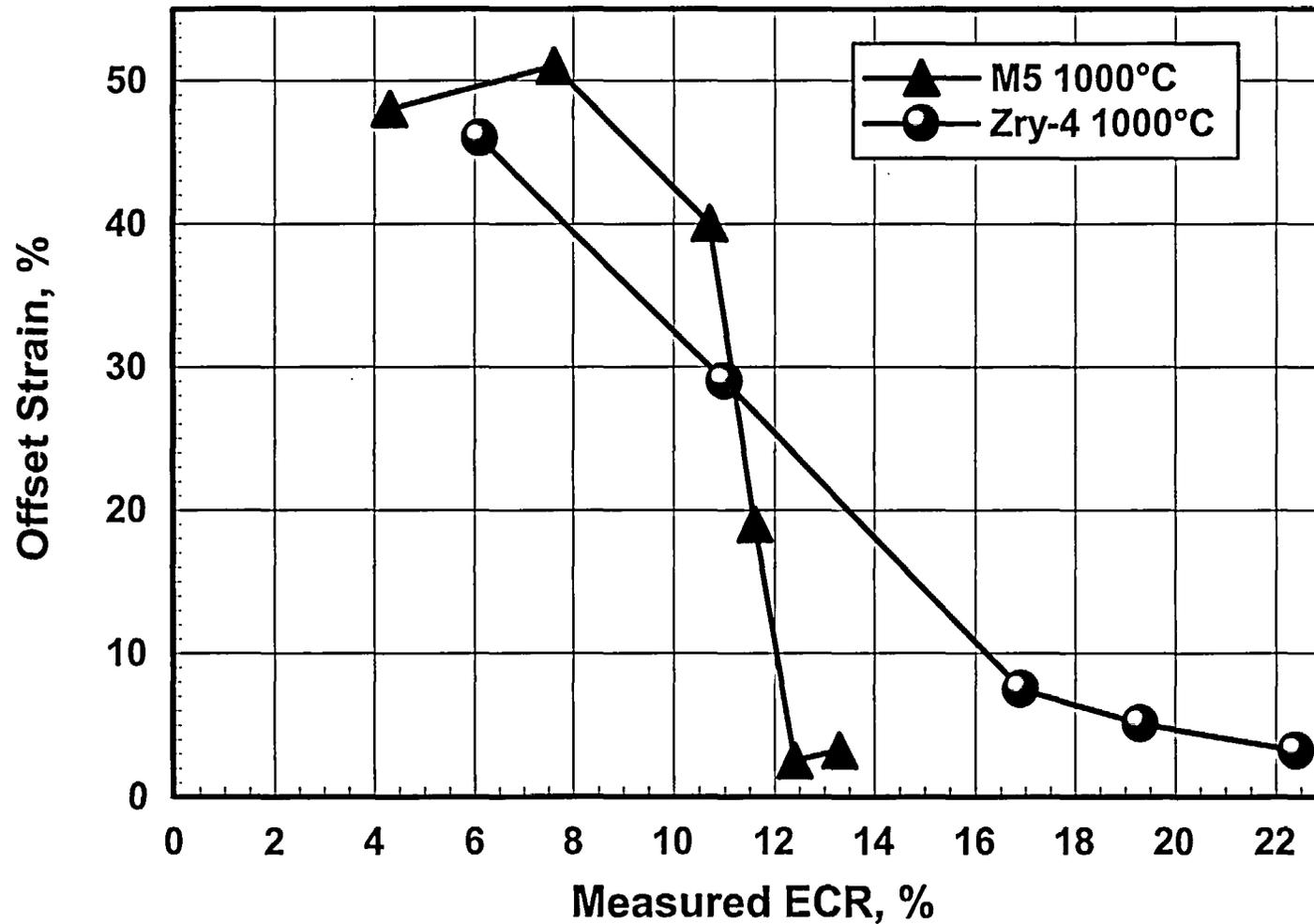


24

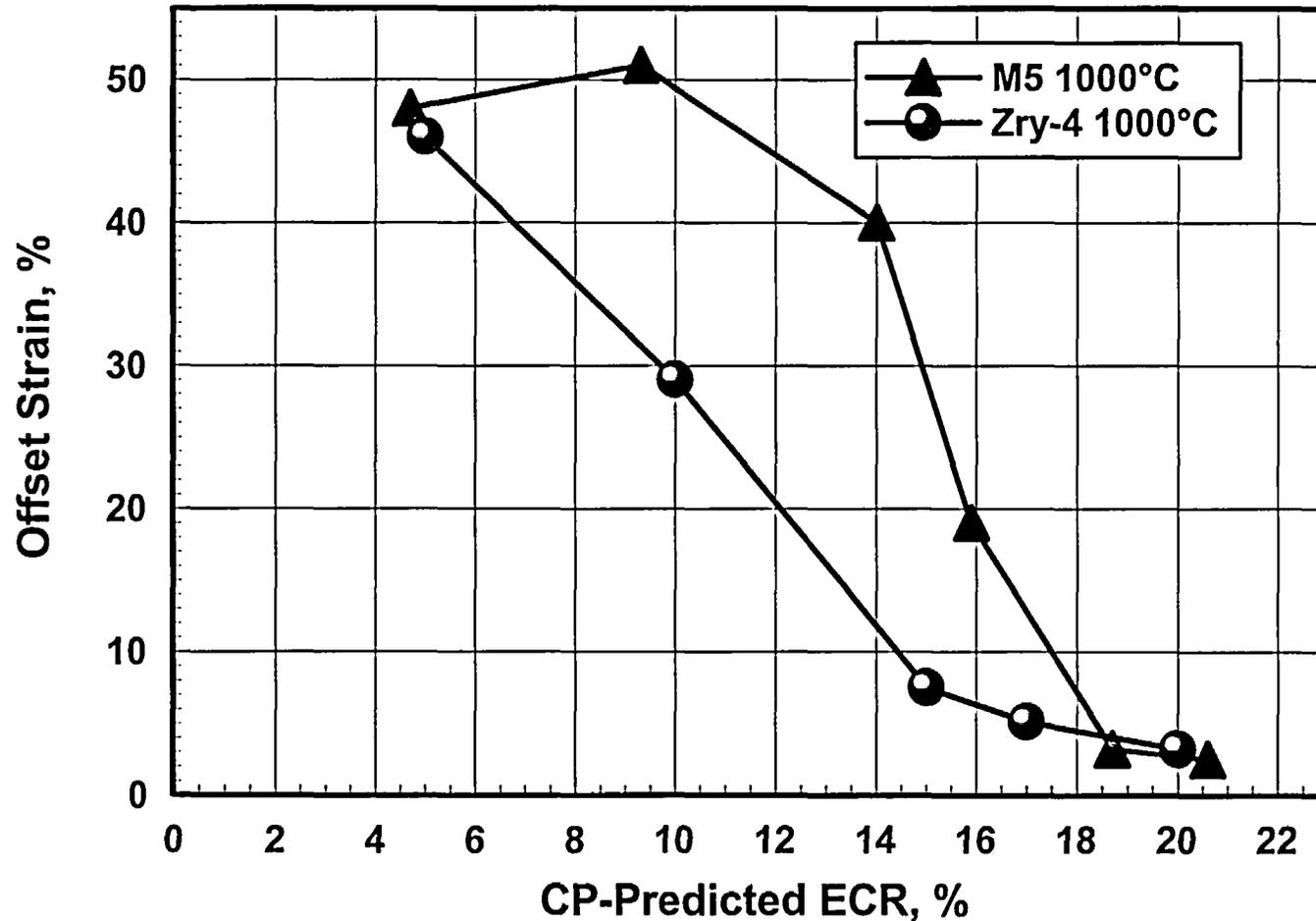
Temperature History for 1000°C Steam Oxidation for 17×17 Cladding Samples (Quench not Shown)



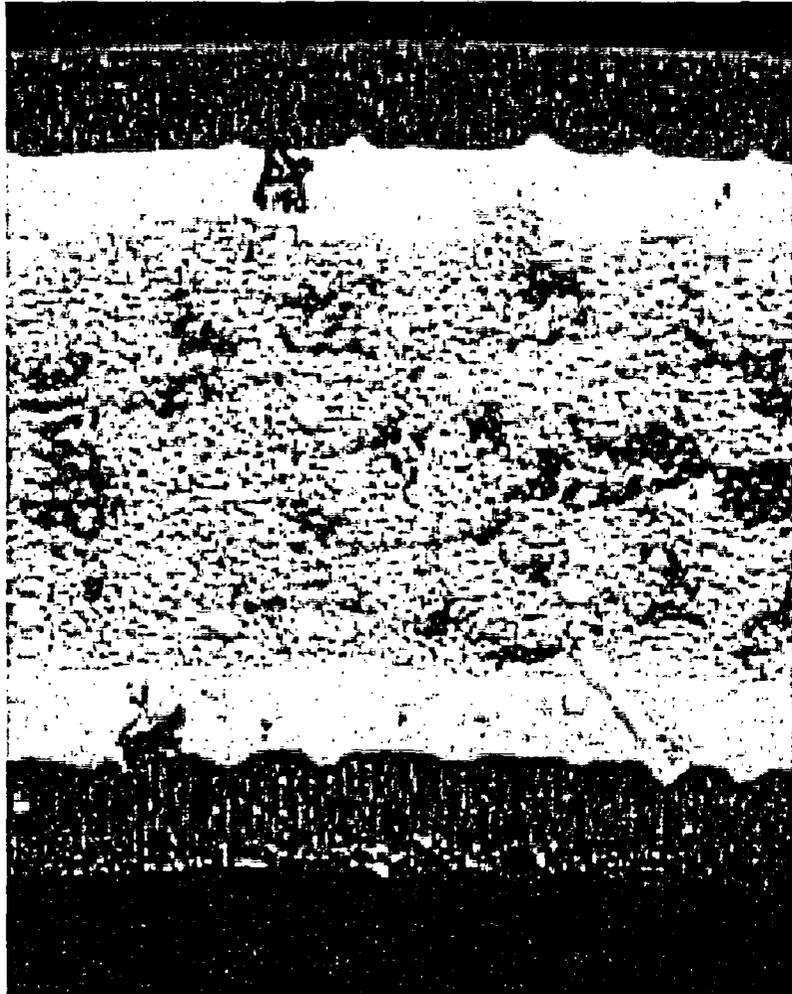
Post-Quench Ductility at Room Temperature M5 & Zry-4 Oxidized at 1000°C vs. Measured ECR



Post-Quench Ductility at Room Temperature M5 & Zry-4 Oxidized at 1000°C vs. Calculated ECR



*Microstructure of M5 and Zry-4 Oxidized for ≈ 3400 s
at 1000°C , cooled at 10°C/s to 800°C & Quenched*

