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

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1 UNITED STATES OF AMERICA

2 NUCLEAR REGULATORY COMMISSION

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4 ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

5 (ACRS)

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7 MATERIALS, METALLURGY, AND REACTOR FUELS

8 SUBCOMMITTEE

9 + + + + +

10 THURSDAY

11 JUNE 23, 2011

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13 ROCKVILLE, MARYLAND

14 + + + + +

15 The Advisory Committee met at the

16 Nuclear Regulatory Commission, Two White Flint

17 North, Room T2B1, 11545 Rockville Pike, at 8:30

18 a.m., J. Sam Armijo, Chairman, presiding.

19 COMMITTEE MEMBERS PRESENT:

20 J. SAM ARMIJO, Chairman

21 SAID ABDEL-KHALIK, Member

22 CHARLES H. BROWN, Member

23 MICHAEL L. CORRADINI, Member

24 JOY REMPE, Member

1 WILLIAM J. SHACK, Member

2

3 NRC STAFF PRESENT:

4 CHRISTOPHER BROWN, Designated Federal Official

5 PAUL CLIFFORD, NRR

6 MICHELLE FLANAGAN, RES

7 KATHY GIBSON, RES

8 MICHELLE HAYES, NRO/DSRA

9 SHANA HELTON, NRR

10 TARA INVERSO, NRR

11 RALPH LANDRY, NRO/DSRA

12 RICHARD LEE, RES/DSA

13 PATRICK RAYNAUD, RES/DSA

14 HAROLD SCOTT, RES

15 JOHN VOGLEWEDE, RES

16 SUNIL WEERAKKODY, NRR/DSA

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4 ALSO PRESENT:
5 JOHN ALVIS, Anatech/EPRI
6 MIKE BILLONE, ANL*
7 GORDON CLEFTON, NEI
8 BERT DUNN, AREVA NP
9 TOM EICHENBERG, TVA/EPRI
10 YANG-FI LIN, GNF/GEH
11 ERIK MADER, EPRI
12 ROBERT MONTGOMERY, PNNL*
13 KURSHAD MUFTUOGLU, GEH
14 KEN YUEH, EPRI
15
16 *Participating via telephone
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6 P-R-O-C-E-E-D-I-N-G-S
7 8:30 a.m.
8 CHAIRMAN ARMIJO: Good morning. The
9 meeting will now come to order. This is a meeting
10 of the Materials, Metallurgy, and Reactor Fuels
11 Subcommittee. I'm Sam Armijo, chairman of the
12 subcommittee. ACRS members in attendance are
13 Charles Brown. We're missing a few people here.
14 Joy Rempe. I thought I saw Mike Corradini here.
15 PARTICIPANT: Yes, he's here.
16 CHAIRMAN ARMIJO: Is he here? Showing
17 up, Dr. Corradini. Michael Ryan, Said Abdel-Khalik
18 and perhaps we'll see Mr. Jack Sieber shortly.
19 The purpose of this meeting is to
20 receive a briefing on the expanded technical basis
21 for 50.46b rulemaking. In particular, a briefing
22 will be given on the mechanical behavior of
23 ballooned and ruptured cladding. We will hear
24 presentations from representatives of the Office of

1 Nuclear Reactor Regulation and Nuclear Regulatory
2 Research. In addition, a presentation will be heard
3 from the Electric Power Research Institute, EPRI.
4 The subcommittee will gather information, analyze
5 relevant issues and facts and formulate proposed
6 positions and actions as appropriate for
7 deliberation by the full committee.
8 The rules for participation in today's
9 meeting were announced as part of the notice of this
10 meeting previously published in the *Federal Register*
11 on June 14, 2011. We have received no written
12 comments or requests for time to make oral
13 statements from members of the public regarding
14 today's meeting.
15 A transcript of the meeting is being
16 kept and will be made available as stated in the
17 *Federal Register* notice. Therefore, we request that
18 participants in this meeting use the microphones
19 located throughout the meeting room when addressing
20 the subcommittee. Participants should first
21 identify themselves and speak with sufficient
22 clarity and volume so that they can be readily
23 heard.
24 I'd like to ask everyone here to silence

1 all phones and we can now proceed with the meeting.
2 But I do understand we have people on the bridge
3 line. And if they're on the bridge line, I would
4 appreciate if you keep your phones on mute until
5 we're ready to hear from you.
6 I'd like to turn the meeting over to Ms.
7 Kathy Gibson of the Office of Research to make
8 introductory remarks.
9 MS. GIBSON: Thank you. I'm Kathy
10 Gibson, the director of the Division of Systems
11 Analysis. We're here as a part of the continuing
12 saga of the 50-46 rulemaking effort. We briefed you
13 most recently on the three regulatory guides that
14 Michelle put together with the working group.
15 Just to go back, bring everybody up to
16 where we started and where we are now, in May of
17 2008 we issued a Research Information Letter titled,
18 "Technical Basis for Revision of Embrittlement
19 Criteria in 10 C.F.R. 50.46." It was RIL 0801. And
20 in that RIL we recommended that the experimental
21 results from our LOCA research program be used as
22 the basis for rulemaking to revise the cladding
23 embrittlement criteria in 10 C.F.R. 50.46.
24 And then in December of that year we

1 briefed you on the LOCA research program findings
2 and the rulemaking strategy for the ECCS
3 requirements.
4 Since then, as you know, we have an
5 interoffice working group that has been working on
6 the rulemaking revisions. In developing the rule
7 language the working group discussed the treatment
8 of the portion of the fuel rod predicted to balloon
9 and rupture during a LOCA.
10 In RIL 0801 we acknowledged that no
11 criteria have been found that would ensure ductility
12 in the cladding balloon. However, loss of ductility
13 in the short portion of a fuel rod should not lead
14 to an uncoolable geometry as long as the amount of
15 oxidation in the ballooned region remains limited in
16 the current manner. So, the staff discussion
17 regarding this in the working group focused on how
18 to document and support the statement in the
19 Statements of Consideration for the current
20 rulemaking.
21 At the same time we were completing an
22 ongoing research program at Studsvik specifically
23 designed to investigate the mechanical behavior of
24 the ballooned and ruptured region that had been

1 interrupted by the closure of the hot cell
2 facilities at Argonne.
3 So, today's briefing is on the results
4 and conclusions of this research program that
5 supports the treatment of the ballooned and ruptured
6 region in the Proposed Rule Statements of
7 Consideration.
8 The report documenting these results and
9 conclusions along with necessary updates to the RIL
10 will be provided as enclosures to the proposed rule
11 package that we're scheduled to brief you on in
12 December and then the full committee in February
13 2012.
14 So, the briefing today is intended to
15 familiarize you with this material in anticipation
16 of these future briefings. A formal review of the
17 information presented today will be part of the
18 proposed rule package and no letter on this subject
19 is being requested at this time. However, as
20 always, the feedback and discussion of this
21 subcommittee is welcomed, encouraged and helpful to
22 us as we develop a strong and thorough regulatory
23 product.
24 So, let me introduce the staff that's

1 here today to brief you. Tara Inverso of the Office
2 of Nuclear Reactor Regulation, Division of Policy
3 and Rulemaking will begin today's briefing with a
4 status of the cladding embrittlement rulemaking
5 project.
6 Let me acknowledge that Paul Clifford is
7 also here from NRR.
8 Following Tara, Michelle Flanagan of my
9 staff will present the briefing on the results and
10 conclusions of the research program and discuss how
11 these results and conclusions are being used to
12 support the treatment of the ballooned and ruptured
13 regions in the proposed rule.
14 John Voglewede, our senior level advisor
15 for fuels, is also here to answer questions as need,
16 as well as Mike Billone, our contractor from Argonne
17 is also on the phone.
18 So, I would like to turn the floor over
19 to Tara.
20 MS. INVERSO: Thank you, Kathy.
21 As Kathy mentioned, my name is Tara
22 Inverso and I'm the project manager for the 50.46c
23 rulemaking activities, and I'll begin today's
24 meeting with an overview of the rulemaking project.

1

2 As Kathy also mentioned, the purpose of
3 today's meeting is to present the expanded
4 regulatory basis which confirms regulatory treatment
5 of the ballooned and ruptured region within the
6 50.46c rulemaking. And as she also mentioned, the
7 purpose of this is to provide familiarization to the
8 ACRS Subcommittee members in anticipation of a
9 formal review of the proposed rule package later
10 this calendar year.
11 CHAIRMAN ARMIJO: Tara, as it's
12 currently written, does the 50.46c rule language
13 deal with a balloon, or is it implied that it's
14 dealt with, or are you going to have to add
15 language?
16 MS. INVERSO: As the rule is currently
17 and the version that was released in anticipation of
18 the May 10 ACRS Subcommittee meeting, the ballooned
19 region is not specifically called out. And in that
20 regard, the presentation that Michelle is about to
21 give would not alter the rule language. Michelle
22 will talk that the recommendation through this
23 research and the report is that the same cladding,
24 the brittle-to- ductile transition zone will apply

1 to the ballooned region also. So, there would be no
2 changes, no specific call out.
3 CHAIRMAN ARMIJO: Okay. So, that's
4 really the bottom line?
5 MS. INVERSO: Yes.
6 CHAIRMAN ARMIJO: Okay. So, I'll wait
7 to hear what you have to say.
8 MS. INVERSO: Today's meeting will begin
9 with this overview presentation. It will then move
10 directly into Michelle's technical discussion. EPRI
11 will then lead a discussion of their remarks on the
12 mechanical behaviors of the balloon document, and
13 the meeting will wrap up with a discussion led by
14 the ACRS members.
15 There are four main objectives of this
16 rulemaking. The first objective is to revise the
17 acceptance criteria based on recent research
18 findings. This research focused on high burnup fuel
19 rods after accident conditions and they identified
20 some previously unknown embrittlement mechanisms,
21 specifically how hydrogen interacts in the
22 embrittlement process and then also shed some more
23 light on previously known embrittlement mechanisms.
24 The Commission also provided direction

1 in this rulemaking through SECY-02-0057, and that
2 was released on March 3, 2003. And the Commission
3 directed us to rewrite the acceptance criteria such
4 that they are more performance-based in nature. And
5 they also directed us to expand applicability to all
6 fuel designs and cladding materials. In other
7 words, the current regulation applies to just
8 zircaloy and ZIRLO, and this regulation would be
9 expanded.
10 MEMBER CORRADINI: And just remind me;
11 and if an applicant came in as all this was
12 transpiring, they'd have to come in on a case-by-
13 case basis for different cladding and make a case
14 for it?
15 MS. INVERSO: Correct. As this is
16 transpiring before the rule language is released and
17 implemented; and as Paul mentioned in the last
18 presentation, we're proposing a staged
19 implementation, so there will be a point where some
20 licensees fall under the current regulations and
21 some will be adopting the new. And while the
22 current regulations are in place, they will still
23 need to go through with the exception procedure that
24 they have been using to use alternate cladding

1 materials. When the proposed rule language, if it
2 is adopted, the cladding would have to meet the
3 acceptance criteria and that would have to be proven
4 to us before it could be loaded into the reactor.
5 MEMBER CORRADINI: And currently how
6 many licensees have used the exemption path to have
7 alternative cladding than the two that are in the
8 rule?
9 MS. INVERSO: I think I'll turn that one
10 over to Paul. If you --
11 MR. CLIFFORD: Okay. Yes, since the
12 rule is specific to zircaloy and ZIRLO, there's
13 many. The exact number, I would say around 20.
14 MEMBER CORRADINI: So significant?
15 MR. CLIFFORD: Yes, we've issued
16 exemptions for all plants that have gone to M5
17 cladding alloy, which is an AREVA proprietary alloy.
18 And we've also issued exemptions for optimized
19 ZIRLO, which is a Westinghouse cladding allow.
20 MEMBER CORRADINI: And then just so I
21 get it clear in this transition, so then with those
22 exemptions they have to show that they meet the
23 current rule. But the way you described it to me,
24 if this is being implemented, would they have to

1 then -- how does it happen in this transition for
2 those exemptions? They just meet the current rule
3 period until the new rule comes in? I'm trying to
4 specific the transition.
5 MR. CLIFFORD: Yes.
6 MEMBER CORRADINI: I'm a bit cloudy as
7 how all this transpires. That is, does everybody
8 meet the current rule whether it be by exemption or
9 by directly applying to the rule and then the new
10 rule, assuming it's in in the current form, comes
11 into play and then everybody gets reevaluated?
12 MR. CLIFFORD: Correct.
13 MEMBER CORRADINI: Okay.
14 MR. CLIFFORD: Each applicant, each
15 licensee would need to at some staged scheduled
16 implementation date be in compliance with the new
17 requirements.
18 MEMBER CORRADINI: And I'm sorry, again
19 from an impact standpoint, that would then
20 potentially limit the burnup they can go to? I
21 mean, I'm trying to figure it out from the
22 standpoint of now this current rule is fine. I go
23 to this sort of burnup running the fuel. Life is
24 good. Now, the new rule is implemented. To meet