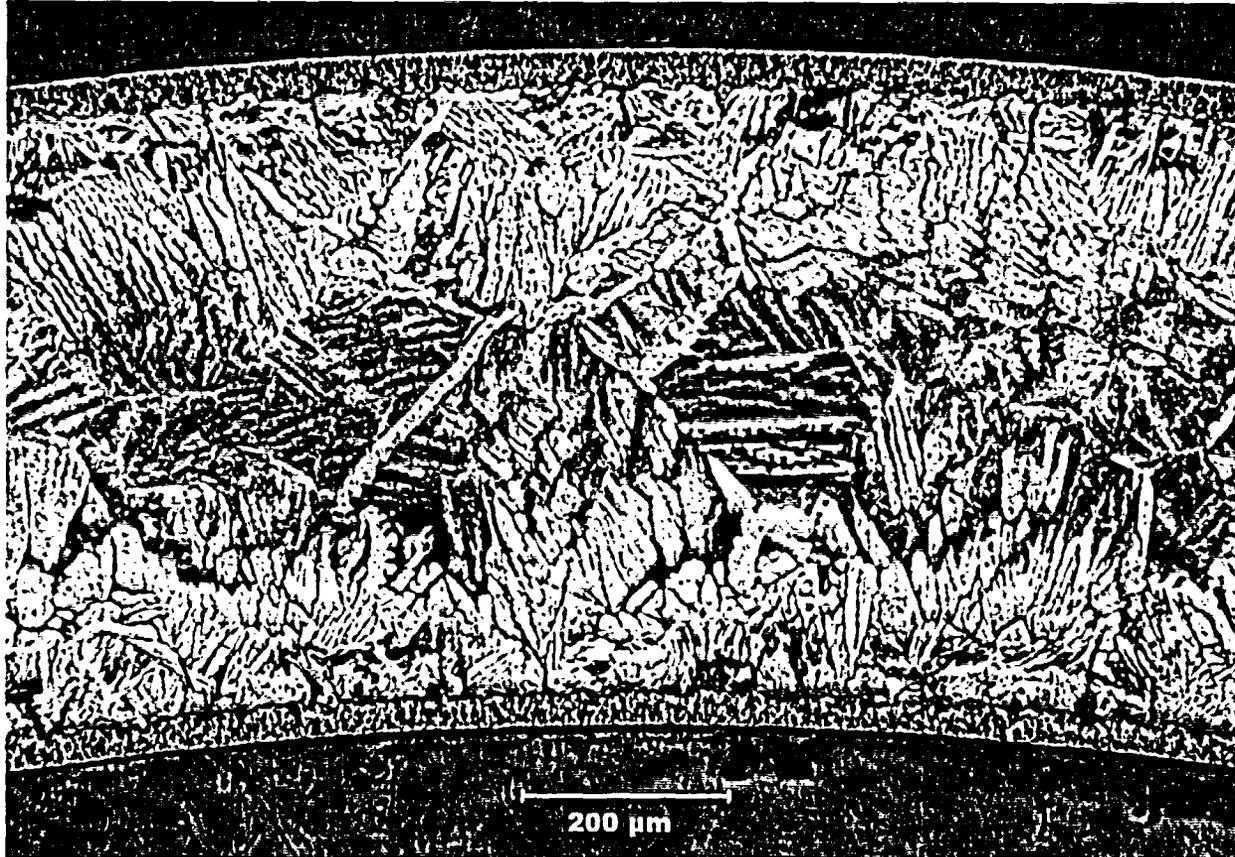


Zry-4



M5

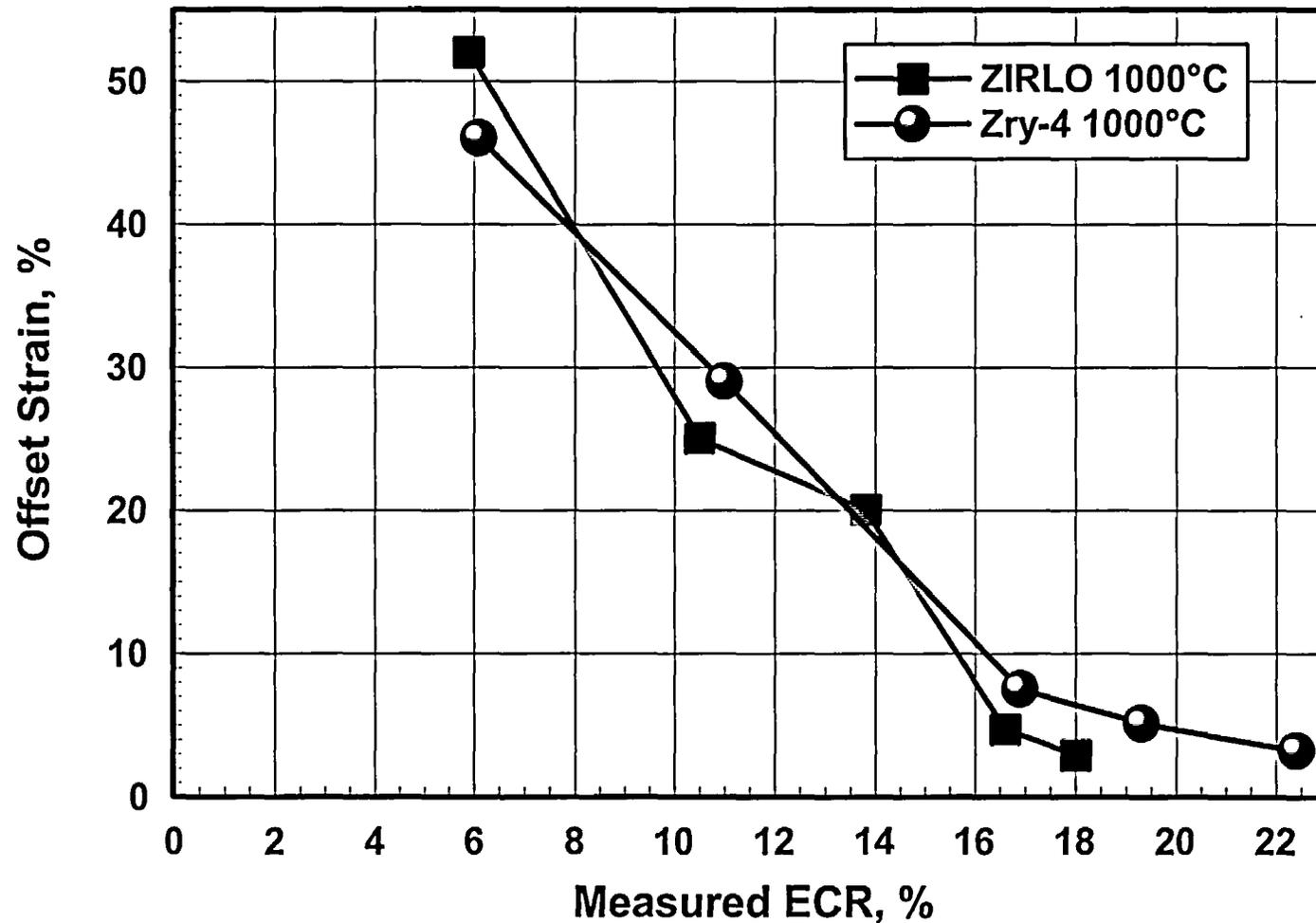
*Microstructure of Etched M5 Oxidized for ≈ 3400 s
at 1000°C , cooled at 10°C/s to 800°C & Quenched*



Microhardness

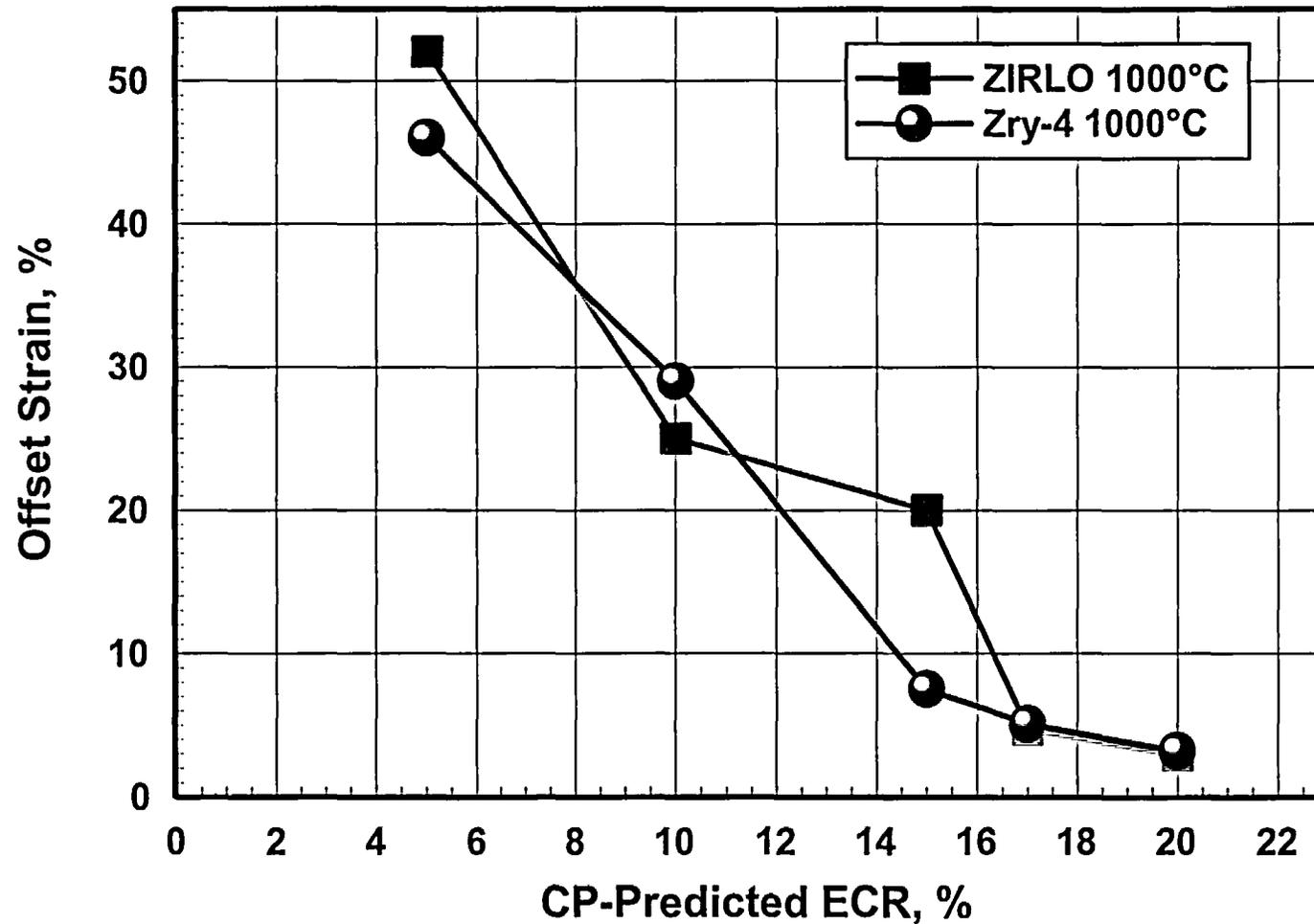
**M5: 300-430 DPH
Zry-4: 290-420 DPH**

Post-Quench Ductility at Room Temperature ZIRLO & Zry-4 Oxidized at 1000°C vs. Measured ECR



30

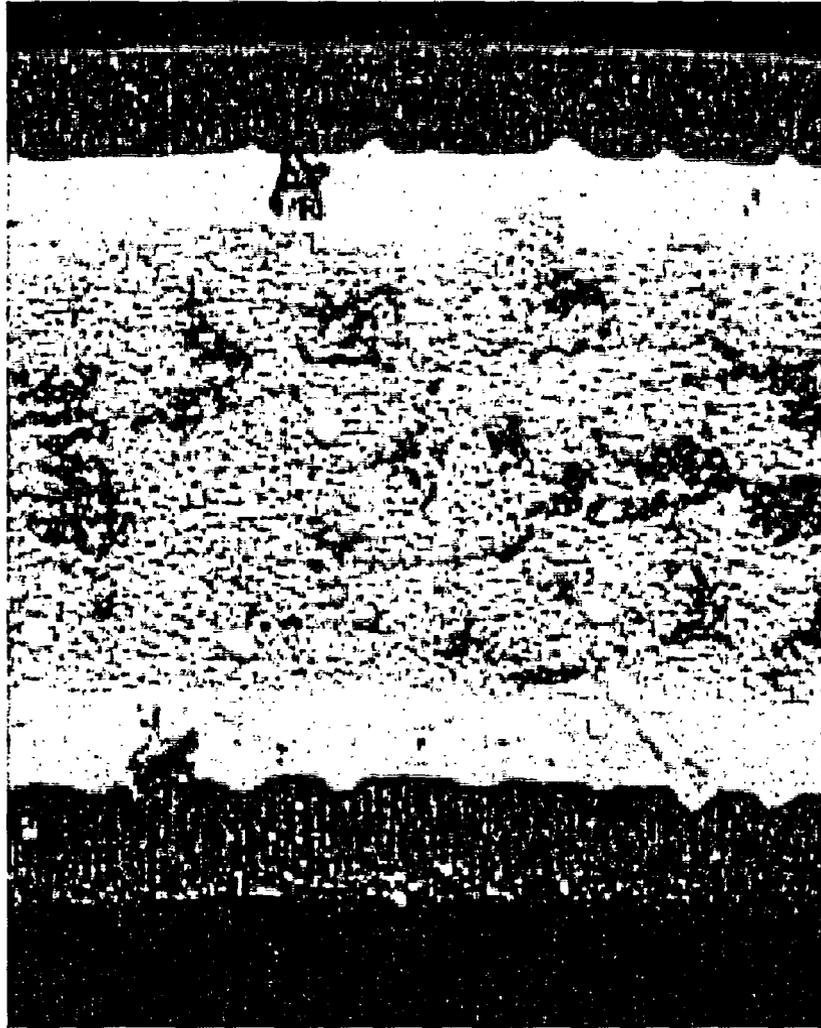
Post-Quench Ductility at Room Temperature ZIRLO & Zry-4 Oxidized at 1000°C vs. Calculated ECR



31



Microstructure of ZIRLO and Zry-4 Oxidized for ≈ 3400 s at 1000°C , cooled at 10°C/s to 800°C & Quenched



Zry-4



ZIRLO

*Microstructure of Etched ZIRLO Oxidized for ≈ 3400 s
at 1000°C , cooled at 10°C/s to 800°C & Quenched*



Microhardness
290-400 DPH

H-Pickup = 100 wppm



Summary of M5 PQD following Oxidation at 1000°C

- **Weight Gain and Measured ECR vs. Time at 1000°C**

- 3364 s: $W_g = 9.2 \text{ mg/cm}^2$, measured ECR = 13.3%
- 4064 s: $W_g = 8.6 \text{ mg/cm}^2$, measured ECR = 12.4%

- **Post-Quench Ductility**

- Correlates better with CP-ECR (\sqrt{t}) than measured ECR
- 3364 s: RT $\delta_p/D_o = 0.307\text{-mm}/9.50\text{-mm} = 3.2\%$
- 4064 s: RT $\delta_p/D_o = 0.238\text{-mm}/9.50\text{-mm} = 2.5\%$

Test interrupted after 1st significant load drop

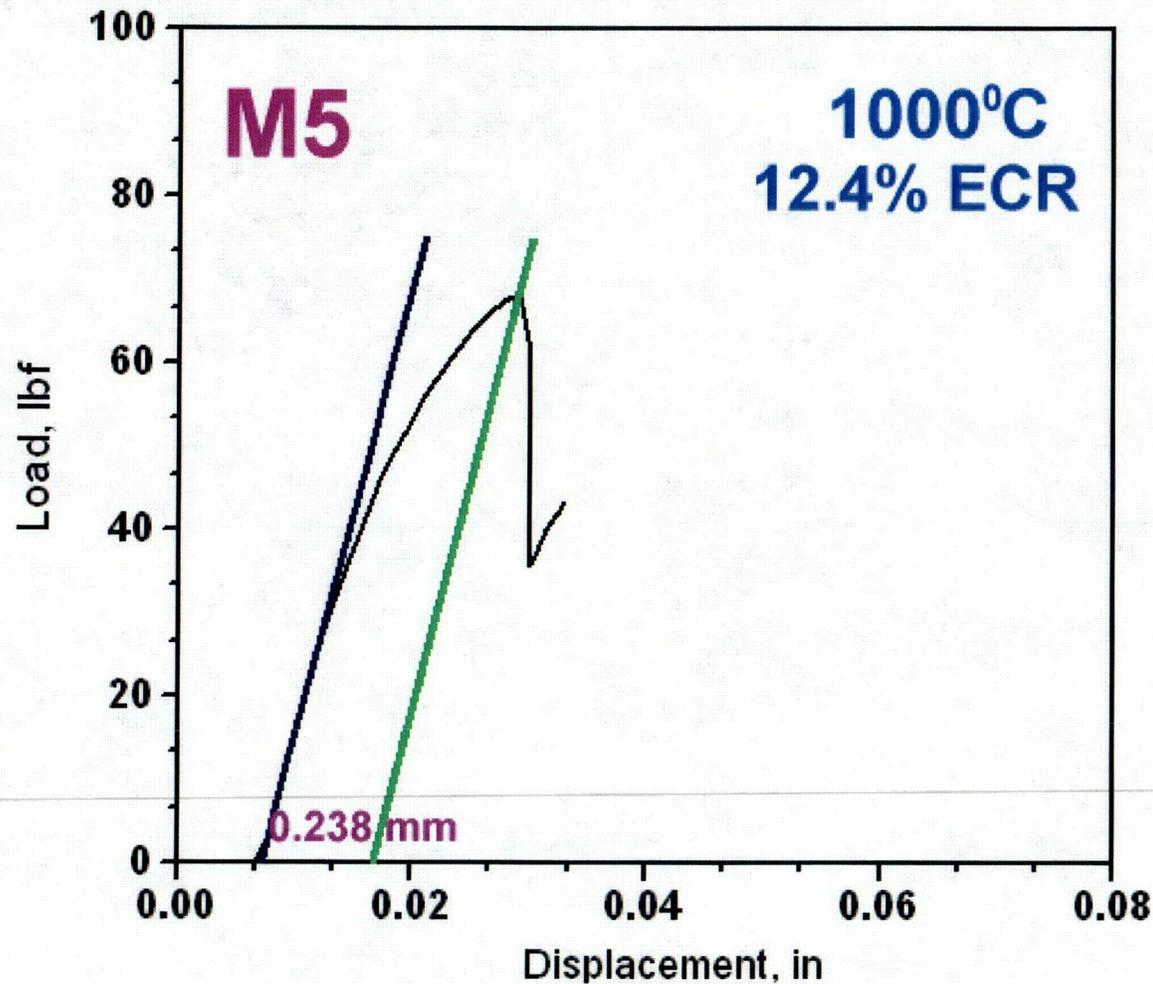
Measured change in diameter (d_p) = 0.2 mm \rightarrow 2.1% permanent strain

135°C $\delta_p/D_o = 0.504\text{-mm}/9.50\text{-mm} = 5.3\%$

$d_p/D_o = 0.304\text{-mm}/9.50\text{-mm} = 3.0\%$

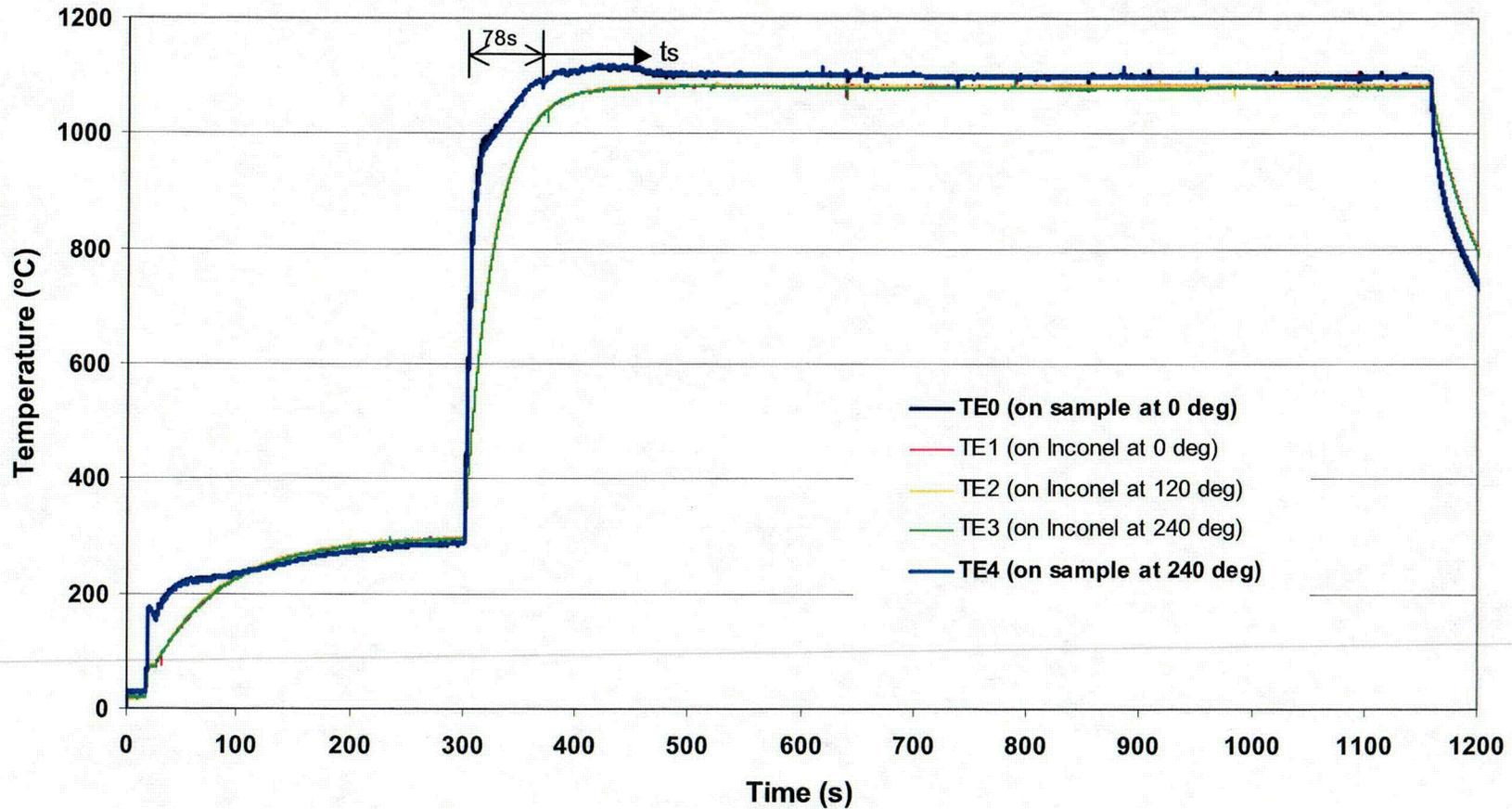


Load-Displacement Curve for M5 Oxidized at 1000°C for ≈ 4100 s and Ring-Compressed at RT

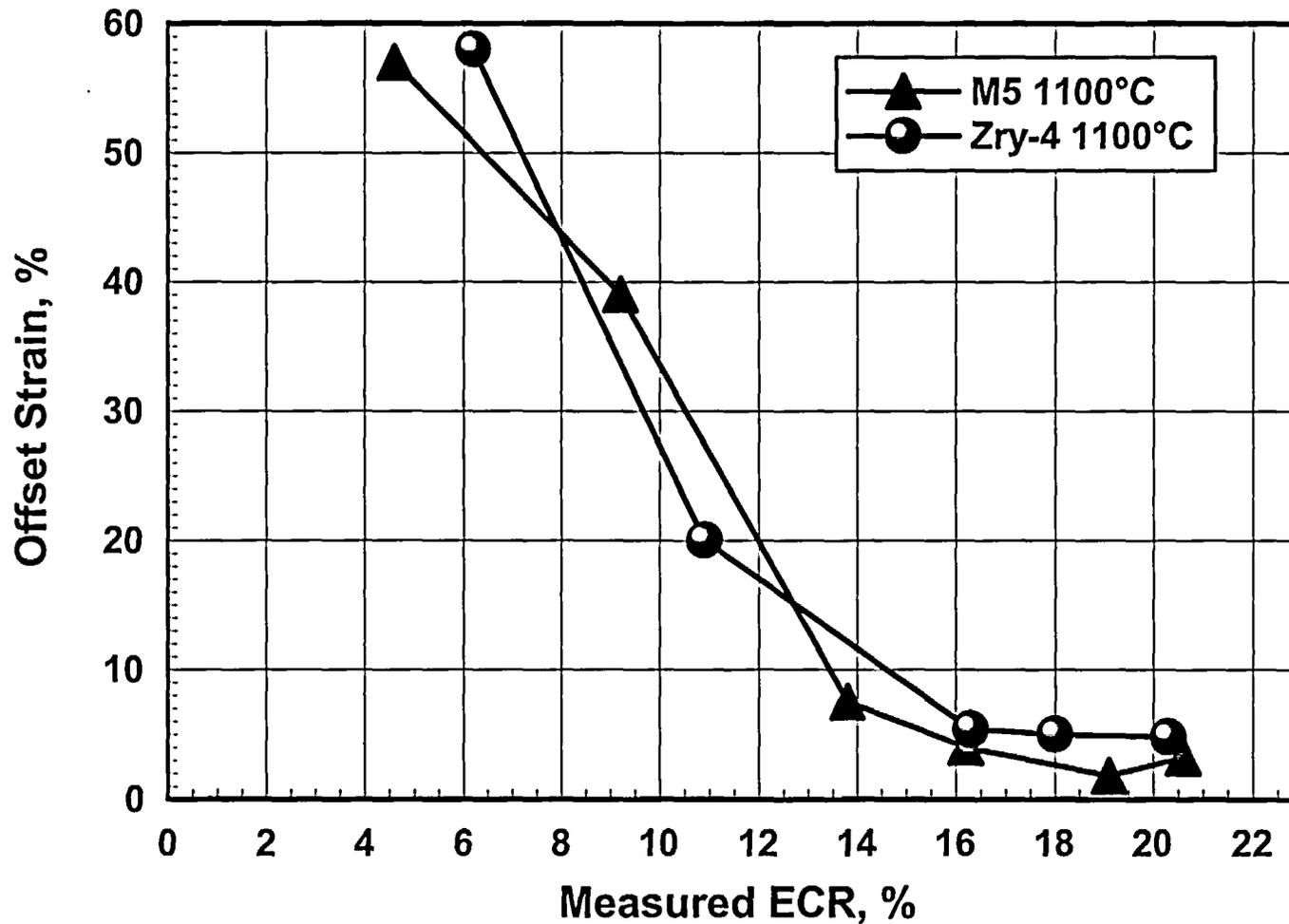


Temperature History for 1100°C Steam Oxidation for 17×17 Cladding Samples (Quench not Shown)

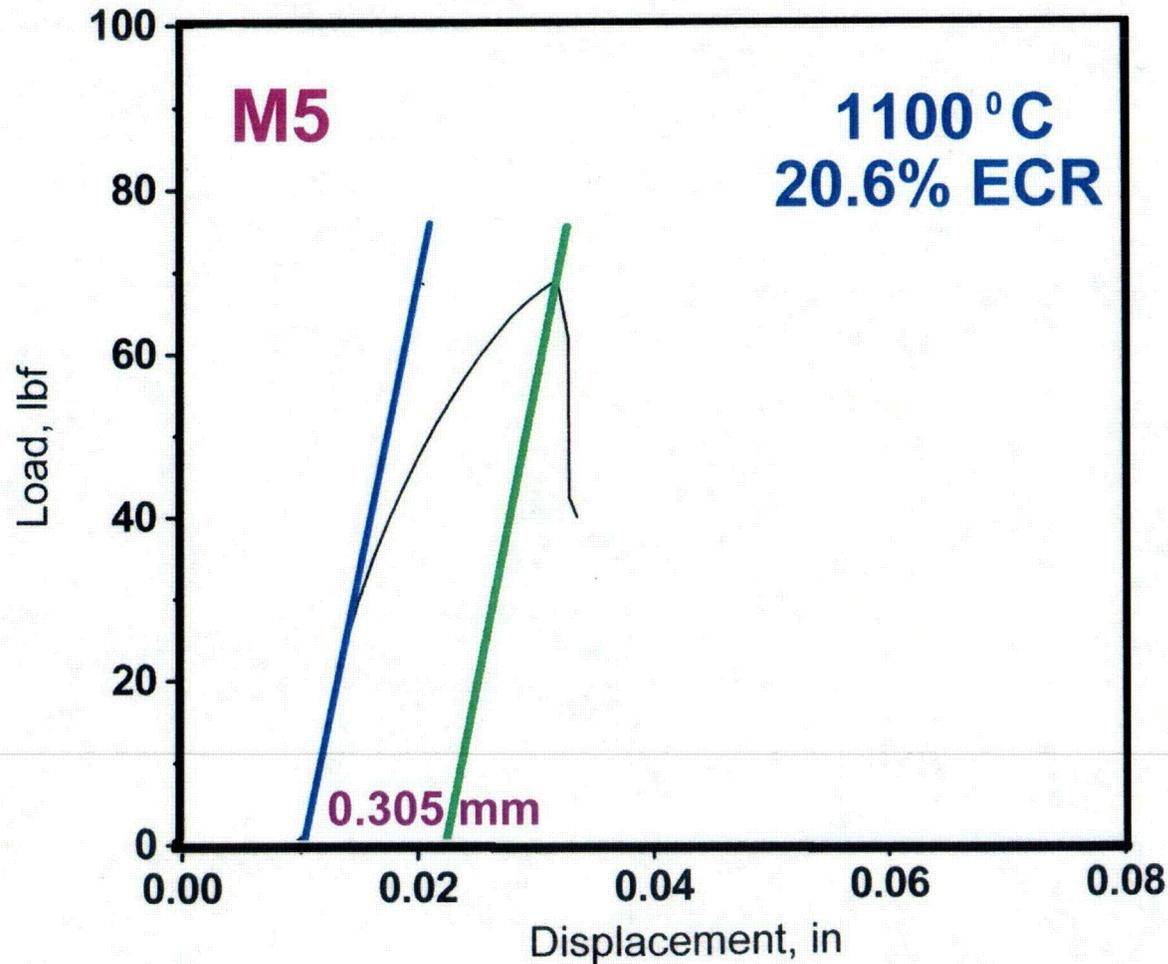
Thermal Benchmark Test (M5 Sample in Steam) at 1100°C Hold Temperature for 780s



Post-Quench Ductility at Room Temperature M5 & Zry-4 Oxidized at 1100°C vs. Measured ECR



*RT Post-Quench Ductility of M5 Oxidized
at 1100°C to ≈21% ECR: $d_p/D_o = 1.1\%$*



Post-Quench Microstructure of M5 and Zry-4 following Oxidation at 1100°C for ≈ 1100 s