1 the new rule they would probably have to roll back,
2 potentially roll back the burnup.
3 MR. CLIFFORD: Based upon the
4 information that's been provided to the owners
5 groups on a plant-by-plant basis we don't expect
6 that any plants, when they implement the new
7 requirements, would need to make significant changes
8 to either tech specs or licensed burnup plants.
9 MEMBER CORRADINI: Okay. Thank you.
10 MS. INVERSO: This rulemaking would also
11 address concerns raised in two Petitions for
12 Rulemaking. The first is PRM-50-71 that was
13 received in March of 2000 on behalf of the Nuclear
14 Energy Institute and it requested that we rewrite
15 the regulation to expand its applicability to all
16 fuel designs and cladding materials, well
17 specifically cladding materials, which, as we just
18 mentioned, was also a Commission direction.
19 The second PRM is PRM-50-84, and that
20 was submitted by Mr. Mark Leyse on March 15, 2007,
21 and he requested that the licensees operate in such
22 a manner that they minimize the build of crud of
23 oxide.
24 Recent developments. The Office of

1 Nuclear Regulatory Research has drafted three
2 regulatory guides. The first was to establish a
3 test procedure for measuring post-quench ductility.
4 The second, Draft Guide 1262, was a test procedure
5 for measuring breakaway oxidation. And the third,
6 Draft Guide 1263, was a method for establishing
7 analytical limits.
8 Michelle presented those three draft
9 guides to the ACRS Subcommittee on May 10, 2011 and
10 the full committee on June 8, 2011. And at those
11 meetings we presented our plan to publish those
12 draft guides along with the proposed rule such that
13 when the public comments, they can comment on both
14 the rule and the draft guides and be able to see how
15 the two interact with each other.
16 The staff mentioned at the full
17 committee meeting on June 8, 2011 that we're
18 evaluating results of the fuel fragmentation
19 dispersion research in parallel with this
20 rulemaking. We have nothing new to update on that
21 phenomenon today besides what we stated at the June
22 8 meeting. And the purpose of today's meeting is
23 Michelle's presentation on the mechanical behavior
24 of the ballooned and ruptured cladding, which was a

1 document that the Office of Nuclear Regulatory
2 Research has drafted.
3 CHAIRMAN ARMIJO: Okay. Well, I just
4 want to make sure I understand the fuel
5 fragmentation dispersion issue. Is that or is that
6 not going to be treated in the 50.46c rule?
7 MS. INVERSO: This is a phenomenon that
8 we are at the beginning stages of evaluating
9 research results. I would like to be able to tell
10 you exactly how everything will evolve, but it will
11 continue to evolve as we go on in parallel. Our
12 goal is to continue with this embrittlement rule.
13 And as of today I would say it would not be included
14 in the proposed rule language. We will provide that
15 proposed rule based on embrittlement to the
16 Commission by the established due date. Whether or
17 not we will be at a point that we can provide a
18 discussion of the evaluation within the SECY paper,
19 we'll have to see as the evaluation continues.
20 CHAIRMAN ARMIJO: Well, if you were
21 going to have fuel fragmentation language in the
22 rule, I would expect that you would brief the ACRS
23 on that matter before you do it.
24 MS. INVERSO: We will note that and

1 we'll keep the ACRS updated as we progress through
2 our evaluation.
3 CHAIRMAN ARMIJO: All right. Thank you.
4 MEMBER CORRADINI: But, I mean, I'm kind
5 of with Sam on this. The way you answered it before
6 he asked the question was there will be nothing in
7 the rule about fuel fragmentation dispersion. There
8 might be discussion in the reg guide at best.
9 MS. INVERSO: Probably the SECY paper.
10 MEMBER CORRADINI: Or the SECY paper;
11 excuse me.
12 CHAIRMAN ARMIJO: Yes, and then so --
13 MEMBER CORRADINI: I'm sorry.
14 CHAIRMAN ARMIJO: -- if it's in the SECY
15 paper, what does that mean and --
16 MEMBER CORRADINI: Nothing as far as I
17 can tell.
18 CHAIRMAN ARMIJO: Well --
19 MEMBER SHACK: Well, as I recall from
20 the previous meeting, there was a somewhat stronger
21 statement that they might include a recommendation
22 that you hold off.
23 MR. CLIFFORD: At this time we may have
24 a discussion. It's not final, but there may be a

1 discussion in the SECY paper that identifies the
2 phenomenon, identifies the potential impact, and
3 then there would be a recommendation from the staff.
4 We haven't solidified what that recommendation will
5 be.
6 MEMBER CORRADINI: But, not to pin you
7 down, but to pin you down, that means the rule will
8 -- I mean, the way at least I heard it described,
9 the rule will proceed forward on the timeline as you
10 currently have regardless of what might appear in
11 the SECY paper?
12 MR. CLIFFORD: Correct. The rule will
13 be complete and the rule will be ready to be
14 published for public comment --
15 MEMBER CORRADINI: Okay.
16 MR. CLIFFORD: -- at the Commission's
17 discretion.
18 CHAIRMAN ARMIJO: Okay. Let's move on.
19 I have to think about it.
20 MS. INVERSO: The rulemaking schedule.
21 We expect to come back to the ACRS Subcommittee on
22 December 15, 2011 and then again to the full
23 committee on February 9, 2012. And our ultimate due
24 date to the Executive Director for Operations is

1 February 29, 2012.

2 And that concludes the overview, unless

3 there are questions.

4 (No audible response.)

5 MS. INVERSO: Okay. With that, I will

6 turn it over to Michelle.

7 MS. FLANAGAN: Thank you. My name is

8 Michelle Flanagan and I am in the Division of Safety

9 Systems Analysis in the Office of Nuclear Regulatory

10 Research. And my presentation today will review the

11 contents of the technical report titled, "Mechanical

12 Behavior of Ballooned and Ruptured Cladding." And

13 the purpose of this document is to serve as the

14 technical basis for the treatment of ballooned and

15 ruptured cladding in the proposed rule.

16 The presentation today will for the most

17 part follow along with the contents of this report.

18 And so, that begins with a review of the regulatory

19 history of the ballooned region and then presents

20 the results of NRC's integral LOCA research program,

21 and then finally describes how these research

22 results will be used to support the treatment of

23 ballooned and ruptured cladding within the

24 rulemaking to revise 50.46c.

1 So, if we look for the overarching
2 requirements for ECCS systems, we see that general
3 design criteria and 50.46 require that an ECCS
4 system is available to ensure that if a loss of
5 coolant accident took place that the core remains
6 amenable to cooling and that decay heat is removed
7 to ensure long-term cooling.
8 And in 1973, the Commission hearings
9 established that coolable geometry could be
10 maintained if the cladding remained ductile. This
11 position falls out of the belief that specific
12 prediction and quantification of LOCA loads isn't
13 possible or wasn't possible at that time to a
14 satisfactory extent and that maintaining ductility
15 is the best approach to preserving coolable
16 geometry. And at that time ring compression test
17 data, among other experimental observations, were
18 used to establish ductility thresholds and those
19 ductility thresholds were written and codified in
20 the regulation.
21 And over 10 years ago the question was
22 first posed are these criteria still appropriate for
23 high burnup cladding? And like the program that
24 defined the LOCA acceptance criteria in 1973, this

1 new program particularly targeted at high burnup
2 cladding also used ring compression tests to assess
3 the oxidation and temperature limits at which
4 embrittlement occurs. And staying close to the
5 existing basis an emergency core cooling system
6 computations was an important regulatory
7 consideration.
8 NRC's test program concluded with the
9 finding that the oxidation criteria was not
10 sufficient for high burnup cladding. And
11 specifically what was found was that hydrogen
12 content had a significant impact on cladding
13 embrittlement. The greater the hydrogen content,
14 the less oxidation was required to embrittle the
15 cladding material. And as Kathy mentioned, the
16 Office of Nuclear Regulatory Research issued
17 Research Information Letter 0801, which recommended
18 that the experimental results from this program be
19 considered as the basis for rulemaking and then an
20 interoffice working group was formed to develop rule
21 language.
22 And in developing rule language for
23 revision to 50.46b, the staff discussion focused on
24 how to treat the ballooned region. And in

1 particular, the staff discussed whether the
2 hydrogen-based embrittlement correlation derived
3 from ring compression tests as shown on the previous
4 slide was the appropriate limit to apply in the
5 ballooned region, and particularly in the way that
6 the current regulations would dictate.
7 So, on this slide it's awfully small
8 text, but I'll read what is described for how to
9 apply the oxidation criteria in the ballooned
10 region, and this is codified language.
11 Where the calculated conditions of
12 transient pressure and temperature lead to a
13 prediction of cladding swelling, with our without
14 rupture, the unoxidized cladding thickness shall be
15 defined as the cladding cross-sectional area taken
16 at the horizontal plane of elevation.
17 So, basically where there is ballooning
18 and rupture, the regulations specify that the
19 average wall thickness should be used in the
20 oxidation calculation, and that upon rupture double-
21 sided oxidation should be assumed. And so, the
22 question that the staff was looking at was whether
23 this approach to calculating oxidation should
24 continue to apply with the hydrogen-based limit.

1 CHAIRMAN ARMIJO: Okay. I want to
2 understand that.
3 MS. FLANAGAN: Yes?
4 CHAIRMAN ARMIJO: If you have some pre-
5 transient hydrogen pickup --
6 MS. FLANAGAN: Yes?
7 CHAIRMAN ARMIJO: -- maybe 200, 300 ppm
8 in cladding of a certain thickness, and you balloon
9 and you thin the cladding by a factor of 2, does
10 that put you into effectively the 600 ppm hydrogen
11 concentration in the ballooned region?
12 MS. FLANAGAN: No, it's a weight
13 percentage, weight ppm of hydrogen.
14 MEMBER SHACK: But it changes your ECR
15 calculation?
16 MS. FLANAGAN: Right.
17 CHAIRMAN ARMIJO: It does change
18 something.
19 MEMBER SHACK: Yes.
20 MS. FLANAGAN: Yes, the denominator of
21 the --
22 CHAIRMAN ARMIJO: Yes, I'm just trying
23 to find out what's really the limiting mechanical --
24 the weak point is the hydrogen-enriched oxidized

1 thinnest wall.

2 MS. FLANAGAN: Yes.

3 CHAIRMAN ARMIJO: That's the ballooned

4 region, I think. So, what is the limiting

5 mechanical portion of the fuel?

6 MS. FLANAGAN: So, I'll start out an

7 explanation and I think Mike Billone might be able

8 to describe this in a more precise way.

9 CHAIRMAN ARMIJO: Okay.

10 MS. FLANAGAN: But what we're measuring

11 is the strength, the properties of the residual beta

12 layer, which is influenced -- or it degrades with

13 oxidation and oxygen ingress, and that oxygen

14 ingress is enhanced by hydrogen. And so, it's not

15 necessarily the oxide thickness that's creeping into

16 the thickness of the cladding as much as it is how

17 much oxygen is absorbed in the base metal.

18 Mike, do you have anything that would be

19 even more precise?

20 DR. BILLONE: I'm not sure the question

21 is for ballooned and ruptured cladding. What is the

22 weak point? Is that the question?

23 CHAIRMAN ARMIJO: Yes, that's basically

24 it, Mike.

1 DR. BILLONE: There are three weak
2 points. One is -- are you on slide 7 yet, Michelle?
3 MS. FLANAGAN: Yes.
4 DR. BILLONE: Oh, okay. I don't know,
5 the red curve is oxygen and weight percent. And
6 you'll see at the center of the ruptured node or the
7 burst area you have the maximum oxygen content which
8 causes embrittlement. And then as you move away
9 from the rupture zone, in between the peak of the
10 red curve and the peak of the blue curves your
11 combination of hydrogen and oxygen also favors
12 possible failure at those locations. So, just to
13 the left and just to the right are possible failure
14 locations, and also the center of the rupture
15 region. And then it gets into how big is your
16 rupture, what is the balloon strain, how weak is
17 that region compared to the higher hydrogen region.
18 CHAIRMAN ARMIJO: Now, where is the
19 thickest alpha layer on this same curve? Would it
20 be where you have your peak hydrogen?
21 DR. BILLONE: Well, basically where your
22 peak hydrogen is you basically have one-sided
23 oxidation on the surface of the cladding. And it's
24 not shown there, but your oxide layer thickness is

about the same as your alpha layer thickness. But it's not shown on this picture, because what you're looking at at the left is a low magnification. It should give you the shape of the balloon and how we calculate the circumferntial strength or the circumference of that picture divided by the initial circumference.

MEMBER SHACK: But wasn't that really the point of the test program, to do experiments to find out where those locations really were?

DR. BILLONE: Exactly. And then the --

MEMBER SHACK: So, I mean, we have to look at the results of the experiments to answer your question.

DR. BILLONE: And we're getting ahead of Michelle's --

CHAIRMAN ARMIJO: Okay. Well, then let's go on and --

DR. BILLONE: I don't want to usurp the presentation.

MEMBER SHACK: But since Sam started this, let me start off on a slightly different tack; and that was, we had a lot of discussion last time about two-sided oxidation and, you know, whether it

1 was real or not. Now, nobody disputes two-sided
2 oxidation in a ballooned region, so my question is
3 whether you get ballooning depends on the internal
4 pressure in the rod presumably, and I calculate it
5 from 06-30. Is it going to really turn out in
6 practice that it's always the ballooned region that
7 controls whether I'm going to hit my oxidation
8 limit? That is, I'm really always going to have
9 two-sided oxidation to consider because in my
10 susceptible rod I'm always going to have ballooning.
11 Or am I simplifying it too much?
12 DR. BILLONE: No, I think people at NRC
13 could answer that better. And I think the answer
14 depends on whether you do an Appendix A conservative
15 thermohydraulics calculation or you do a best
16 estimate as to whether your limiting oxidation is in
17 the balloon, where I believe it is if you do the
18 calculation right, or if it's somewhere above.
19 MEMBER SHACK: Can I make sure I
20 understand you passing it back to the staff? Are
21 you saying that if you did an Appendix A calculation
22 you'd get higher temperatures and put the location
23 in a different non-physical place?
24 DR. BILLONE: That is my understanding

1 from Harold Scott. And I'm quoting thermohydraulics
2 experts who have been RES when I make that
3 statement.
4 MR. CLIFFORD: This is Paul Clifford
5 from NRR. I would say you're right, first of all.
6 Yes, when you have ballooning and bursting, you
7 introduce double-sided oxidation. Also, the wall
8 thinning goes into the equation. So, if you have a
9 balloon and burst, that will generally be the
10 location, the node of peak calculated oxidation.
11 However, there is some effects, cooling effects due
12 to the changes in the hydraulic conditions around
13 the ballooned region that can cause the temperatures
14 to be a little lower. But that's usually
15 overshadowed by the double-sided --
16 PARTICIPANT: (Off microphone.)
17 MR. CLIFFORD: Yes. So, that won't be
18 the location of peak cladding temperature, but it
19 will probably be the location of --
20 MEMBER SHACK: Because of the way they
21 shuffle the fuel around, will the rod be likely to
22 balloon? The hot rod, will it be also likely to
23 balloon, or will there be such low burnup that maybe
24 you won't have enough pressure to balloon?

1 MR. CLIFFORD: Well, there's competing
2 effects.
3 MEMBER SHACK: Yes.
4 MR. CLIFFORD: The rod internal pressure
5 increases with burnup, but power, rod power
6 decreases with burnup.
7 MEMBER SHACK: Right.
8 MR. CLIFFORD: So, you'd have competing
9 effects and both will be taken into account in
10 predicting whether or not the rod will balloon and
11 burst.
12 MEMBER SHACK: But, just in experience
13 does it turn out that the critical rod is usually a
14 ballooned rod? I guess that's my real question.
15 MR. CLIFFORD: It depends on the
16 methodology that's being applied in some ways, but
17 in general, yes, the hottest rod will balloon and
18 burst, certainly for a large break as break size
19 diminishes and the rate of RCS depressurization
20 changes.
21 MEMBER CORRADINI: Then it could move
22 around?
23 MR. CLIFFORD: It could depend on where
24 the steam water interface is.

1 MEMBER SHACK: But doesn't that make
2 this other argument about two-sided oxidation where
3 there's no ballooning somewhat moot? Right. Yes,
4 that was sort of where I was getting at, that, you
5 know, if the critical region is always the ballooned
6 one and everybody agrees there's two-sided oxidation
7 --
8 MR. CLIFFORD: Right.
9 MEMBER SHACK: -- then I'm not sure why
10 there was such a dispute over two-sided oxidation
11 when it wasn't likely to be ballooned in this
12 situation.
13 MR. CLIFFORD: The other issue was a
14 high burnup phenomenon.
15 MEMBER SHACK: Right.
16 MR. CLIFFORD: You're talking about the
17 oxygen ingress from the cladding ID surface. The
18 issue there is you could have a location that had a
19 higher peak cladding temperature, which means it
20 didn't have the beneficial hydraulic effects of the
21 balloon, but now would have to be penalized with a
22 double-sided oxidation calculation.
23 MEMBER SHACK: Okay. So, I really do
24 have to look at these beneficial effects of the

1 cooling associated with the turbulence around the
2 balloon?
3 MR. CLIFFORD: Correct.
4 MEMBER CORRADINI: Can you say that
5 again what you just said at the end? I didn't catch
6 it. Can you repeat it, please?
7 MR. CLIFFORD: If you had an un-
8 ballooned un-deformed rod, at high burnups you would
9 have -- because of the fuel bonding layer you could
10 have a source of oxygen on the cladding ID surface
11 so that you would in a sense have double-sided
12 oxidation even though you didn't have a balloon and
13 burst. So, at the location of peak cladding
14 temperature, which is generally outside the
15 ballooned region, you would now have to do double-
16 sided oxidation. So, it would be somewhat of a
17 penalty on that calculation, which today you
18 wouldn't have that effect.
19 MEMBER CORRADINI: Okay. So, there'd be
20 a penalty, but would that change Bill's conclusion
21 about for a large break where it would matter? It
22 might, or --
23 MR. CLIFFORD: No, not really, because
24 that's a high burnup effect, so it's only going to

1 be on the really high burnup fuel, which is
2 operating at lower initial powers, which is going to
3 have a lower cladding temperature than the fresh
4 fuel.
5 MEMBER CORRADINI: So --
6 MR. CLIFFORD: I mean, there's many
7 competing effects that are our all accounted for in
8 the model.
9 MEMBER CORRADINI: Right, right. Right.
10 Okay.
11 MEMBER BROWN: How are you getting
12 oxygen if you don't have a --
13 CHAIRMAN ARMIJO: What was that,
14 Charlie?
15 MEMBER BROWN: How do you get the
16 oxygen? CHAIRMAN ARMIJO: In from the
17 --
18 MEMBER BROWN: If you don't have a
19 rupture, how do you get it on the --
20 CHAIRMAN ARMIJO: The contention is that
21 when you have U-02 bonded to the zirconium oxide,
22 that you basically have a large source of oxygen to
23 pump into the cladding.
24 MEMBER BROWN: Okay. All right. I got

1 it.

2 CHAIRMAN ARMIJO: And that's the

3 argument --

4 MEMBER CORRADINI: Basically it's not U-

5 02 anymore. You steal some of the oxygen from the

6 U-02.

7 CHAIRMAN ARMIJO: Well, they're just

8 saying that if it's bonded to the zirc oxide, it's

9 effectively oxygen. Now, that's a contingent.

10 There's a dispute on whether that oxygen is truly

11 available to --

12 MEMBER BROWN: So, it's not necessarily

13 released. It's a matter of --

14 CHAIRMAN ARMIJO: Well, it has to --

15 MEMBER BROWN: -- transferring from the

16 U-02, from the uranium --

17 CHAIRMAN ARMIJO: Right, it has diffused

18 from the U-02 into the zirc and stabilized.

19 MEMBER BROWN: But there may not --

20 there's still a boundary? It's just got to diffuse?

21 CHAIRMAN ARMIJO: Right.

22 MEMBER BROWN: Okay. Interesting.

23 MS. FLANAGAN: Okay. So, on --

24 CHAIRMAN ARMIJO: That being said --

1 MS. FLANAGAN: On slide 7; I think we've
2 talked a little bit about what these two images are
3 really depicting, but just to complete the picture
4 here, on the left-hand side what we're noticing is
5 non-uniformity in the thickness of the cladding, and
6 this was known in 1973 when the rule was written.
7 What it leads to is very thin-walled cladding very
8 near the rupture and a thicker area towards the
9 back. So, the very thin regions near the rupture
10 opening are all in all likelihood brittle, even if
11 the back region is ductile.
12 And on the right-hand side we see
13 locations of peak oxidation and peak hydrogen. And
14 in both of these situations we notice that there are
15 locations of brittle material and these can occur
16 even if you're below the criteria that are
17 established in the rule.
18 And so, both of these observations were
19 understood around 1980. And nevertheless, the U.S.
20 -- and some of this work was also done in Japan to
21 identify these high-hydrogen regions. They also
22 noticed this. And despite these findings, the
23 oxidation limits in 50.46 were maintained and
24 weren't adjusted. And this was based on two

1 findings: One is that the ballooned specimens
2 survived quenching even with high oxidation levels,
3 and that the quench specimens didn't fracture
4 following the loss of coolant accident conditions
5 even when modest loads were applied as long as the
6 oxidation level was less than the regulatory limit.
7 And so, as I said, with these findings in hand, NRC
8 made no changes to the LOCA acceptance criteria.
9 So, reflecting this historical
10 treatment, RIL 0801 stated that no criteria have
11 been found which would ensure ductility in the
12 cladding balloon. However, loss of ductility in the
13 short portion of the fuel shouldn't lead to an
14 uncoolable geometry as long as the amount of
15 oxidation in the ballooned region remains limited in
16 the current manner. And then the current manner in
17 this case referred to the text and the approach
18 that's in 50.46 right now.
19 And so, in an effort to support the
20 staff discussion about the treatment of the
21 ballooned region, the working group staff turned to
22 the results coming out of NRC's integral LOCA
23 research program. This integral LOCA research
24 program was designed to measure the mechanical

1 behavior of ballooned and ruptured cladding
2 following LOCA conditions.
3 And in the images here a single rod was
4 exposed to LOCA conditions in a test train. This
5 particular one is the test train at Studsvik and it
6 was designed and fabricated to replicate the
7 equipment that's at Argonne. And so, companion
8 tests were run at Argonne and Studsvik.
9 And then following the LOCA simulation
10 bend tests were conducted. And the best test is a
11 test that applies a uniform bending moment to the
12 entire ballooned region.
13 CHAIRMAN ARMIJO: Michelle, in all of
14 these tests you took them up to the 1,200, or 2,200
15 F for what, how many --
16 MS. FLANAGAN: For varying amounts of
17 time depending on the target oxidation level.
18 CHAIRMAN ARMIJO: Okay.
19 MS. FLANAGAN: But, yes, the oxidation
20 was accumulated at 1,200.
21 CHAIRMAN ARMIJO: Okay.
22 MS. FLANAGAN: Sometimes only for a
23 couple of seconds, but yes, that's where the tests
24 were conducted.

1 CHAIRMAN ARMIJO: All right.

2 MS. FLANAGAN: So, in this test when --
3 we pointed out before that there's a location where
4 due to wall thinning you have a maximum ECR and then
5 you also have regions of high hydrogen content. In
6 this mechanical test you have the entire region
7 subjected to a uniform bending moment. And so, in
8 this case you would identify the weakest location
9 without biasing it.

10 CHAIRMAN ARMIJO: What was the span over
11 which you had, you know, four-point bending? What
12 was the span? Did you cover past the ballooned
13 region and into this hydrogen-enriched region where
14 --

15 MS. FLANAGAN: Yes, so I don't have a
16 figure that's going to be that good for that, but
17 yes, the hydrogen-rich region is -- let me see if I
18 can -- is more like around here.