M5



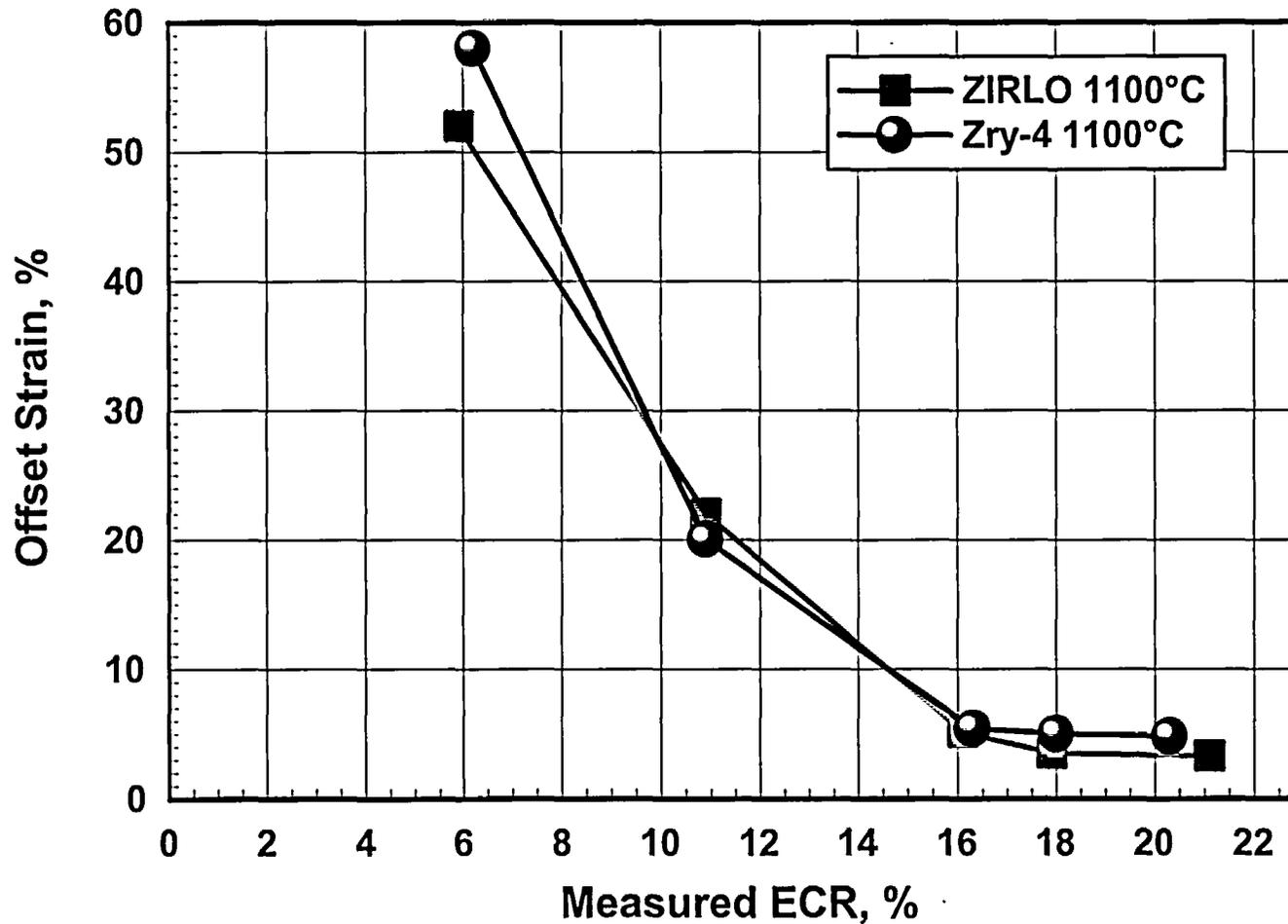
Zry-4



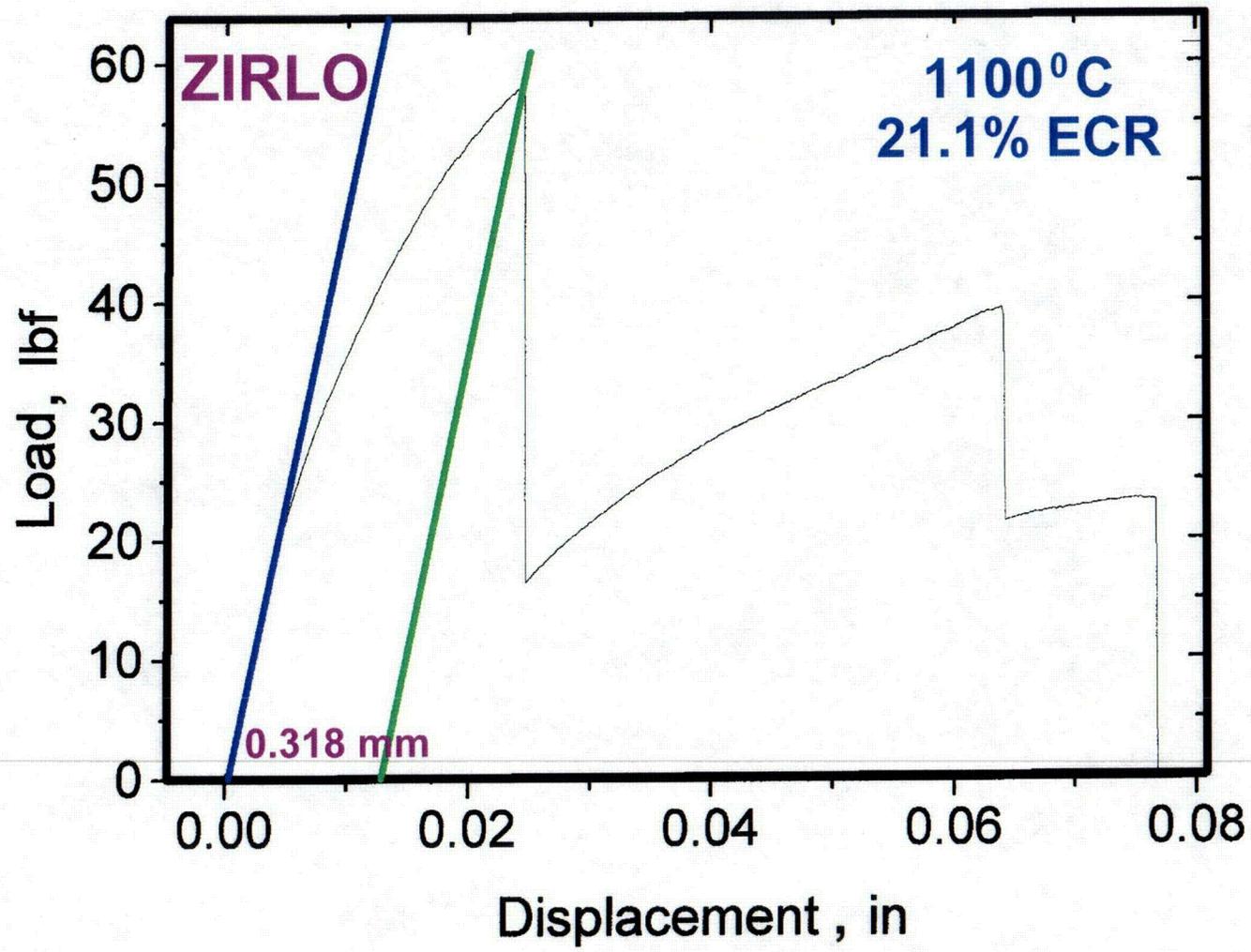
Microhardness = 260-400 DPH for M5; 240-470 DPH for Zry-4

39

Post-Quench Ductility at Room Temperature ZIRLO & Zry-4 Oxidized at 1100°C vs. Measured ECR



RT Load-Displacement Curve for ZIRLO Oxidized at 1100°C to 21% ECR

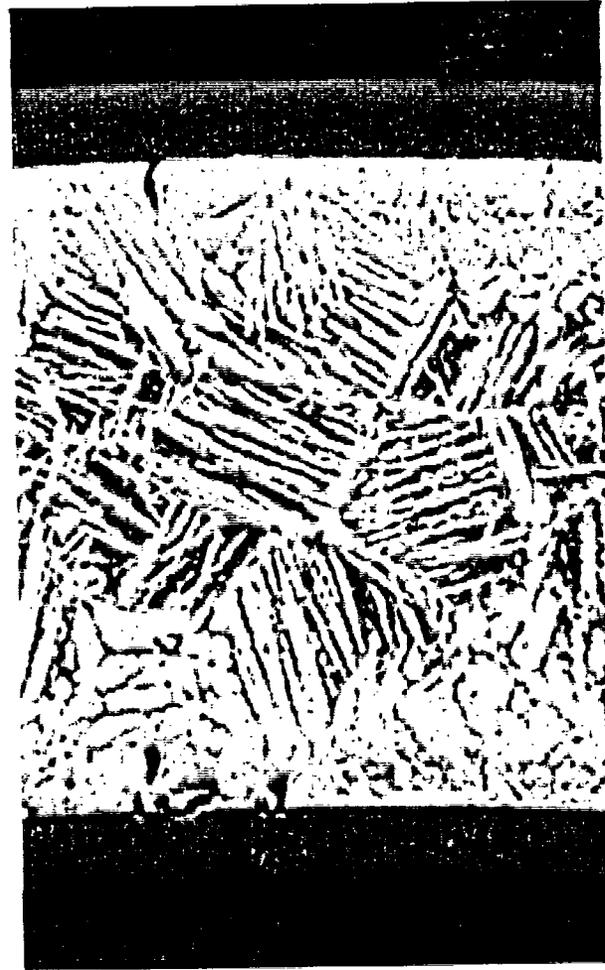


Post-Quench Microstructure of Zry-4 & ZIRLO following Oxidation at 1100°C for ≈ 1100 s