19 CHAIRMAN ARMIJO: Yes. Okay.

20 MS. FLANAGAN: Relative to the loading.

21 CHAIRMAN ARMIJO: And the four points
22 are where?

23 MS. FLANAGAN: Oh, sorry. Here.

24 CHAIRMAN ARMIJO: Okay. There?

1 MS. FLANAGAN: Here.
2 CHAIRMAN ARMIJO: Okay.
3 MS. FLANAGAN: Here and there.
4 CHAIRMAN ARMIJO: All right. Thank you.
5 MS. FLANAGAN: As I mentioned, the
6 failure location was significant. And so, during
7 these tests the failure location was recorded and
8 the observations of bend tests in irradiated
9 material tested at Studsvik were compared to the
10 results of as-received and pre-hydrided material
11 that was tested at Argonne. And in the tests
12 what we looked at was the load displacement curve.
13 And from the load displacement curve the bending
14 moment, failure energy and offset strain were
15 determined, and also, as I mentioned, the failure
16 location was recorded. And then by comparing the
17 parameters that we can derive from the load
18 displacement curve, we can investigate the relative
19 influence of oxidation, irradiation, balloon size,
20 bend test temperature, as well as hydrogen content.
21
22 So, these are the results from the as-
23 fabricated test series. And my intention isn't to
24 go through them on this graph, because later I have

1 plots which do a better job of reviewing what these
2 results show, but one thing I want to point out is
3 the range of rupture strains that are a part of this
4 test matrix. They range from 21 percent strain all
5 the way up to almost 70 percent strain. So, we have
6 a large range of balloon strain.
7 In addition, all of the samples here,
8 and actually all of the ones that we tested in our
9 program, did survive quench, the actual quench
10 process. And this is significant, because for
11 unrestrained as-fabricated cladding quench will
12 induce a sharp thermal gradient across the cladding
13 wall in both hoop and axial thermal stresses induced
14 in the cladding lead to the cladding surface being
15 in tension on the inner surface and compression --
16 oh, sorry, tension on the outer surface and
17 compression on the inner surface. And regardless of
18 the stress and magnitude of these quench stresses,
19 all the samples shown here and in the remainder of
20 the program did survive quench itself and had some
21 residual properties that were observed in the bend
22 tests.
23 MEMBER SHACK: Michelle, are these
24 pressures really representative of reasonable ranges

of burnup?

MS. FLANAGAN: You mean the fill pressure?

MEMBER SHACK: The fill pressures.

MS. FLANAGAN: The fill pressures -- okay, in this test program one of our objectives was to generate various balloon sizes. So, in some cases that meant dictating a fill pressure for that intention. I will say that most of these are within expected values of operating fill pressure.

MEMBER SHACK: So, 600 would correspond to what kind of burnup, and 1,200 would correspond to what kind of burnup?

MR. CLIFFORD: You want me to answer the question?

MS. FLANAGAN: Yes, I think I'll defer that to Paul, because I'm not sure.

MR. CLIFFORD: All right. Paul Clifford. Well, it's very dependent on fuel design, obviously, and the amount of void volume you have and burnup history. But say for a PWR rod, you're going to have an initial fill of say 250 psi just out of the shop. And then when you get to hot conditions that will go up to 400 or 500.

1 MEMBER SHACK: Okay. So, that's really
2 the bottom?
3 MR. CLIFFORD: Right, that's the bottom.
4 And then towards the end of life that could get up
5 to 20 -- well, worst case calculations, it could get
6 up to 3,000 psi. But best estimate calculations are
7 more around 2,000 psi.
8 CHAIRMAN ARMIJO: Now, Michelle, was
9 there any pre-hydriding of these samples? Are these
10 just as-fabricated?
11 MS. FLANAGAN: All of the results on
12 this slide are as-fabricated.
13 CHAIRMAN ARMIJO: Okay.
14 MS. FLANAGAN: Later when I show the
15 plots, there are two points that were recently
16 generated that are for pre-hydrided material. But a
17 lot of the work that was done at Argonne was on as-
18 fabricated cladding in this campaign with bend
19 tests.
20 CHAIRMAN ARMIJO: So, I guess I'm
21 missing the point. If there's survival of a quench
22 and they're high-ductility, it's really not relevant
23 to something that's been in the reactor for a few
24 years and has a few hundred ppm of hydrogen. So,

1 what am I missing?

2 MS. FLANAGAN: At this point, this set

3 of data is really to observe the impact of

4 oxidation. And so, we're looking at how much

5 oxidation is required to degrade properties. On the

6 next slide I think --

7 CHAIRMAN ARMIJO: Okay. I'll wait.

8 MS. FLANAGAN: -- this is where all --

9 MEMBER CORRADINI: So, this is a set of

10 baseline experiments with no preexisting hydrogen?

11 MS. FLANAGAN: That's correct. But

12 during the ballooning and rupture process there will

13 be the secondary hydriding developed.

14 MEMBER CORRADINI: Right.

15 MS. FLANAGAN: So, I mean, in -- yes.

16 MEMBER CORRADINI: But, I mean, to get

17 to Sam's -- I mean, I'm a novice at this, so I'll

18 only ask questions after an expert asks it. But I

19 guess to Sam's point, if I went -- all right. I

20 guess it's on this one. If I went back to your

21 qualitative graph of 5, all this data is sitting to

22 the left-hand side where there's no preexistent

23 hydrogen.

24 MS. FLANAGAN: Right, it would be on the

1 y-axis itself.

2 MEMBER CORRADINI: And it would be in

3 the survive region? Essentially it's created a

4 database that says -- that's my interpretation of

5 what you just said.

6 MS. FLANAGAN: Yes.

7 MEMBER CORRADINI: Am I misinterpreting?

8 MS. FLANAGAN: No, the only part that

9 I'm hesitating about is when you said it's in the

10 survive region, because this is a different -- this

11 is more to look at the qualitative -- quantitative -

12 - sorry, no, qualitative impact of oxidation. And I

13 think this will make more sense --

14 MEMBER CORRADINI: Okay. So, the answer

15 is I should wait? That's what you're telling me and

16 I'll wait.

17 MS. FLANAGAN: Yes, and if your question

18 isn't answered, then let's return to --

19 MEMBER CORRADINI: Yes, that's fine.

20 You can tell us to wait. That's allowed.

21 MS. FLANAGAN: Oh, okay.

22 MEMBER CORRADINI: It's a very

23 acceptable answer: Wait.

24 MS. FLANAGAN: I know, but I just love

1 answering questions.

2 MEMBER CORRADINI: You don't have to be

3 so nice to us. You don't have to. It's not

4 required.

5 MS. FLANAGAN: Okay. So, what I'd like

6 to show from this slide is that this is the bending

7 moment that was observed in the load displacement

8 curve for the tests that were shown on the previous

9 slide. And so, the main thing we noticed from this

10 is as oxidation increases, the bending moment

11 decreases. The more oxidation you have, the less

12 bending moment you have.

13 And I want to point out, as I said

14 before, there was a large range of ballooning

15 strains that were part of this test matrix. And

16 despite the fact that there was a large range of

17 balloon strains, we seen the general dominating

18 trend as oxidation. And if you look at the two

19 shapes, circles on this plot represent ballooning

20 strains above 40 percent and the squares represent

21 ballooning strains 33. So, you have a

22 differentiation on the figure of large balloons and

23 small balloons, and we don't see a separation of the

24 results based on that finding.

1 And on the next slide I'm going to point
2 out there's two different failure locations that we
3 saw in these tests. And what I'll say while on this
4 slide is despite the fact that in some cases we saw
5 failure taking place in the center of the rupture
6 opening at the location of maximum oxidation, and
7 then sometimes in the region of highest hydrogen
8 content, we don't see a separation of data points
9 still. It's still dominating by oxidation.
10 MEMBER SHACK: But you've scaled your
11 ECR here by the --
12 MS. FLANAGAN: Yes, that's a good point
13 actually, and it's written here and I just forgot to
14 say it. The x-axis is a calculated value. And in
15 this case it was calculated with the approach to
16 oxidation and ECR that defined in the current rule,
17 so it's scaled in that sense by the wall thickness
18 and the strain. Thank you for reminding me to say
19 that.
20 So as I said, we observed two failure
21 locations during these bend tests. One on the left-
22 hand side is where a combination of high hydrogen
23 content and oxidation was observed. I tried to
24 scale this figure to kind of orient relative to the

1 hydrogen plot above. The location of failure wasn't
2 at the maximum hydrogen at about 40 millimeters away
3 from the burst center, but about 24 millimeters
4 below at a location where there is high hydrogen
5 content, but we also have high oxygen content as
6 well.
7 The other type of failure location that
8 we observed was failure right in the center of the
9 rupture. And as I mentioned in the previous slide,
10 even when we see these two different failure
11 locations, the conclusion that we can draw from this
12 is that you still need oxidation in order to cause
13 failure. The more oxidation you have, the lower the
14 bending moment. And we saw the same trend when we
15 observed the maximum energy of failure in these bend
16 tests.
17 So, after the as-fabricated test series
18 was complete, four tests on irradiated material were
19 conducted at Studsvik. And I want to point out that
20 prior to the testing at Studsvik there was a lot of
21 work that was done to compare the apparatus, the
22 LOCA heating apparatus, as well as the bend
23 apparatus between Studsvik and Argonne so that we
24 could ensure that we could really put these points

on the same plot. And when we looked at the four tests at Studsvick, the values that we targeted were informed by the hydrogen content of this irradiated material and our proposed limit. So, the irradiated material that we had at Studsvik had a pre-transient hydrogen content of around 200 weight ppm. And with the proposed rule that material will be subject to 12 percent ECR. That would be its oxidation limit.

And so, the oxidation values that we were targeting were just above and just below that line. And then we also conducted a test at 17 percent and at 0 percent ECR. So, the 0 percent ECR was just ballooned and ruptured, and then the test was terminated.

MEMBER ABDEL-KHALIK: The extent of ballooning on these pictures is greater probably than the spacing between rods --

MS. FLANAGAN: This is correct.

MEMBER ABDEL-KHALIK: -- in an actual bundle.

MS. FLANAGAN: This is correct and it was unexpected.

MEMBER ABDEL-KHALIK: So, if that is the

1 case, should the test procedures be modified to
2 limit the extent of deformation in the ballooning
3 region as if there's a neighboring rod that would
4 limit?
5 MS. FLANAGAN: Well, we don't see a
6 large impact from the strain on the results, but I
7 agree with you that there is some non-
8 prototypicality in this large balloon strain. We
9 don't see that it impacts the conclusions that we
10 can draw from these particular tests. And the test
11 procedures that you're referring to are our internal
12 procedures for -- this isn't combined with the
13 regulatory guide test procedures.
14 MEMBER ABDEL-KHALIK: I'm just trying to
15 understand the prototypicality of the results. And
16 if the geometry of the ballooned region in the tests
17 is nowhere near what you would expect in reality,
18 I'm just wondering how you can justify this.
19 MS. FLANAGAN: I would agree, but we
20 don't see a large influence of the ballooning
21 strain. So what I'm saying is that even though
22 these balloon strains are very large, I don't think
23 that that invalidates the conclusions that you draw
24 from comparing two rods and looking at the influence

1 of oxidation.

2 CHAIRMAN ARMIJO: But if you didn't have

3 as much strain wouldn't you expect that the maximum

4 energy would be greater than something that had a

5 lot of strain in your mechanical test?

6 DR. BILLONE: No.

7 MS. FLANAGAN: Yes, maybe Mike can

8 interject.

9 Mike, I have slide 16 up, and I can go

10 back to slide 14 where we were looking at the plots

11 of the values that were measured. And they include

12 balloon strains of 70 percent all the way down to 20

13 percent.

14 DR. BILLONE: Right, so then there's two

15 different issues here. Relative to Michelle's

16 slides, because we don't see a significant

17 difference in strain, which is maximum bending

18 energy -- I mean, maximum bending moment, or maximum

19 energy, you just look at the square points versus

20 the circular points. And the square points are as

21 low as 20 percent circumferential strain, which is

22 certainly well within the ability of the cladding to

23 deform in an array. As you get to higher strains,

24 you've got possibly balloon cladding pushing against

1 other cladding and you vary the shape.

2 But the reason we went for the higher

3 strains is we wanted to also look at fuel

4 relocation, kind of a maximum upper bound on fuel

5 relocation and possibly fuel dispersion through the

6 rupture opening. And that historically has been the

7 way we've conducted the program since 1998.

8 My last comment is that when vendors use

9 Appendix A, for example, to do some hydraulics

10 analysis, they have ballooning strains, and it could

11 be as high as 100 percent, you know, as high as 20

12 percent, regardless of whether it's typically

13 realistic or not.

14 MS. FLANAGAN: Does that answer that

15 question?

16 MEMBER ABDEL-KHALIK: No, but that's

17 okay.

18 MS. FLANAGAN: Let me try one more thing

19 and --

20 MEMBER ABDEL-KHALIK: I'm just trying to

21 understand how these results can actually be

22 invariant, and I can't convince myself that they can

23 ever be invariant.

24 MEMBER SHACK: But they've stilled over

1 a range of a strains that exceed what they expect to
2 find, which I think is sort of her point, is that
3 clearly if you're not getting too much scatter over
4 this range of strains, over the real range of
5 strains it's going to be even less. And so, you
6 know, they're trying to sort of -- because in
7 reality they don't know this average strain all that
8 well. It's something they compute. So, you'd like
9 to show that it's relatively insensitive to that,
10 and that's sort of what the results are showing
11 here.
12 MS. FLANAGAN: Of the four tests that
13 were run at Studsvik here's a couple parameters of
14 the tests. I'm going to go right into a plot which
15 has the Studsvik values along with the as-fabricated
16 values.
17 So, on this plot the Studsvick high
18 burnup tests are indicated with open red triangles.
19 And those points as well as the as-fabricated
20 points were all documented in the report that was
21 provided a couple weeks ago.
22 MEMBER SHACK: Where are the triangles?
23 DR. BILLONE: The diamonds.
24 MS. FLANAGAN: Diamonds; sorry.

1 MEMBER SHACK: Diamonds?

2 MS. FLANAGAN: Yes.

3 MEMBER SHACK: Okay. All right.

4 MS. FLANAGAN: Here, here, here and then

5 there's one up here.

6 And then since the report was provided

7 to the ACRS a couple weeks ago, two pre-hydrided

8 results were produced. And so, I'm putting them on

9 here to make a point in a second about the effect of

10 hydrogen. But what I'd like to point out

11 in this figure are that the values of bending

12 moment, as I said before, decrease with increasing

13 oxidation and therefore limiting oxidation in

14 ballooned and ruptured cladding we determined is

15 appropriate and the ballooned region should have an

16 oxidation limit applied.

17 The values of bending moment for

18 irradiated fuel have been shown to be reduced

19 relative to as-fabricated cladding with the same

20 oxidation level. And in addition, recent pre-

21 hydrided data has shown that the bending moment of

22 pre-hydrided material is also reduced from as-

23 fabricated cladding for the same oxidation level.

24 And taken together this data suggests that there is

1 a hydrogen effect for the mechanical behavior of the
2 balloon that should be accounted for.
3 Applying the proposed hydrogen-dependent
4 oxidation limit in the balloon preserves favorable
5 mechanical properties. And I say this -- recall
6 that the tests at Studsvik had a pre-transient
7 hydrogen content of around 200 weight ppm, and so
8 therefore their oxidation limit would be around 12
9 percent. And so, if we assume that this trend is
10 depicting a value around here for 12 percent, we see
11 that the bending moment value is higher than the as-
12 fabricated cladding at 17 percent. And we also see
13 the same general trends when we examine the failure
14 energy.
15 DR. BILLONE: Michelle, may I make a
16 small point?
17 MS. FLANAGAN: Yes.
18 DR. BILLONE: Argonne is just showing
19 two data points for pre-hydrided cladding and we
20 have four more tests we're in the middle of. So,
21 we'll be able to populate this data with lower
22 hydrogen contents comparable to Studsvik. Currently
23 we're testing at 200 to 250 weight parts per
24 million. So, we'll have four more data points on

1 this plot.

2 CHAIRMAN ARMIJO: Okay. That's in the

3 pipeline, or is already done?

4 DR. BILLONE: We're in the process of

5 completing those tests.

6 CHAIRMAN ARMIJO: Yes, okay. Back on

7 that same chart, so just let me get this straight:

8 The blue data points have some level of hydrogen,

9 but less than 200 ppm?

10 MS. FLANAGAN: The blue dots are as-

11 fabricated cladding.

12 CHAIRMAN ARMIJO: Okay.

13 MS. FLANAGAN: So, they began with no

14 hydrogen.

15 DR. BILLONE: Five to ten weight parts

16 per million.

17 MS. FLANAGAN: Oh, sorry. Right.

18 CHAIRMAN ARMIJO: So, it's only whatever

19 hydrogen that they picked up during the test?

20 MS. FLANAGAN: Yes.

21 CHAIRMAN ARMIJO: And the 200 ppm is for

22 the HB Robinson cladding that was irradiated and you

23 had measured that before. And then the new --

24 DR. BILLONE: It's not HB Robinson.

1 It's --

2 PARTICIPANT: High burnup.

3 CHAIRMAN ARMIJO: High burnup? Oh,

4 okay.

5 DR. BILLONE: -- high burnup from North

6 Anna.

7 CHAIRMAN ARMIJO: Okay.

8 MS. FLANAGAN: Yes.

9 CHAIRMAN ARMIJO: High burnup.

10 DR. BILLONE: But HB means high burnup.

11 CHAIRMAN ARMIJO: Okay. So, you're just

12 saying here's your hydrogen effect demonstrated in

13 this curve and we can account for that by the same

14 oxidation limits that we're going to apply in other

15 parts of the cladding?

16 MS. FLANAGAN: Yes.

17 CHAIRMAN ARMIJO: Is that basically what

18 you're saying?

19 MS. FLANAGAN: That's --

20 CHAIRMAN ARMIJO: Even for balloon

21 stuff.

22 MS. FLANAGAN: Yes, it's saying that if

23 you apply the hydrogen-based oxidation limit, you

24 will preserve balloon properties.

1 CHAIRMAN ARMIJO: And you'll maintain a
2 sufficient level of ductility even in the ballooned
3 region? I'm just trying to get to --
4 MS. FLANAGAN: Yes.
5 CHAIRMAN ARMIJO: -- the conclusion of -
6 -
7 MS. FLANAGAN: I think if we wanted to
8 say a lot more, we would really need a lot more data
9 points. So, we're kind of struggling to say what we
10 can conclude. The data that we have confirms that
11 applying the oxidation limit in the balloon is
12 appropriate. Applying a hydrogen-based limit is
13 also appropriate.
14 CHAIRMAN ARMIJO: Okay. Well, I'll let
15 you finish then. See where you're going.
16 MS. FLANAGAN: I'm not going too much
17 further.
18 CHAIRMAN ARMIJO: That's it.
19 MS. FLANAGAN: Now, I'm going to state
20 the program conclusions.
21 MEMBER BROWN: Go back. You said you
22 had a dearth of data points.
23 MS. FLANAGAN: I did? For as-fabricated
24 cladding we have a large number of data points. For

1 irradiated material we have four.

2 MEMBER BROWN: Yes, you didn't have

3 much. And so, we're going to set a rule based on a

4 limited data set as opposed to -- I'm just trying to

5 understand. I'm a neophyte also; as Mike commented,

6 and I would have thought that on the material

7 standpoint we'd want a wider range and a more

8 populated data set for the irradiated material as

9 opposed to just as-fabricated material, which is not

10 totally representative, at least in my own mind, of

11 what you experience under the actual LOCA conditions

12 that we're projecting to try to protect against.

13 MS. FLANAGAN: I think if we started to

14 see trends that we didn't expect, we would want a

15 lot more data. There was nothing that we saw that

16 we weren't expecting. And so then as a confirmatory

17 research program we're comfortable with the amount

18 of data that we have to make our decisions.

19 MEMBER BROWN: How much data do you

20 have, these three data points? Is that --

21 MS. FLANAGAN: For irradiated material

22 we have four tests that were integral, LOCA, bend

23 test.

24 MEMBER BROWN: Okay. Four data points.

1 MS. FLANAGAN: For these -- I mean, yes,
2 this is in addition to a large amount of work that
3 was completed to just look at the effect of oxygen
4 and hydrogen through the ring compression tests.
5 So, this is kind of a targeted program specifically
6 on the balloon properties. And in that case we did
7 four integral LOCA tests.
8 MEMBER BROWN: I'm not a metallurgist,
9 so I'm not going to sit here and -- it just seems
10 like that -- for a major rule change that just seems
11 like a low amount of data in order to draw a
12 conclusion for a rule change that's been in place
13 for --
14 MS. FLANAGAN: Well, I should say that
15 the existing basis that was established in 1973
16 looked at this also. And what I'm saying is that
17 now our question was is there a hydrogen effect in
18 the balloon? And for that we did a number of tests
19 and we didn't see anything that we didn't expect.
20 And so as a confirmatory program, that was
21 satisfying. As establishing a new understanding of
22 new phenomenon that would probably not be
23 sufficient. Does that make sense?
24 MEMBER BROWN: Sort of. I'll continue

1 to listen.

2 MS. FLANAGAN: Okay. Back to slide No.
3 21, the program conclusions. A lot of these I've
4 already stated. And what I mean to say with the
5 program conclusions is if we look at the results of
6 the data, we can notice a couple things. All of the
7 samples survived quench. The values of bending
8 moment and failure energy decreased with increasing
9 oxidation, and this was noted even through a wide
10 range of balloon strain.

11 Even though very high values of hydrogen
12 were observed within the ballooned region for as-
13 fabricated samples and also for the irradiated
14 samples, no matter where the failure was observed,
15 the residual bending moment and the failure energy
16 remained a function of oxidation. The values of
17 bending moment and failure energy reveal a hydrogen
18 effect on the mechanical behavior of the ballooned
19 region that should be accounted for. And when the
20 new proposed hydrogen-based criteria is applied in
21 the rupture region, the mechanical properties of
22 this region are maintained to that of fresh
23 cladding.

24 So, then when we look at the program

1 conclusions within the regulatory context, we look
2 at three aspects: One is how can we use these
3 results to address the treatment of the ballooned
4 region within the rulemaking to revise the
5 embrittlement criteria of 50.46? Another aspect is
6 to address the extrapolation of these research
7 findings to new cladding alloys and lower oxidation
8 temperatures. And then finally, we addressed the
9 regulatory question of alternate performance metrics
10 for the ballooned and ruptured region of the fuel.
11 And these are topics that are elaborated
12 on in the report, and I'm just going to give some
13 highlights of what this report concludes within this
14 regulatory context. So, regarding --
15 CHAIRMAN ARMIJO: Michelle, before you -
16 -
17 MS. FLANAGAN: Yes?
18 CHAIRMAN ARMIJO: Go back to that slide
19 21.
20 MS. FLANAGAN: Yes. Oh, yes.
21 CHAIRMAN ARMIJO: You say all samples
22 survived the quench, and that included the
23 irradiated high burnup cladding?
24 MS. FLANAGAN: Correct.

1 CHAIRMAN ARMIJO: It included the as-
2 fabricated low-hydrogen cladding, and it included
3 the pre-hydrided cladding, the 400 to 700 ppm
4 hydrogen. The ballooned regions in all of those
5 samples survived this quench in your test. So, then
6 the question I have is if this ballooned region
7 under all of these conditions has sufficient
8 ductility to survive the quench, why is there any
9 concern that a non-ballooned region -- hasn't been
10 deformed, doesn't have any more hydrogen, is no more
11 irradiated. Why would we have any concern about the
12 non-ballooned region? Why wouldn't we just say,
13 hey, if the ballooned region which is already
14 fractured, thin, loaded with irradiation, loaded
15 with hydrogen survives a quench, why do we worry
16 about the non-ballooned region?
17 MS. FLANAGAN: Let me make sure I
18 understand the question. When I say that the sample
19 survived quench, what I mean is that after the
20 transient and the apparatus is disassembled, the rod
21 was in one piece, and then we did a mechanical test
22 to see what was left.
23 CHAIRMAN ARMIJO: Well, that's my point.
24 MS. FLANAGAN: Right.

1 CHAIRMAN ARMIJO: It survived the
2 quench, you know?
3 MS. FLANAGAN: Right.
4 CHAIRMAN ARMIJO: Whatever loading was
5 in that apparatus, it did survive it. And so, if
6 something that is clearly thinner wall, obviously
7 more fragile than the un-deformed portion of a fuel
8 rod, can survive that, why wouldn't we focus all our
9 concerns strictly on the ballooned region as a
10 limiting region and not spend a lot of time worrying
11 about the un-deformed cladding?
12 DR. BILLONE: Michelle, may I try that
13 one?
14 MS. FLANAGAN: Sure.
15 DR. BILLONE: These samples that we're
16 testing, they're segments, they're not full fuel
17 rods, but they're free to expand in the axial
18 direction and contract in the axial direction. So,
19 basically surviving quench means surviving the
20 thermal stresses induced by quench. However, you
21 know there's additional stresses on the cladding to
22 the extent that it's not free to contract during a
23 quench and it may get hung up at grid spacers or
24 what not. So, we know there are loads above and

1 beyond -- in particular there are axial loads due to
2 partial constraint above and beyond what we call
3 quench loads or when we talk bout thermal stresses.
4 So, that's the whole point of this program is what
5 do you have left in the cladding above and beyond
6 surviving thermal loads, not counting the partial
7 constraint-type thermal loads, just the temperature
8 gradient to the cladding-type thermal loads.
9 CHAIRMAN ARMIJO: Yes, I hear you, Mike,
10 but you know, if we're measuring fracture toughness
11 or we're looking for something to retain ductility,
12 it would seem to me that if you've demonstrated
13 sufficient ductility in a region that has half the
14 wall thickness --
15 DR. BILLONE: I'm sorry, where are you
16 getting the impression that we've demonstrated
17 ductility? I'm missing that.
18 CHAIRMAN ARMIJO: Well, if --
19 MEMBER SHACK: Demonstrated sort of
20 strength to survive quench. There may be no
21 ductility left at that point.
22 CHAIRMAN ARMIJO: Well, then if there's
23 --
24 DR. BILLONE: We're maintaining

1 ductility in the majority of the --

2 CHAIRMAN ARMIJO: Well, I thought all

3 your measurements here showed you measured the

4 strain energies, you measured offset strains in

5 these four-point bend tests.