Zry-4

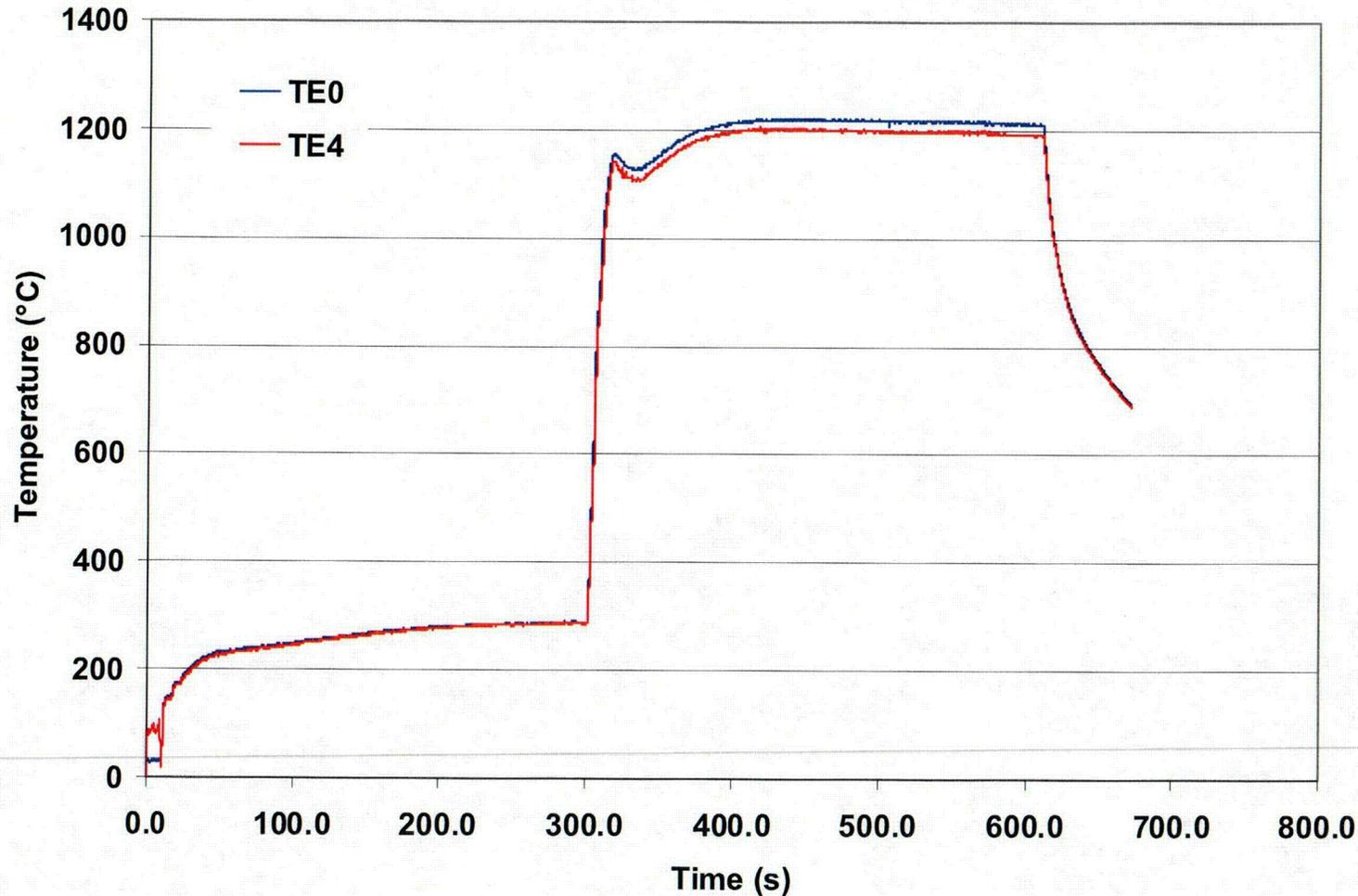


ZIRLO

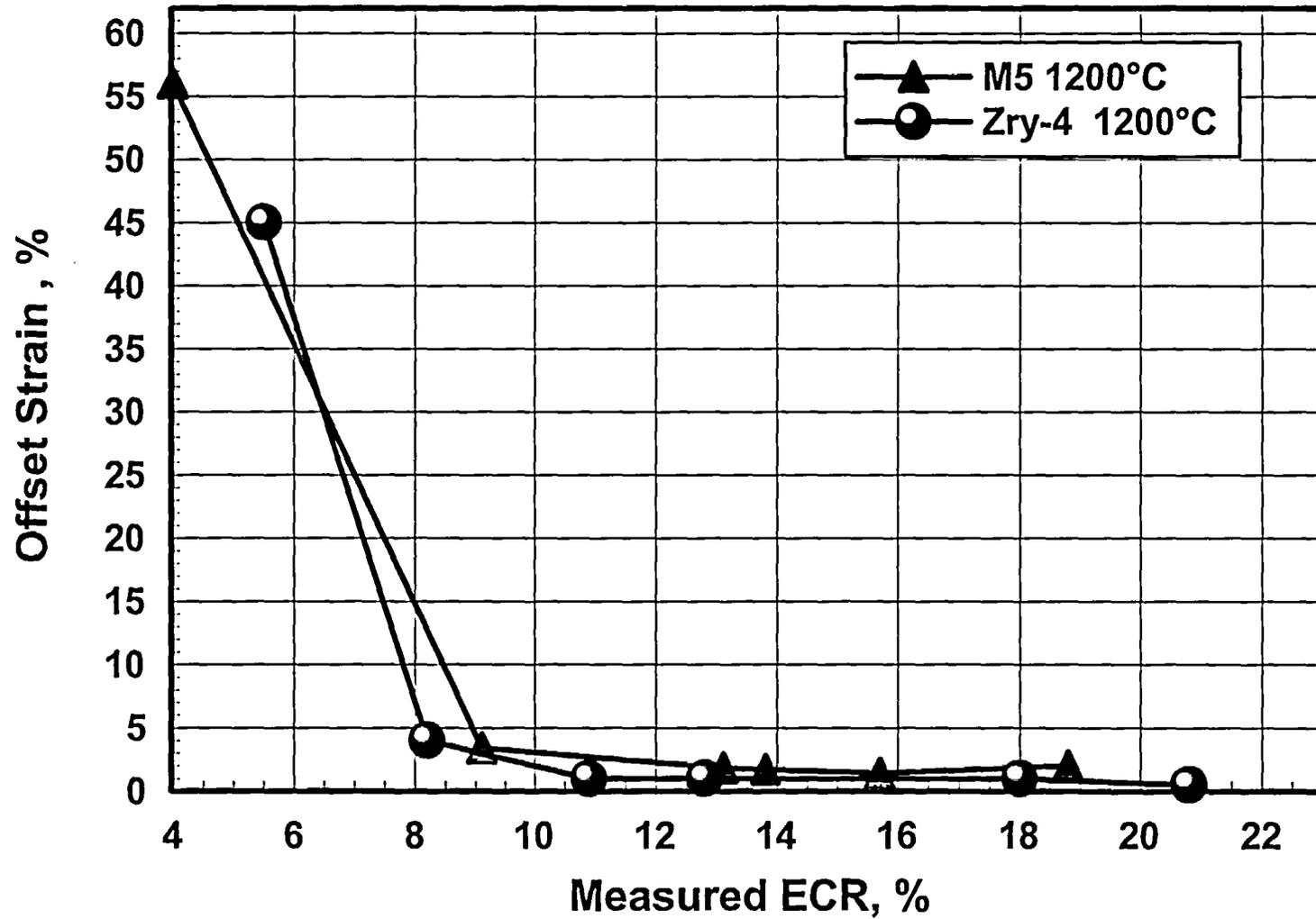


Microhardness = 240-470 DPH for ZRY-4; 330-460 DPH for ZIRLO

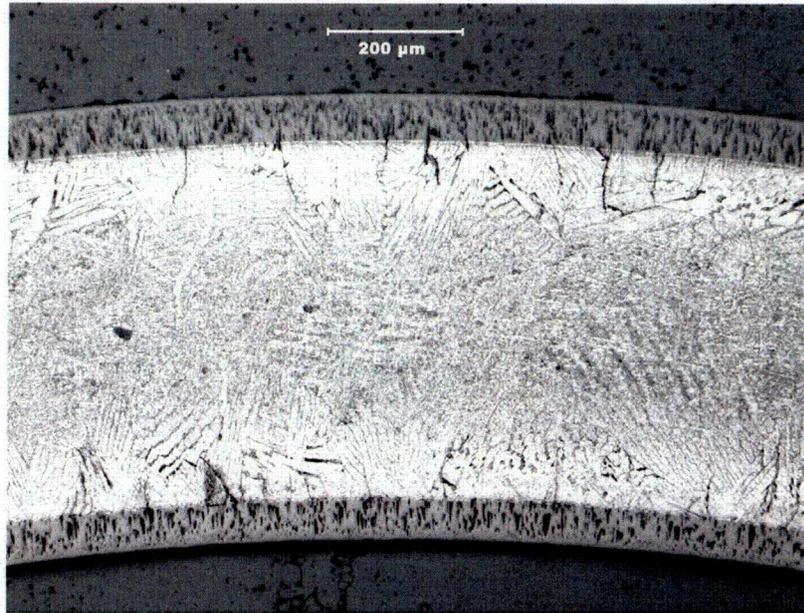
Temperature History for $1200 \pm 5^\circ\text{C}$ Steam Oxidation for 17×17 Cladding Samples (Quench not Shown)



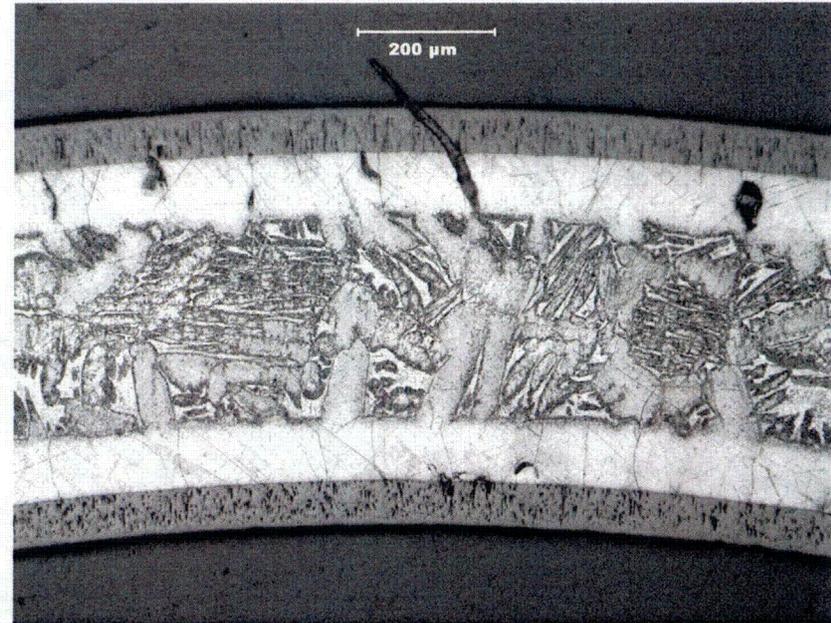
RT Offset Strain for 1200°C-Oxidatized M5 vs. Zry-4



Post-Quench Microstructure of M5 and Zry-4 following Oxidation at 1200°C for ≈ 400 s



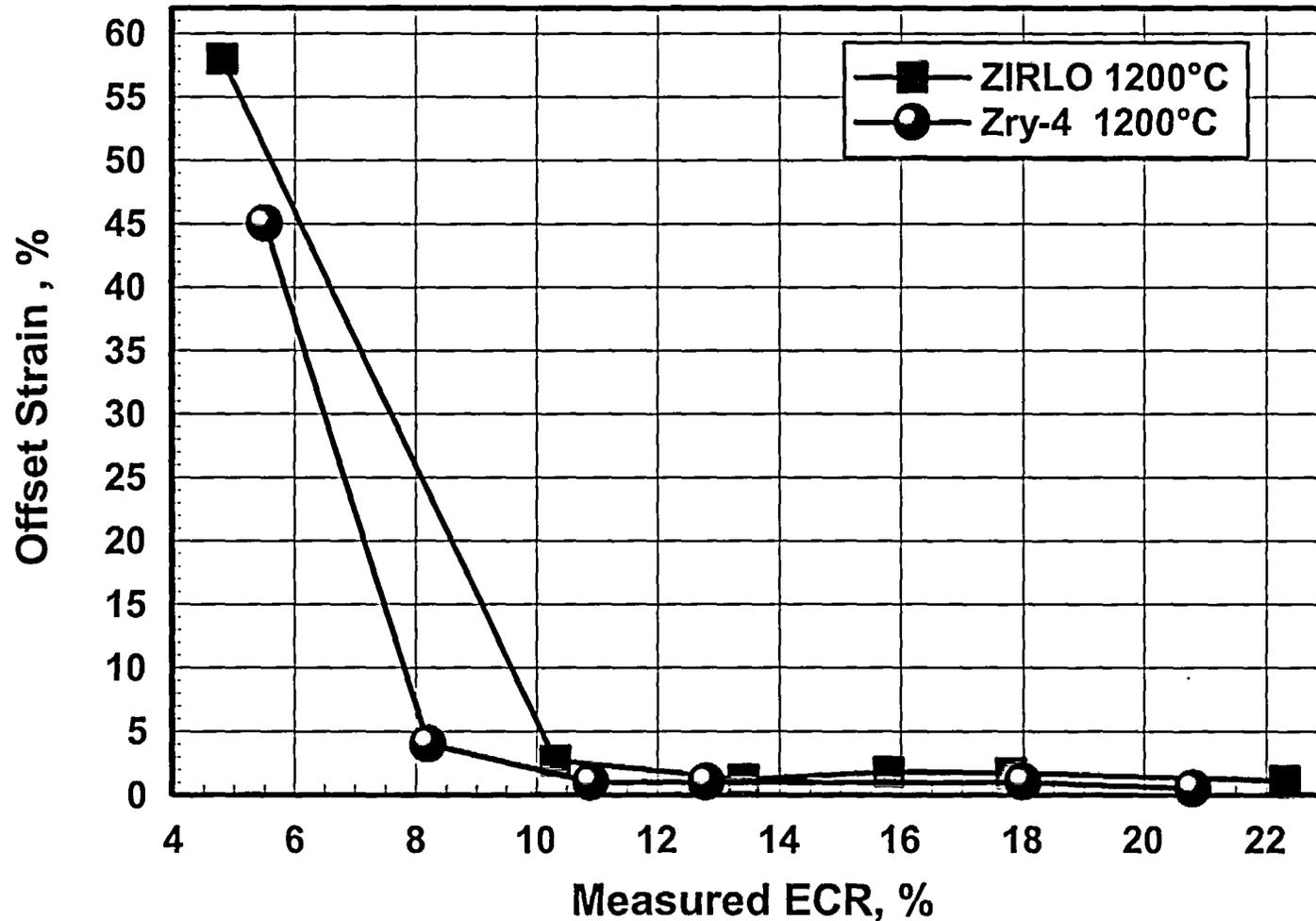
M5



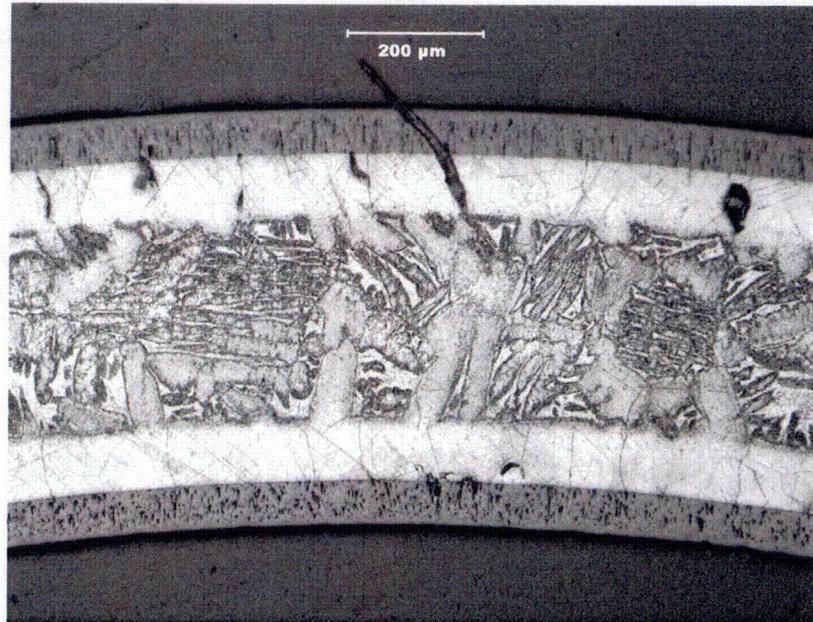
Zry-4

Microhardness = 280-450 DPH for M5; 280-600 DPH for Zry-4

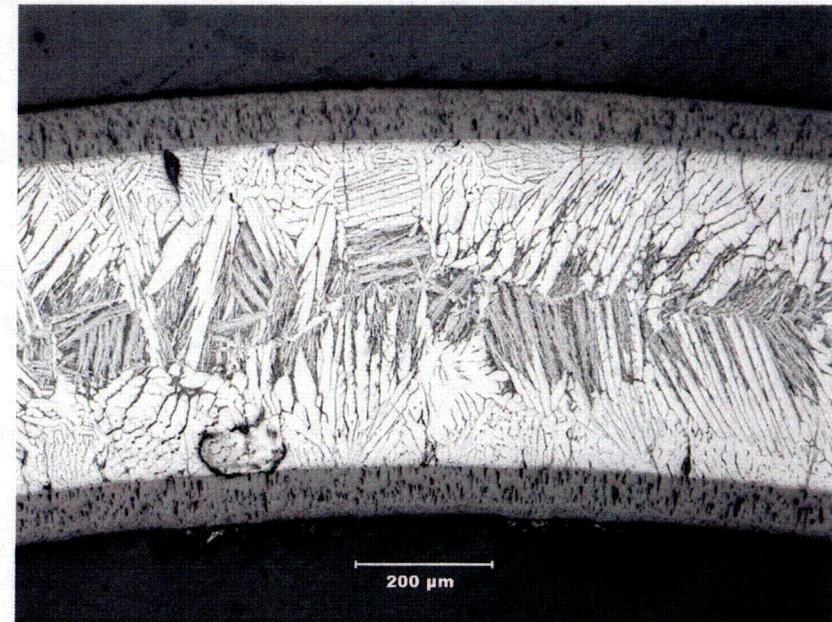
RT Offset Strain for 1200°C-Oxidatized ZIRLO vs. Zry-4



Post-Quench Microstructure of Zry-4 & ZIRLO following Oxidation at 1200°C for ≈ 400 s