6 DR. BILLONE: Right.

7 CHAIRMAN ARMIJO: And if that doesn't

8 give you some information on ductility, I don't know

9 what --

10 DR. BILLONE: Well, in general we didn't

11 measure any offset strain for most of our tests.

12 Particularly if you fail in higher hydrogen regions

13 the material is brittle, but it has strength. And

14 most of our failures in the rupture region, when you

15 subject the rupture opening, detention failed with

16 no offset strain. So, I mean, I hesitate to use the

17 word "ductility" to include the whole ballooned

18 region with everything from the hydrogen peak all

19 the way to the oxygen peak.

20 CHAIRMAN ARMIJO: So, where is the

21 limiting region? What part of the fuel rod should

22 we be worried about?

23 MS. FLANAGAN: I think we're getting

24 back to the question that Dr. Shack asked earlier.

1 I mean, in some cases you're right that we may be
2 limited in the ballooned region, but I'm not sure
3 that that leads to the conclusion that we should not
4 have any limit in other areas. Because depending on
5 the conditions and the large break versus small
6 break and the different transient history there's
7 still a need to have a limit for other areas. And I
8 think it gets back to the particular transient of
9 interest where you're going to identify your worst
10 case.
11 MEMBER SHACK: But I think you can also
12 make the argument that maintaining the ductility
13 with the criteria they have for the un-deformed ring
14 seems to give you results for the balloon that
15 assure that it's got some sort of integral strength.
16 Even if you can't sort of talk about ductility in a
17 meaningful way, that it doesn't -- you know, if you
18 follow those rules, at least you're with something
19 that looks reasonable in the ballooned region even
20 though you're sort of basing that largely on
21 engineering judgment. Because as Michelle says, you
22 really can't calculate all the loads it has to take.
23 And then you're going come back to the argument,
24 okay, it's only a ballooned region. A failure there

1 doesn't mean you've lost coolable geometry. But
2 it's --
3 CHAIRMAN ARMIJO: Well, I --
4 MEMBER SHACK: You know, the criterion
5 they're imposing seemed to give you --
6 CHAIRMAN ARMIJO: I see the argument
7 starting with the un-ballooned region saying if we
8 can protect it there, it turns out that the
9 ballooned region isn't catastrophic. But it still -
10 -
11 MEMBER SHACK: Yes, there's something a
12 little less than totally satisfying.
13 CHAIRMAN ARMIJO: Yes, there you go.
14 MEMBER SHACK: But I think that comes
15 back to the fact that as she comes to her alternate
16 metric she's going to say she doesn't really know
17 what they could be, because you can't really -- we
18 don't -- we're not really smart enough to calculate
19 all the loads.
20 CHAIRMAN ARMIJO: Yes, but I'm just
21 trying -- getting back at the coolable geometry, I'm
22 looking at these pictures of these fractured
23 ballooned regions and a fracture in a ballooned
24 region, I can see where you could have actual

1 relocation of fuel, stuff falling out of that. I
2 think it's still coolable, but compare what would
3 happen in a fractured un-deformed, relatively un-
4 deformed region, I'd say that's a non-event. Unless
5 it fractures in many places, I don't see why that
6 wouldn't be a priori coolable. I'm just trying to
7 get back to our fundamental goal of assuring
8 coolable geometry. And any way you look at it, the
9 fracture in the ballooned region would be less
10 coolable than fracture in the un-ballooned region.
11 And so, why don't we concentrate on the ballooned
12 region. I guess that's where I'm at.
13 MS. FLANAGAN: And in practice that may
14 be how the calculations turn out, that that's the
15 focus and that's the limiting region. So, I don't
16 know if
17 -- I think --
18 CHAIRMAN ARMIJO: Okay. Well, maybe --
19 MS. FLANAGAN: -- that might be how it
20 is.
21 CHAIRMAN ARMIJO: When we get to the
22 point of how do we treat it and what does somebody
23 that has to assure they have adequate ductility and
24 compliance with the rule, what do they have to do in

1 the ballooned region as compared to the un-ballooned
2 region to meet the requirements?
3 MEMBER CORRADINI: And in the rule. I
4 view all of this as --
5 MEMBER SHACK: You have to compute your
6 ECR for the ballooned region and make sure it meets
7 the rule. You're going to go back to that diagram.
8 MEMBER CORRADINI: But, yes, I'm -- I
9 should be --
10 MEMBER SHACK: So, they're --
11 MEMBER CORRADINI: I'm still confused.
12 I'm still confused. It seems to me that the
13 ballooned region would still dominate because any
14 non-ballooned region, if it could dominate, would
15 probably be in a low-power region, therefore it
16 wouldn't -- I'm still missing something. Your
17 original question to Paul still is in my mind.
18 MEMBER SHACK: Yes, but then it comes
19 back to this peak clad temperature is likely to be
20 something other place because I'm going to get
21 cooling. And so, I have a whole bunch of competing
22 effects going on here. I mean, I think we'd
23 actually need to see some calculations to really
24 understand what's happening. Bert's going to say

1 something.

2 CHAIRMAN ARMIJO: Well, the peak clad

3 temperature can't move too far away from the balloon

4 because that's where it was the hottest originally.

5 That was where --

6 MEMBER SHACK: Well, it balloons at 800

7 C, so I mean, you know --

8 CHAIRMAN ARMIJO: I understand, but that

9 was the first part that got hot.

10 MEMBER SHACK: Yes, but then it cools

11 off.

12 CHAIRMAN ARMIJO: Locally, but as far as

13 the decay heat and the source of heat and the things

14 that caused it to get hot, it's still in that same

15 nodal region. So, it's not going to be far away.

16 MEMBER CORRADINI: Yes, it's not going

17 to be a foot up or a foot down. It might be a few

18 inches up or down.

19 CHAIRMAN ARMIJO: Yes. Yes.

20 MR. DUNN: Dr. Armijo?

21 CHAIRMAN ARMIJO: Yes?

22 MR. DUNN: Bert Dunn, AREVA. Could I

23 could enter the conversation?

24 CHAIRMAN ARMIJO: Sure.

1 MR. DUNN: I don't mean to be too
2 critical, but I would disagree with Paul's statement
3 earlier that it was likely that the ballooned region
4 would be limited. I think there are an awful lot of
5 variables associated with it and that it is kind of
6 fruitless to try and define the limiting location on
7 the pin. If you account for the cooling effects on
8 the pin, you are likely to produce, as Dr. Shack
9 just said, a cooling effect at the time of rupture.
10 That will occur at about 800 degrees C. You're
11 going to carry up the calculation to where -- a
12 region just below the location of rupture, probably
13 on the order of eight to twelve inches below it,
14 because that will probably move to the next lower
15 grid span, to get that thing, which will be at
16 essentially the same power, maybe about 10 percent
17 lower in power. And that area will go on up to
18 2,000 degrees, over 1,900 degrees, something on that
19 order. Whereas, the ruptured area will stay about
20 200 degrees below that. And then we will wind up
21 getting a much higher oxidation at that lower level
22 because of the temperature relationship of oxidation
23 rate.
24 And we see both results. Sometimes

limited at the rupture location; more frequently for the B&W design limited at an un-ruptured location. And in our calculations; this is AREVA's calculations, for the Westinghouse and CE plants that we're serving, we see that the maximum location for the new criteria even -- well, maximum location of oxidation will be removed from the ruptured area.

Now, at present those calculations do not include fuel relocation for us, and fuel relocation would modify that a little bit towards the ruptured area. But I don't think you can predict where the limiting location is.

CHAIRMAN ARMIJO: Okay. Well, you know, you still have to be in that zone, within a node or two from the reason that ballooned region got hot earliest, because that's where the highest decay heat was.

MR. DUNN: The highest decay heat or some sort. There's a cooling pattern within a grid span that could change that a little bit. But you're right; very likely the highest decay heat, highest power.

CHAIRMAN ARMIJO: And as far as loss of coolable geometry, a fracture of a ballooned open

1 region would seem to me to be more severe than a
2 fracture of a un-deformed tube in which it would be
3 very difficult for pellets to come out of a simple
4 cracked round tube.
5 MR. DUNN: Well, except that you will
6 have ruptures in that assembly all the way around.
7 The pins will kind of locked into a position,
8 whether or not they rupture or not. I mean, not
9 whether -- whether they crack or not.
10 CHAIRMAN ARMIJO: Well, you know, the
11 issue is if they cracked, have you lost coolable
12 geometry? And the answer I'd have is I don't see
13 how that's lost coolable geometry. If you break a
14 balloon and fuel spills out, that's probably still
15 pretty coolable, but seems to me that it's worse.
16 But, I think we can go on and see where the staff is
17 headed.
18 MEMBER CORRADINI: But, can I ask a
19 question? I mean, maybe I'm missing it, but all of
20 these experiments are single rod experiments, right?
21 MS. FLANAGAN: Yes.
22 MEMBER CORRADINI: It would never expand
23 like this in a rod bundle. So, I'm missing
24 something here that maybe has been discussed and I

1 was not at that subcommittee meeting. But the P
2 over D of these things is like 1.3, 1.25. These
3 things have gone to like 2, right? So, what am I
4 missing in terms of the reality of how this would
5 occur within a rod bundle? Somebody help me here.
6 MR. DUNN: I think in terms of my
7 response to that is the rods, if they expand as a
8 circle with the same degree of expansion all the way
9 around, which they never do, but -- that they will
10 touch an adjacent rod at about 30 percent strain.
11 So past 30 percent strain you have stopped your
12 circular expansion and you've moved into something
13 that might look like a cloverleaf or a child's jack,
14 or something, and that they will wrap around the
15 adjacent rod. You'll provide some additional
16 strength to stop the tertiary expansion at that
17 point, the tertiary strain, and you'll probably wind
18 up with slightly lower strains for the rods.
19 MEMBER CORRADINI: So, let me ask my
20 next question.
21 MR. DUNN: But I think largely strain
22 will be preserved.
23 MEMBER CORRADINI: Okay. All right.
24 So, that makes some -- qualitatively that makes

1 sense to me. So, then why is the cooling better?
2 It seems to me I would get contact to contact and
3 all of a sudden things would get ugly
4 circumferentially.
5 MR. DUNN: Well, one thing --
6 MEMBER CORRADINI: Where is that
7 computed?
8 MR. DUNN: One thing is that an
9 azimuthal gradient through the cladding doesn't have
10 to be very strong to move the power to another
11 location. The second thing is that you have direct
12 droplet enhancement. You're in re-flood probably.
13 You're carrying water droplets up with the steam.
14 They're interacting directly with that cladding
15 expansion. And that's occurring throughout the
16 entire bundle. And the rupture distribution axially
17 has a variation to it so that you --
18 MEMBER CORRADINI: Well, I mean, okay, I
19 hear what you're saying, but I guess I don't want to
20 take us off track because there's a whole lot more
21 to go over.
22 MR. DUNN: We are. I'm sorry.
23 MEMBER CORRADINI: But I guess my only
24 point is that -- I was holding this one until later,

1 but it's just striking me that I understand how the
2 cooling would be initially enhanced, but if
3 anything, if I start touching I would get some
4 circumferential heating issues that -- and I'd get a
5 blockage. And I'm back to Sam. This is still the
6 limiting location. I mean, I was letting him go
7 with this because I figured it would have to be the
8 limiting location just because eventually you're
9 going to run into the next rod.
10 MR. DUNN: I think my expectations are -
11 - you're talking about something on the order of
12 coplanar blockage where we get a lot of coolant up
13 to that rod --
14 MEMBER CORRADINI: Yes.
15 MR. DUNN: -- and the energy can't be
16 transported out of that rod to adjacent rods.
17 MEMBER CORRADINI: Yes.
18 MR. DUNN: If we got something on the
19 order of 5 by 5 or 7 by 7 coplanar blockage within a
20 fuel bundle, that would be difficult to cool. But
21 if you look at the axial distribution at rupture,
22 it's up here, down here. And so, the coolant varies
23 around like that, like a snake through a path.
24 MEMBER CORRADINI: Okay. All right.

1 MR. DUNN: And there are tests --
2 MEMBER CORRADINI: I'll be quiet.
3 MR. DUNN: -- though not many bundle
4 tests --
5 CHAIRMAN ARMIJO: Well, once it
6 ruptures, you got direct cooling of the fuel.
7 MEMBER CORRADINI: Okay. So, now we're
8 getting to my point. So, repeat your last point?
9 MR. DUNN: My last point?
10 MEMBER CORRADINI: About there's not
11 many bundle tests.
12 MR. DUNN: That's true. There's not
13 very many bundle tests with characteristic cooling
14 measurable.
15 MEMBER CORRADINI: Okay.
16 MR. DUNN: Okay? There are FLECHT tests
17 in which coplanar blockage has been put in place,
18 and distributed blockage. There's FEBA tests in
19 which that's been done. What's missing today would
20 be bundle tests with the possibility of fuel
21 relocation.
22 MEMBER REMPE: What was the second, sir?
23 He said FLECHT. And what was the second?
24 PARTICIPANT: PHOEBUS.

1 MEMBER REMPE: PHOEBUS? It's PHOEBUS is
2 what you're talking about over in France, or --
3 MR. DUNN: What? Did I mis --
4 MEMBER REMPE: Was it PHOEBUS was the
5 second place that you mentioned where they did --
6 MR. DUNN: F-E-B-A.
7 MEMBER REMPE: FEBA? Okay.
8 MR. DUNN: I'm sorry, ma'am. I couldn't
9 hear you very well.
10 MEMBER REMPE: Oh, sorry.
11 CHAIRMAN ARMIJO: Okay. Let's move on.
12 MEMBER SHACK: Sorry, Sam.
13 CHAIRMAN ARMIJO: Oh, that's all right.
14
15 MEMBER SHACK: Well, just to close it,
16 it is interesting to note that in the RIL the last
17 paragraph sort of addresses these issues on the
18 ballooning and the blockage and it sends us off to
19 Grandjean's review where he says that our current
20 ballooning models underestimate potential blockage
21 which would contribute to -- and I was going to ask
22 whether -- the RIL sort of indicated we were going
23 to go off and work with the French on this, and then
24 is there any progress on that?

1 MS. FLANAGAN: I certainly don't have
2 any information on that in this presentation, but I
3 can make a note to get back on that.
4 MEMBER SHACK: Okay. You're not off the
5 top of your head aware of efforts?
6 MS. FLANAGAN: To redo calculations or
7 to revisit conclusions?
8 CHAIRMAN ARMIJO: Experiments.
9 MEMBER SHACK: Well, either conclusions,
10 experiments, to address the criticism that our
11 current estimates of coolant flow blockage are un-
12 conservative, which is Grandjean's conclusion about
13 the way we do it now.
14 MS. FLANAGAN: Okay. I'll make a note
15 of that. And like I said, I don't have material
16 here.
17 CHAIRMAN ARMIJO: Okay. Michelle, just
18 keep going.
19 MS. FLANAGAN: Okay. So, as I
20 mentioned, the program conclusions and the results
21 of the experimental program were then used to
22 reference a regulatory context. And so, regarding
23 the treatment of the ballooned region within the
24 rulemaking to revise 50.46, the report that was

1 provided and is the subject of this briefing uses
2 the observations of the test program to support the
3 position that the time and temperature limit that
4 was developed based on ring compression data to
5 limit oxidation should be applied uniformly into the
6 entire rod and that the provisions within the
7 guidance that were outlined in the existing rule
8 that used average wall thicknesses and double-sided
9 oxidation should continue to apply in the rupture
10 region to calculate the ECR value.
11 MEMBER SHACK: I had a question on this
12 one. You used an average wall thickness. That was
13 a measured average wall thickness, or was that
14 computed the way we would do it if we were doing a
15 calculation?
16 MS. FLANAGAN: Measured.
17 CHAIRMAN ARMIJO: So, do you have to do
18 a ballooning test to come up with that measured
19 average wall thickness, or is that something that
20 you can calculate?
21 MS. FLANAGAN: It is a calculation, and
22 there's models that predict the ballooning strain
23 given pressure and temperature conditions. And what
24 we did in this program was look at what the actual

1 experiments measurements were and then plotted the
2 values relative to the actual observed measurements.
3 Did that answer --
4 DR. BILLONE: There are two reasons we
5 did that. One is this is all ZIRLO you're looking
6 at, and the ballooning strain correlation for ZIRLO
7 is proprietary and wasn't really available to us.
8 We wouldn't be able to publish those results.
9 Secondly is we wanted to take that large
10 scatter in the correlation prediction out of this
11 particular database so we could specifically look at
12 the effects of oxidation. So, we literally measured
13 the outer circumference of the post-balloon sample
14 and post-oxidized sample and had models to convert
15 that into a circumferential strain.
16 CHAIRMAN ARMIJO: Okay.
17 MS. FLANAGAN: So, the next way that we
18 used the next regulatory statement or the regulatory
19 conclusion that's in the document is looking at the
20 extrapolation of these research findings to new
21 cladding alloys and lower oxidation temperatures.
22 So as you recall, our test procedures and the
23 regulatory guides, which we came earlier this month
24 with the full committee and in May to the

1 subcommittee, presented test procedures to do ring
2 compression tests that could be used to develop
3 oxidation limits. And when we look at -- the
4 subject report discusses and supports a position
5 that the embrittlements developed for new cladding
6 alloys and at lower oxidation temperatures based on
7 ring compression tests may be applied uniformly in
8 the entire rod with the provisions of the balloon
9 outlined in the existing rule.
10 The results of this program didn't
11 reveal any reason that oxidation embrittlement
12 limits developed from ring compression tests on non-
13 deformed cladding material should not be indicative
14 of trends in the degradation of ballooned and
15 ruptured regions. So, said in another way, the
16 results of this program did not reveal any reason
17 that materials which demonstrate improved
18 embrittlement performance in ring compression tests
19 wouldn't also demonstrate improved performance in
20 the ballooned region. And then new cladding alloys
21 therefore would not be required to conduct an
22 integral LOCA test program like that which was done
23 here to specifically characterize the balloon region
24 properties.

1 So, another sort of regulatory
2 conclusion, or a description that was in the
3 document was looking at alternate performance
4 metrics for the ballooned and ruptured region. And
5 this is really because there's been a lot of
6 discussion of alternate metrics for fuel rod
7 performance under LOCA conditions within the
8 international community. And these alternate
9 performance metrics for the most part rely on
10 detailed knowledge of LOCA loads, are complex,
11 experimental and modeling research programs. And
12 so, the statement that's expanded on in this report
13 is that the state of the art doesn't support a
14 regulatory position based on these proposals in the
15 near term. And therefore, pursuing more complex
16 performance metrics, more complex modeling
17 approaches for the ballooned and ruptured region
18 isn't recommended at this time.
19 Now, earlier in the presentation I had
20 the text that referred to the ballooned region from
21 RIL 0801. And given that now we have additional
22 information, we've made experimental observations
23 and we have a more specific conclusion about the
24 balloon, it would be appropriate to revisit the RIL

1 and update this statement and possibly expand on it.
2 So, in preparation for this meeting, we transmitted
3 a draft update to the RIL. Now, by the time we're
4 here in December maybe this would be expanded, but
5 the one I want to point out here is an additional
6 two sentences which could be added to the RIL to
7 restate the conclusion that this report finishes
8 with, and then this RIL would reference the subject
9 report of this meeting as a point or two a part of
10 the technical basis.
11 And so, in this case the statement that
12 was there in the original RIL would remain. We
13 still have no criteria that would ensure cladding
14 ductility in the balloon. And we'd note that the
15 bending moment and failure energy were measured
16 using four-point bend tests or as-received pre-
17 hydrided and irradiated material in order to
18 determine the resistance to fracturing. I don't
19 know if I need to read this, but basically what I
20 want to point out here is that given this new
21 information, it would be appropriate to make an
22 update to the RIL that would revisit the conclusion
23 and reference the report.
24 MEMBER SHACK: Now, this revision is a

1 little different than the one you submitted to us in
2 the previous revision.
3 MS. FLANAGAN: It is. That might be an
4 accident on my part in preparing the slides, because
5 do you mean that it's different language --
6 CHAIRMAN ARMIJO: The language --
7 MEMBER SHACK: The wording's different.
8 CHAIRMAN ARMIJO: Yes.
9 MS. FLANAGAN: Oh, it is?
10 MEMBER SHACK: Yes, the context is
11 roughly the same.
12 MS. FLANAGAN: Okay.
13 MEMBER SHACK: But, you know, somebody's
14 been editing.
15 MS. FLANAGAN: Yes.
16 MEMBER SHACK: One way or another.
17 MS. FLANAGAN: We do revisit this a lot.
18 And I think that's why there was a draft on what
19 was submitted. And that wasn't part of the public -
20 - it's very pre-decisional. But the main point that
21 I want to make is that it would be appropriate to
22 update the RIL based on this new information
23 considering that we are calling it the Technical
24 Basis to Apply the Criterion No. 1.

1 So, I'm at the end of my presentation.
2 And the conclusions that I want to end with are to
3 point out or to state that a completed integral LOCA
4 test program has generated new data and
5 understanding of the mechanical behavior of
6 ballooned and ruptured fuel rods. These results
7 indicate that limiting oxidation in the ballooned
8 region continues to be appropriate. And the results
9 also indicate that applying the hydrogen-based
10 embrittlement limit in the ballooned region
11 preserves mechanical behavior to that of as-
12 fabricated rods at 17 percent.
13 And a technical basis document has been
14 drafted which would be a supplement to the technical
15 basis, and particularly focus on treating the
16 ballooned region within the proposed rulemaking.
17 And then updates to RIL 0801 have been proposed
18 which incorporate the findings of this recent
19 research into that document.
20 MEMBER BROWN: Does that mean that --
21 your third bullet?
22 MS. FLANAGAN: Yes.
23 MEMBER BROWN: The way I read that and
24 what they seem to have said is that the 17 percent

1 criteria satisfies the thing regardless of whether
2 you do the new rule or not; in the 17 percent, the
3 old rule?
4 MS. FLANAGAN: Seventeen percent is the
5 old rule for as-fabricated cladding and it would be
6 the limit for the new rule as well for as-fabricated
7 cladding.
8 MEMBER BROWN: Okay. I guess I've
9 missed, I've forgotten what's --
10 MEMBER CORRADINI: Yes, I think what
11 she's saying is --
12 CHAIRMAN ARMIJO: But the criteria for
13 irradiated stuff would follow the same criteria that
14 the un-ballooned region would have to meet.
15 MS. FLANAGAN: The old criteria said
16 that any fuel no matter what its burnup, no matter
17 what its hydrogen content should be subject to 17
18 percent. And this new rule says that as you
19 increase your hydrogen content you should reduce
20 that limit. And so, what I mean when I say as-
21 fabricated rises at 17 percent is that we continue
22 to find that 17 percent is appropriate around --
23 that value is appropriate for actuation system
24 cladding. And the only thing that's new is what's

1 going on with irradiated material.

2 MEMBER BROWN: Okay. I'm trying to

3 understand. If you start out with 17 percent as-

4 fabricated, that changes as you irradiate and

5 operate, but it's going to -- I mean, you've got

6 what you've got when you start out with 17 percent.

7 I guess I've lost the bubble somewhere between the

8 first meetings and this meeting as to what the new

9 rule is going to accomplish. Does that mean you're

10 going to put additional limits on the total fuel

11 burnup based on hydrogen?

12 MS. FLANAGAN: The 17 percent is a value

13 that's accumulated during the accident, so it's not

14 something that accumulates during operation. It's

15 where when I start an accident I have certain

16 properties and I have certain characteristics of

17 each fuel rod, and in the new regulation where I

18 start the accident. The properties of that fuel

19 dictate how much oxidation I can subject that

20 particular rod to during the accident.

21 MEMBER CORRADINI: Would slide 5 be a

22 good graphic to help him? It's qualitative, but

23 isn't that the criteria?