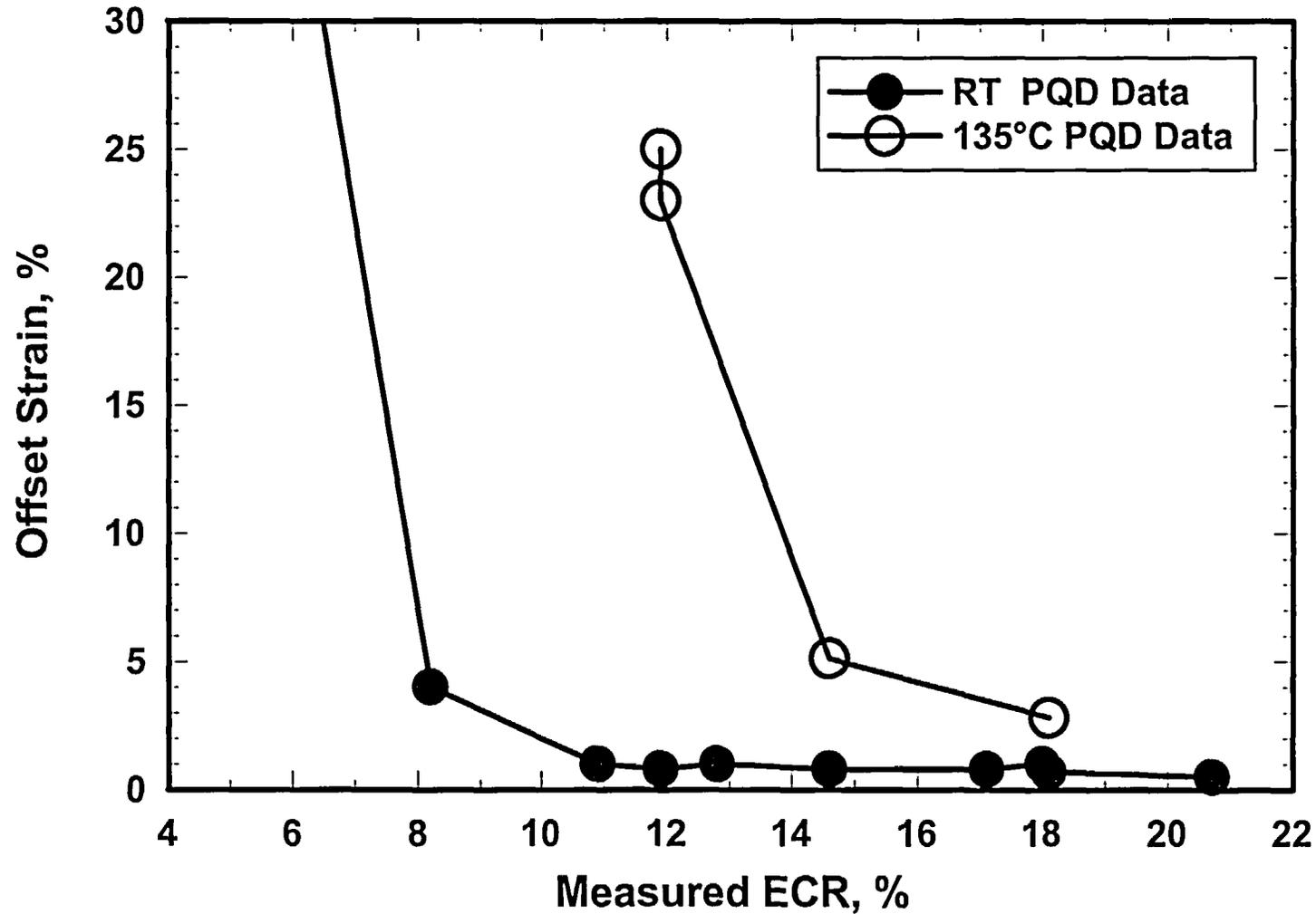
Zry-4



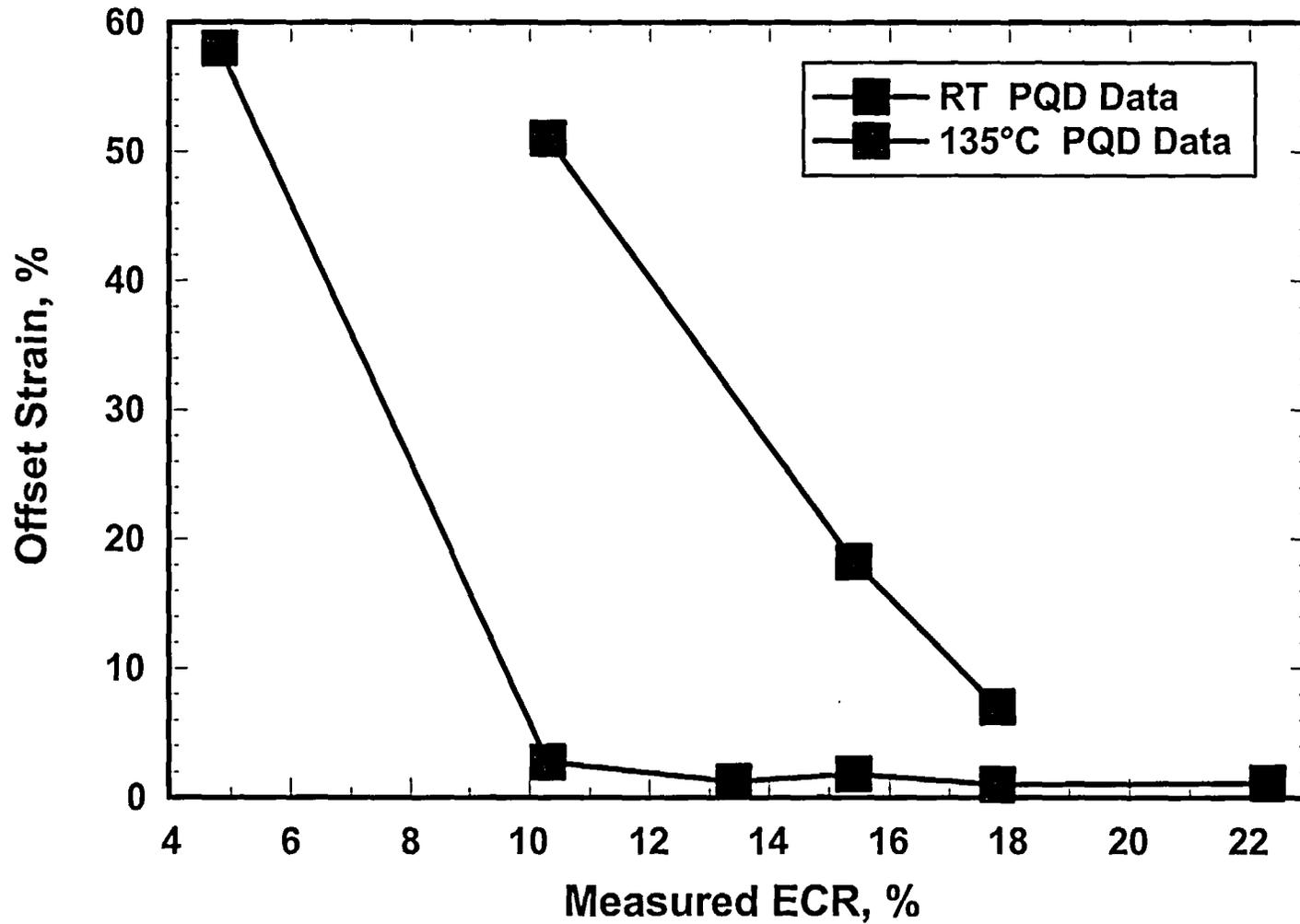
ZIRLO

Microhardness = 280-600 DPH for Zry-4; 350-530 DPH for ZIRLO

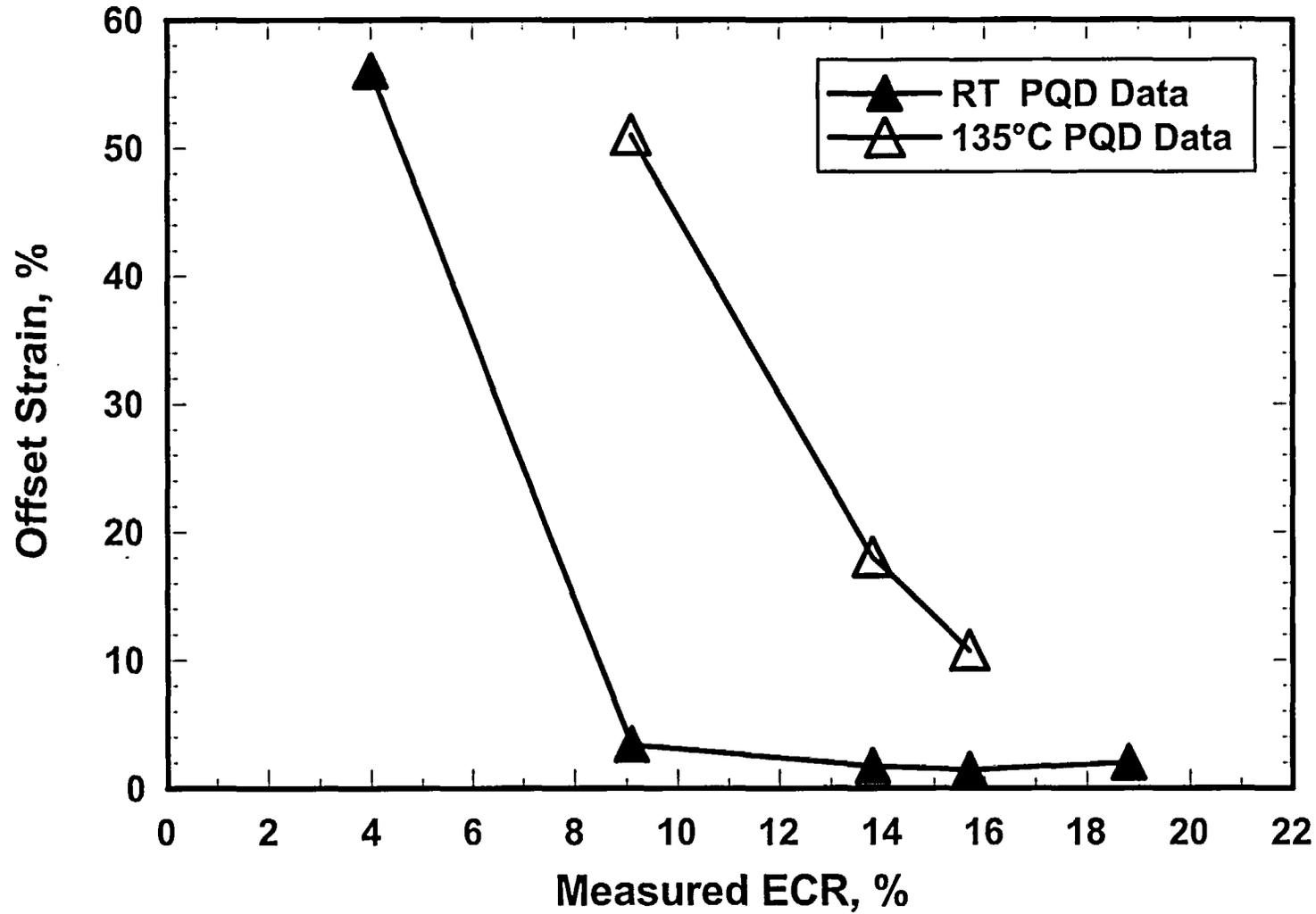
135°C Offset Strain for 17x17 Zry-4 Oxidized at 1200°C



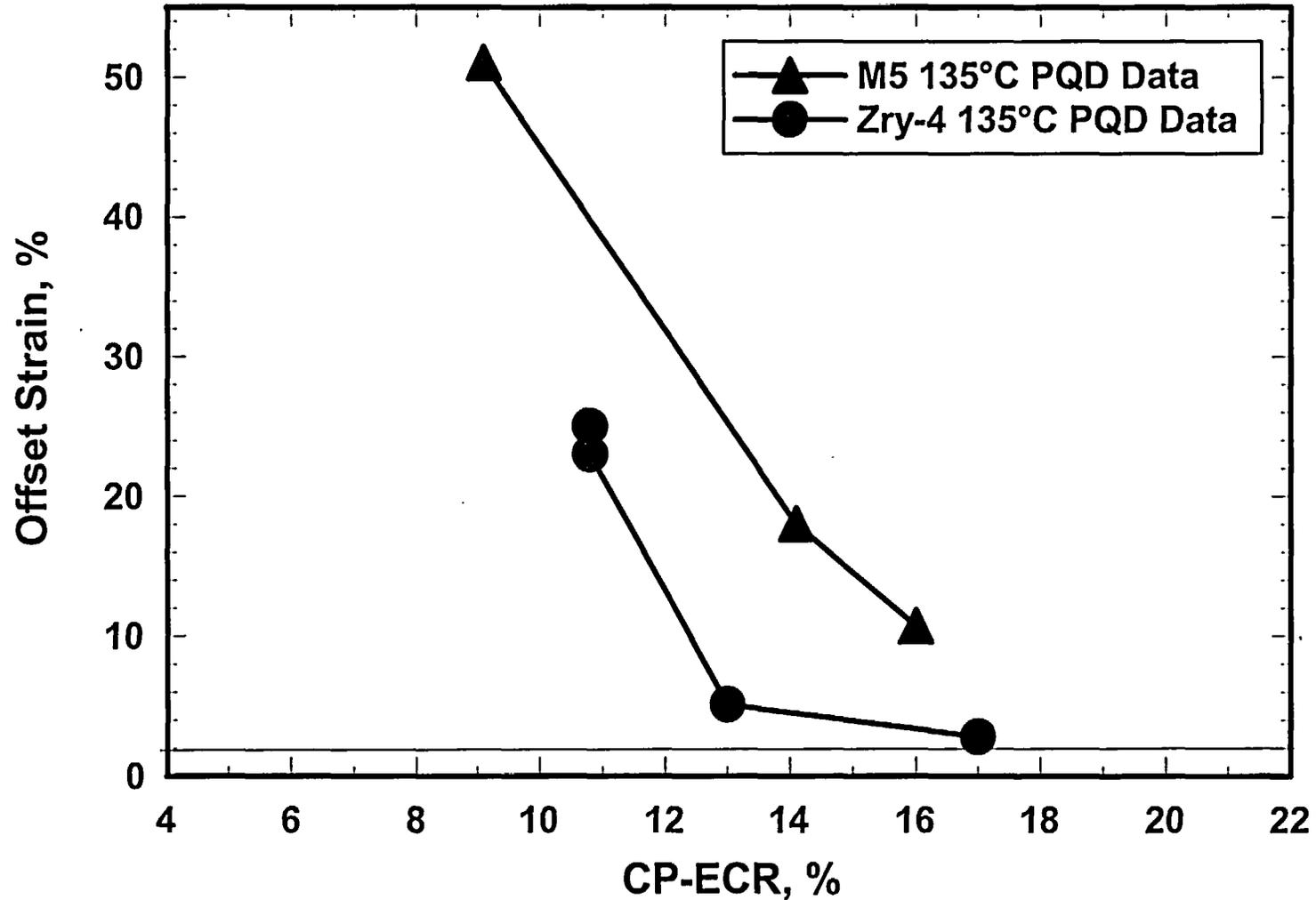
135°C Offset Strain for 17x17 ZIRLO Oxidized at 1200°C



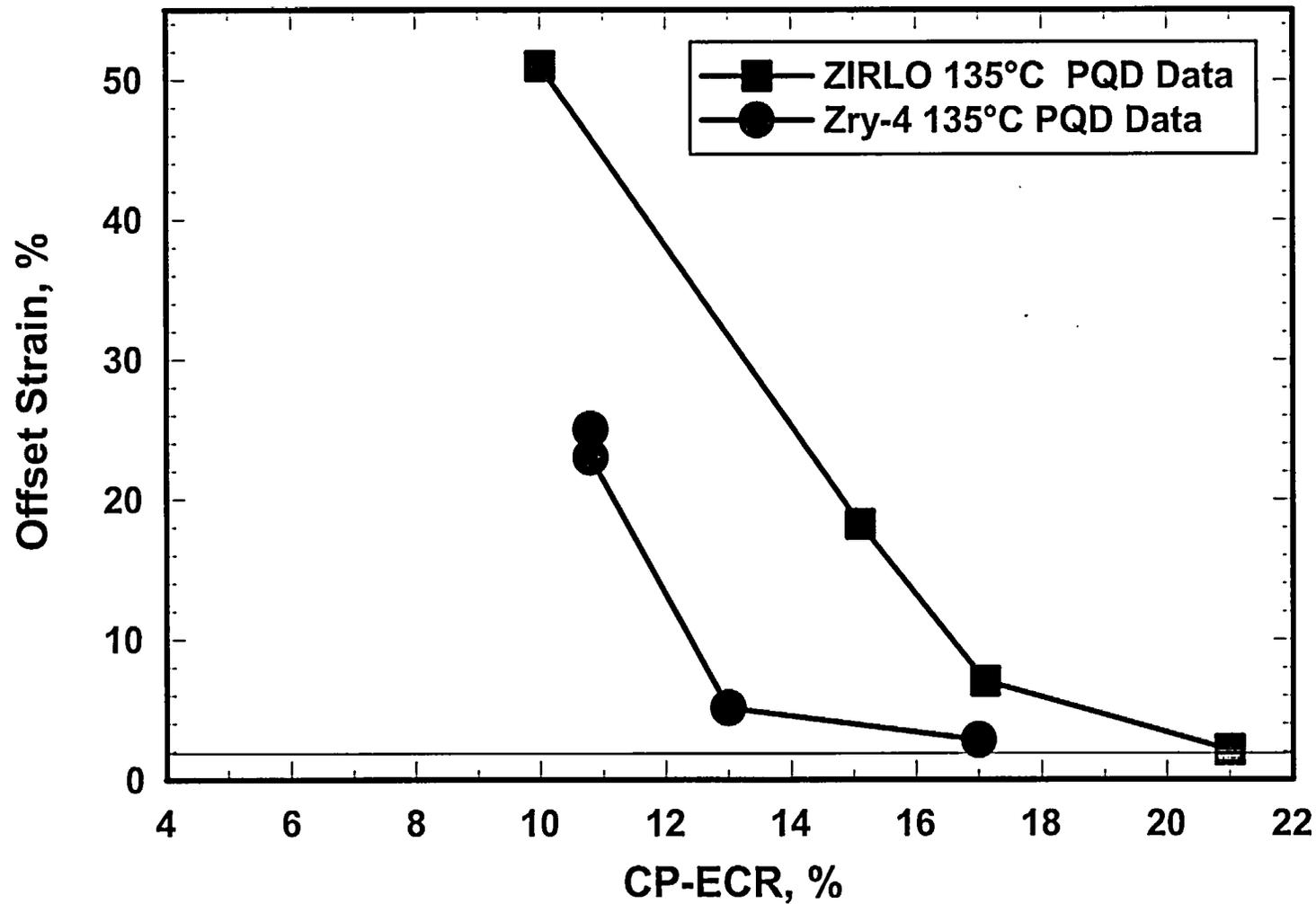
135°C Offset Strain for 17x17 M5 Oxidized at 1200°C



135°C Offset Strain for 17x17 M5 & Zry-4 Oxidized at 1200°C vs. CP-ECR



135°C Offset Strain for 17x17 ZIRLO & Zry-4 Oxidized at 1200°C vs. CP-ECR



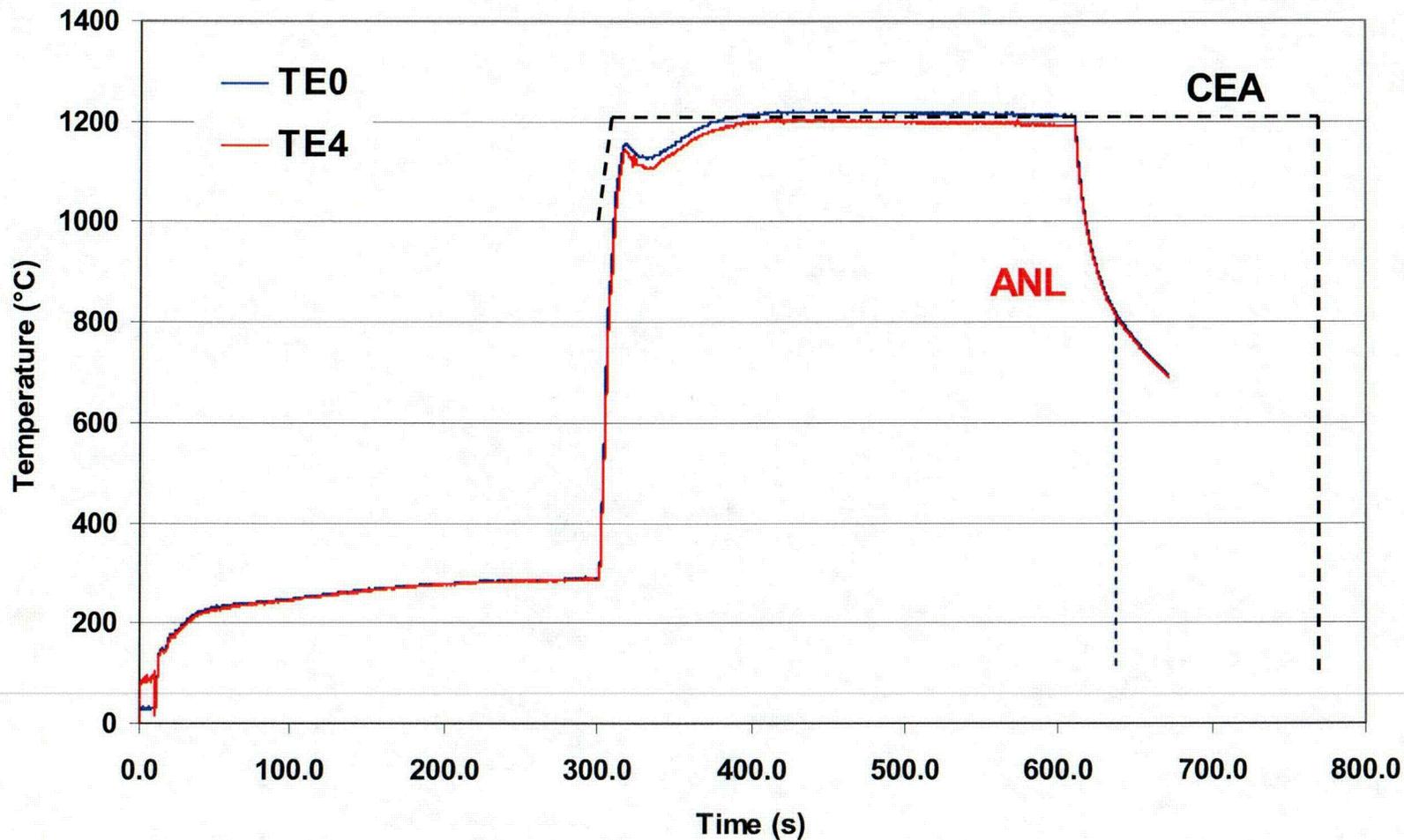
Additional Studies with As-Fabricated Modern Alloys

- **Effects of Quench, Quench Temperature & Slow Cooling**
 - M5 oxidized to 17% CP-ECR with and without quench
 - ANL vs. CEA data for RT total displacement and offset strain at RT
CEA: quench T = oxidation T; one-sided oxidation; curved support;
tests run to zero load; interpretation of load-displacement curve
Comparison for Zry-4 and M5 oxidized at 1000°C, 1100°C, 1200°C
 - No effects of quench temperature or slow cooling on RT PQD
observed for as-fabricated Zry-4 and M5
- **PQD of 15×15 vs. 17×17 M5 at 13% ECR**
 - No effects of cladding thickness on PQD observed at RT and 135°C
- **Strain Rate Increase of 10x for Zry-4 135°C PQD**
 - Small decrease in PQD, but no change in embrittlement ECR
- **Modern 15×15 Zry-4; 9×9 and 10×10 Zry-2(Fall 2005)**

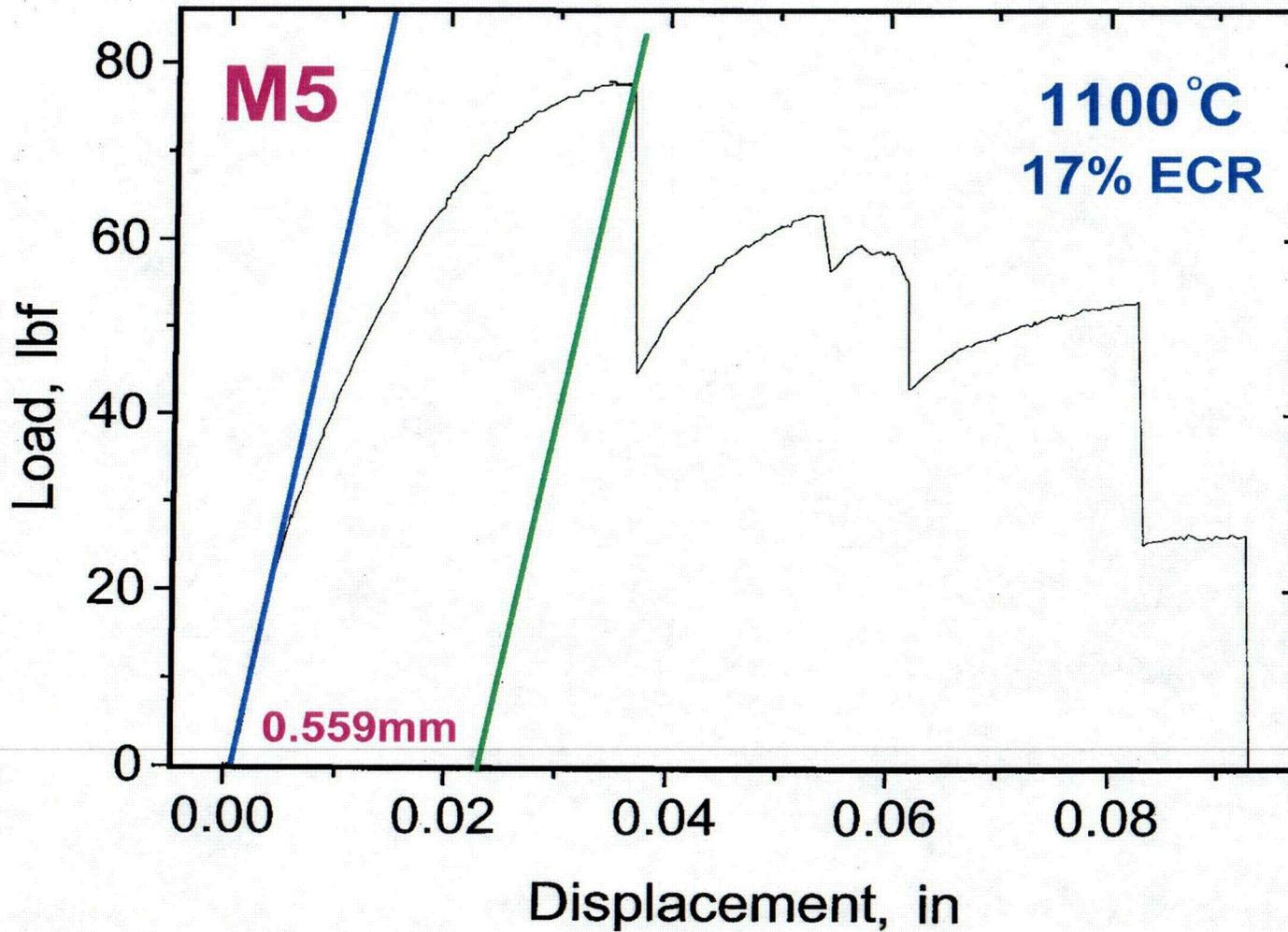
53



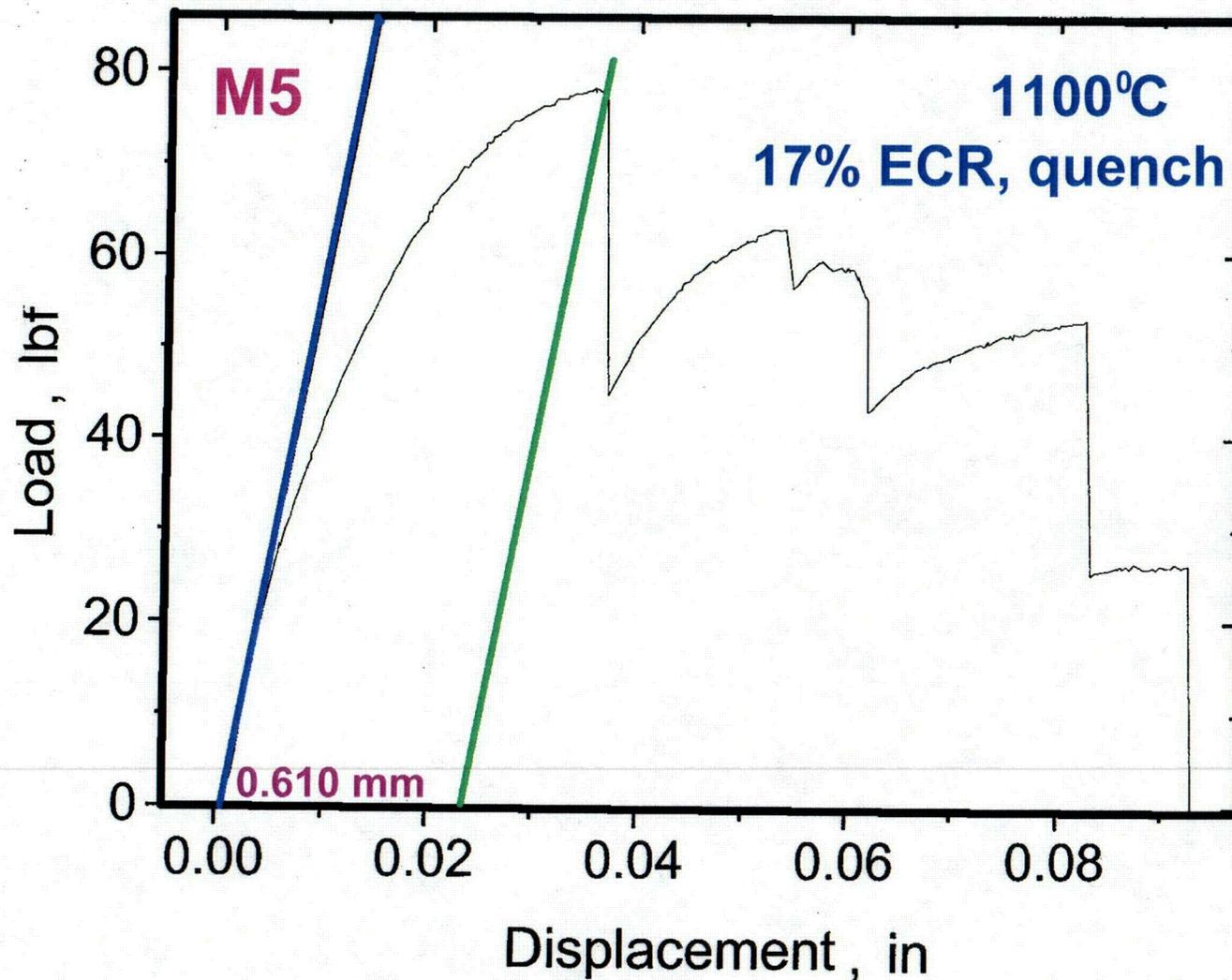
ANL vs. CEA Temperature History for 17x17 Zry-4 Oxidized at 1200°C



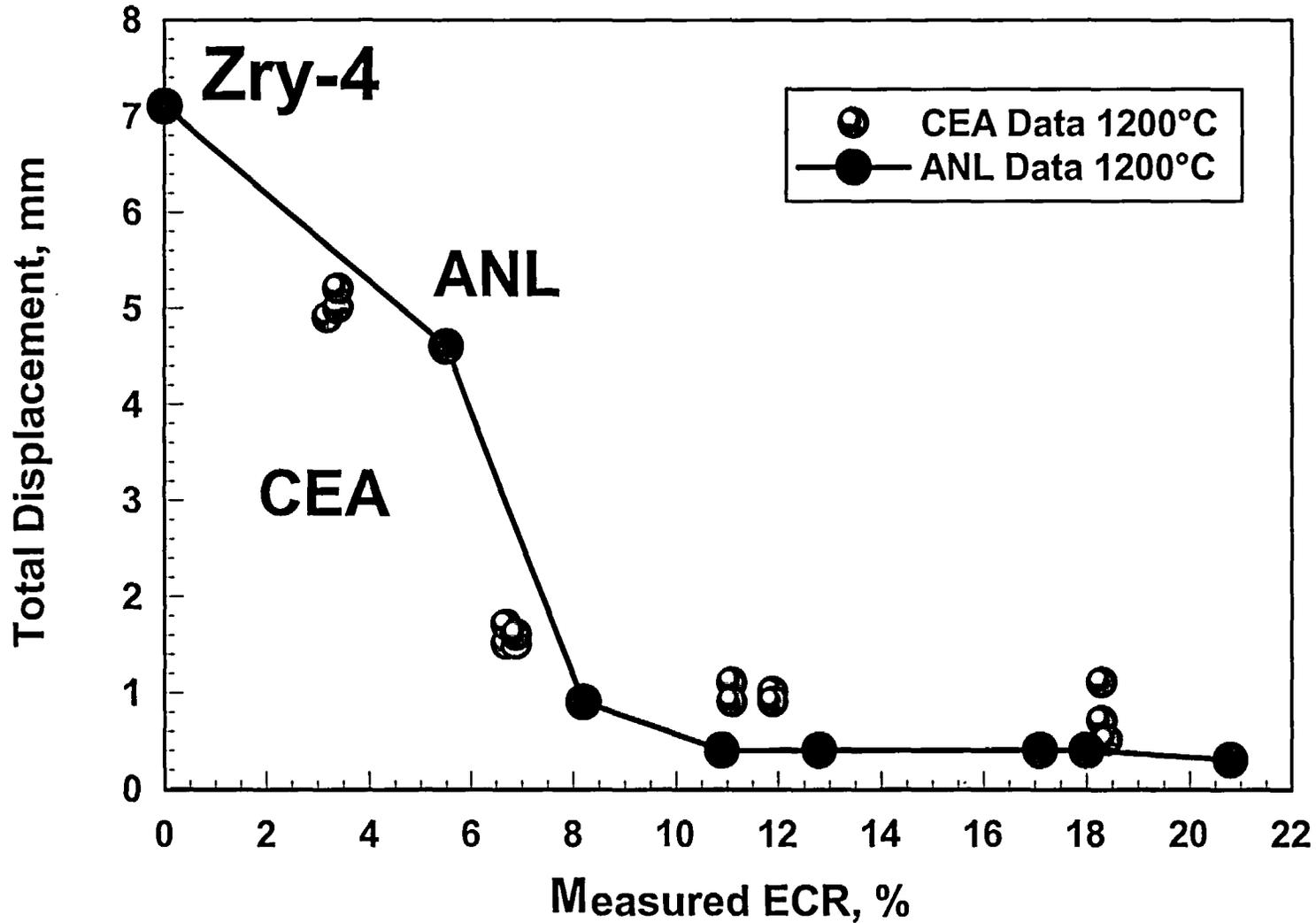
RT Ductility of M5 after 17% CP-ECR at 1100°C (Slow Cooling)



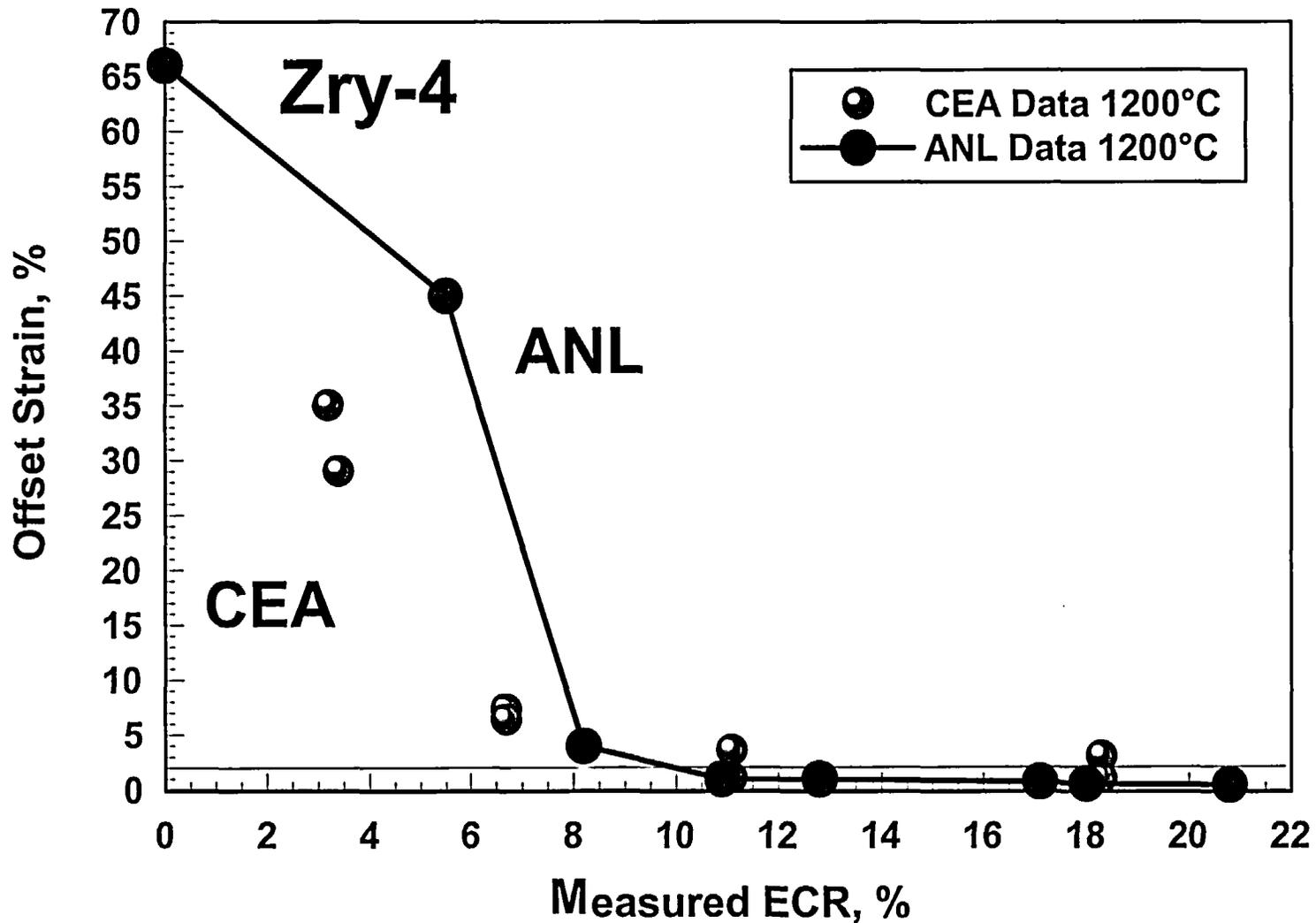
RT Ductility of M5 after 17% CP-ECR at 1100°C (Quench)



ANL vs. CEA Data for RT Total Displacement for Zry-4 Oxidized at 1200°C



ANL vs. CEA Data for RT Offset Strain for Zry-4 Oxidized at 1200°C



Prehydrided 17x17 Zry-4 Oxidized at 1200±5°C

- **Prehydriding of 100-mm-long Samples**

- 400°C in 4% H₂-Ar
- Results highly dependent on purity of Ar and hermeticity of chamber
- Aluminum foil wrapped around samples to minimize oxidation
- Significant axial gradients along samples due to dT/dx
- Significant axial gradients along 25-mm-long oxidation samples
- Axial and circumferential gradients in H concentration remained unchanged after oxidation at 1204°C

- **Results for ≈150 to 600 wppm H**

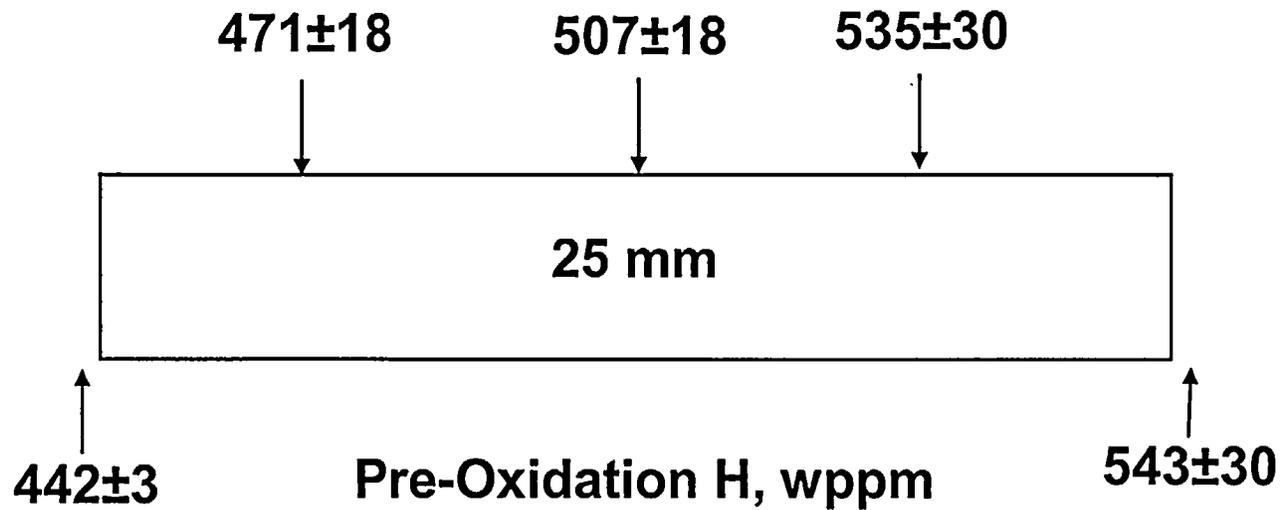
- Ductile-to-brittle transition at 135°C
- 8.5% measured (7.5% CP) ECR and 400 wppm H
- 10.5% measured (10% CP) ECR and 300 wppm H
- No more 17×17 Zry-4 at ANL to continue study

59



*Pre- and Post-oxidation Hydrogen Variation in 15x15
Zry-4: 1204°C Steam Oxidation to 7.5% ECR (≈55 s)*

Post-Oxidation H, wppm



135°C Offset Strain for Prehydrided 17x17 Zry-4 Oxidized at 1200°C