24 MS. FLANAGAN: Right. Yes. So, what

1 this -- here, the y-axis, the oxidation limit is
2 referring to something that takes place during the
3 transient. And then the x-axis could be considered
4 for a particular rod where am I starting into the
5 transient, and therefore what should I limit that
6 particular rod to?
7 MEMBER SHACK: Let me try a different
8 explanation, Charlie. This way with burnup it'll be
9 at least as good as fresh fuel would be.
10 CHAIRMAN ARMIJO: Can you repeat that,
11 Bill? I was talking.
12 MEMBER SHACK: With their current way,
13 the way they're going to treat burnup and accumulate
14 it from hydrogen, they'll at least assure that they
15 have performance equivalent to fresh as-fabricated
16 stuff at 17 percent. So, you know, we don't really
17 know that that's good enough, because we don't
18 really have metrics that tell us that, but we know
19 that it's going to be as good as that.
20 MEMBER CORRADINI: The last part -- I
21 was with you all the way until that last -- you were
22 doing very well. Then you --
23 MEMBER SHACK: The question always is
24 how do I know what is good enough in the ballooned

1 region? And since I don't know all the loads and
2 everything -- and it makes it difficult to provide
3 complete assurance, but --
4 MEMBER CORRADINI: But the way the rule
5 is -- the way I interpret it was, the reason I asked
6 them to go back to No. 5 is they are essentially
7 degrading, they are essentially being more
8 restrictive as the burnup goes up so that it would
9 behave no worse than fresh fuels.
10 MEMBER SHACK: Right.
11 MEMBER CORRADINI: Then you added that
12 sentence that got me --
13 MEMBER SHACK: Well, should have
14 stopped. Like Michelle, I should learn not to
15 answer when I don't have to.
16 MS. FLANAGAN: So, I've covered all of
17 the slides. And I know that we have additional time
18 on the schedule. I think I have until 11:00?
19 CHAIRMAN ARMIJO: 11:00, yes. But
20 you're moving right along, unless you have another
21 handout.
22 MS. FLANAGAN: I do not.
23 CHAIRMAN ARMIJO: Well then, you know
24 what I suggest we do? Unless there's questions from

1 members, I think we can take a 15-minute break. And
2 why don't we reconvene at 10:20?
3 MS. FLANAGAN: And then should we be
4 back up here or are we going on to the --
5 CHAIRMAN ARMIJO: Well, I think we're
6 finished with your presentation, and we could move
7 right into industry remarks.
8 MS. FLANAGAN: Okay.
9 CHAIRMAN ARMIJO: And, but I'd
10 appreciate it if you'd obviously stick around.
11 MS. FLANAGAN: Oh, of course. Yes. I
12 just wanted to know if I needed to be here, or over
13 there.
14 CHAIRMAN ARMIJO: No, I think you've
15 covered your presentation very well.
16 MS. FLANAGAN: Okay.
17 CHAIRMAN ARMIJO: Thank you very much.
18 And so, let's -- Well, we got a little more time.
19 Yes, let's get back at 10:25. Give ourselves
20 another few minutes here. 10:25, please.
21 (Whereupon, at 10:04 a.m. off the record
22 until 10:25 a.m.)
23 CHAIRMAN ARMIJO: Let's reconvene.
24 Okay. EPRI?

1 DR. YUEH: I think Gordon from NEI is
2 going to make a brief statement first.
3 CHAIRMAN ARMIJO: All right. We'll have
4 Mr. Clefton from NEI, and then Dr. Yueh.
5 MR. CLEFTON: We good to go?
6 CHAIRMAN ARMIJO: Go ahead.
7 MR. CLEFTON: Okay. My name's Gordon
8 Clefton. I'm with NEI. I'm representing consensus
9 standpoint from the industry. We've had a
10 cooperative effort of the vendors, the fuel vendors,
11 utilities, owners' groups, and cooperation that's
12 been very good supporting this rulemaking.
13 What we wanted to do is complement the
14 fact that we are supportive of the laboratory work
15 that -- Ken's going to be talking about that quite a
16 bit here, and very supportive of the idea that the
17 Chairman's offered that we'll have multiple meetings
18 in the future to address the details of where we're
19 going with this rulemaking, that we think that
20 there's an opportunity for the industry to provide
21 resources and assistance in optimizing the rule so
22 it's useable and that we have the best industry
23 input that we can put into it. And that comes with
24 communications, either with the ACRS, with work

1 shops, or with public meetings that we have.
2 Certainly encourage that.
3 We didn't bring any slides today as we
4 know we were on a tight schedule for the agenda of
5 this, and we'll just go right into Ken's
6 presentation. If we do have more opportunity to
7 talk afterwards, I'd be happy to address. And we've
8 got Tom, our chairman, from the reg tech from EPRI
9 to address some language issues, a quick summary of
10 where we are with 50.46 Charlie aspects. And of
11 course we have the staff from AREVA, General
12 Electric and Anatech to answer questions; if you
13 come up with us. So, we have resources in the
14 audience, not just Ken up here on the table.
15 MEMBER SHACK: But I take it you have
16 specific problems with some of the language in
17 50.46c?
18 MR. CLEFTON: In quick summary, we think
19 that we're supportive of the concept of bringing it
20 back to coolable geometry in the rule and putting
21 the details in the regulatory guides underneath,
22 which is the direction that we've been progressing
23 over the years since the ANPR comments and
24 suggestions gone in. So, we have some specific

1 comments addressing that. And then we'd
2 certainly like to talk about the implementation plan
3 for it because of the resources available at the NRC
4 and the resources available in the industry. We
5 think that deserves some attention so that we don't
6 get into a position that we collectively set a
7 schedule that's not attainable because of resource
8 limitations.
9 Ken?
10 DR. YUEH: Thank you for the opportunity
11 to present our view. We only notice this document
12 availability last week, although it was issued I
13 think the end of May. We didn't see this, notice
14 it. It was accidently discovered by one of our
15 members, and so we didn't have a lot of time to
16 through the document. I will only be providing
17 almost a first impression of, you know, what we
18 think of the argument presented in the document.
19 As Gordon Clefton stated, the industry
20 is supportive of this type of research. I think,
21 you know, this type of research being conducted by
22 other research organizations and I think the data
23 reported in the mechanical property of the, you
24 know, ballooned and ruptured region in some ways is

1 very similar to what other people have observed,
2 including earlier studies conducted at ANL. And
3 it's specifically a lot of quench survivability
4 tests, and more recently Japanese work with
5 restraint.
6 You know, we made this slide up before
7 we saw the latest presentation which included
8 several more data points, hydrogen pre-charge. I
9 think there's still some questions I think need to
10 be answered with the data. You know, so far we have
11 two data points, but we're seeing a substantial
12 difference with, you know, hydrogen pre-charge
13 compared to the irradiated, particularly at the
14 lower ECR where you have a sample, irradiated sample
15 at zero ECR essentially depart greatly from the as-
16 fabricated material.
17 You know, the international bodies, the
18 research they do are geared towards a more -- I
19 guess a generic requirement of coolability. So, not
20 necessarily -- you know, this type of research not
21 necessarily tied to ductility.
22 The next few slides I will go over some
23 of the published data primarily from the original
24 ANL study to support the two points that we want to

1 make in the last slide.

2 MEMBER SHACK: Are you going to explain

3 that second bullet?

4 CHAIRMAN ARMIJO: The second statement?

5 DR. YUEH: The minor -- which one?

6 MEMBER SHACK: The mechanical strength.

7 PARTICIPANT: Independent of hydrogen

8 concentration.

9 CHAIRMAN ARMIJO: Yes, independent of

10 hydrogen.

11 DR. YUEH: When we saw the original

12 draft and the results, even though the irradiated

13 material had 200 ppm of hydrogen, the result is more

14 or less consistent with as-fabricated material

15 without the hydrogen. Now, there is some difference

16 because I think the irradiated tests, the four-point

17 bend tests were conducted room temperature, while

18 the as-fabricated material were conducted 135. So,

19 that could explain why --

20 MEMBER SHACK: Well, they had one test

21 at room temperature.

22 DR. YUEH: No, I think all of the

23 irradiated material was --

24 MEMBER SHACK: No, I mean the as-

1 fabricated tests. I thought they had one --
2 DR. YUEH: Yes, they had one.
3 CHAIRMAN ARMIJO: What chart are you
4 referring to that --
5 MEMBER CORRADINI: Unless you're going
6 to get back to it later.
7 CHAIRMAN ARMIJO: Oh, I'm just trying to
8 make sure I understand what we're talking about.
9 MEMBER REMPE: So, you're talking about
10 like just slide 19?
11 CHAIRMAN ARMIJO: Yes, I think it's
12 slide 19 of Michelle's slides.
13 DR. YUEH: But the difference, I think
14 it's very small, if you look at the irradiated and
15 that. So, I think it's within the data scatter.
16 MEMBER SHACK: Well, I think you'd have
17 a hard time drawing a strong conclusion, but the
18 tendency seems to be it's the bottom of the scatter.
19 I mean, at least that's the way I'd interpret it.
20 CHAIRMAN ARMIJO: So, you'd say those
21 three diamonds, because they're at 30 degrees C
22 could be equivalent to the --
23 MEMBER SHACK: One-thirty-five.
24 CHAIRMAN ARMIJO: Yes.

1 DR. YUEH: Yes, the difference is very
2 small. So, you know, based on this and some of the
3 earlier studies done at ANL suggest to us that it is
4 hydrogen independent. And I guess one of the slide
5 even -- you know, I will hopefully, you know, show
6 that.
7 MEMBER SHACK: But the ANL 30 degree
8 test is --
9 DR. YUEH: Is the same as -- yes.
10 MEMBER SHACK: -- the same as the one
11 135?
12 DR. YUEH: Yes.
13 MEMBER SHACK: I mean, we are arguing
14 over something with a fair amount of scatter and a
15 relatively small number of data points.
16 DR. YUEH: Very small difference.
17 MEMBER SHACK: But the pre-hydrided
18 material seems to be --
19 CHAIRMAN ARMIJO: Well, there's a clear
20 difference there.
21 DR. YUEH: Yes, but, you know, I think
22 we do not have a full understanding of what is
23 happening. If you look at the irradiated material,
24 you have one data point at zero ECR that performs --

1 CHAIRMAN ARMIJO: Yes.

2 DR. YUEH: -- much, much better. I
3 mean, there's no explanation for that. And through
4 our own testing, you know, it suggests the existing
5 oxide may change the behavior, maybe shielding,
6 providing some protection against degradation. We
7 don't have a lot of data on that as well. There may
8 be something happening that we don't fully
9 understand.

10 MEMBER REMPE: But your comments are
11 tied to the ZIRLO material. What about the PH
12 material, the pre-hydrided material?

13 DR. YUEH: Yes, the pre-hydrided
14 material, right at this point it, you know, gives
15 lower energy absorption or failure lower bending
16 moment.

17 MEMBER REMPE: Right.

18 DR. YUEH: But because we only have
19 limited number of data points and our statements
20 were prepared before we saw these data points, but
21 primary there's lot of scatter with the irradiated
22 material where you have an existing oxide. So, and
23 because our own test shows that there could be an
24 impact if you had a preexisting oxide, whether that

had any impact on this, I do not know.

MEMBER REMPE: Okay.

DR. YUEH: Other data seems to suggest there's no dependence, at least on the strength on hydrogen. Testing of non-irradiated material that have not gone through a LOCA cycle, it was just, you know, material in the alpha phase pre-charged with hydrogen, you can charge this material up to couple of -- 2,000 ppm hydrogen and you will see very little degradation in the strength.

MEMBER SHACK: As measured by what, quench survivability?

DR. YUEH: No, this is tensile testing.

MEMBER SHACK: It's tensile tests?

DR. YUEH: You would see very little degradation in strength.

This slide, you know, the data came from original ANL study, Chung and Kassner, on quench survivability test. So, in this test I think that it's an integral test where they put simulated ceramic pellets inside, taken through a LOCA cycle. The red diamonds are the samples that failed during the quench phase. So, well, if you notice, the 17 percent ECR line is significantly below that.

1 MEMBER SHACK: But again, there's no
2 hydrogen? I mean, that's all --
3 DR. YUEH: There is no hydrogen except
4 in the region above and below the burst.
5 MEMBER SHACK: Right. I mean, which you
6 pick up during the --
7 DR. YUEH: Yes. Yes, this is just to
8 demonstrate, you know, even the 17 percent criteria
9 still provide a lot of margin to survive in the
10 quench. And I think in an accident immediately
11 after you lose the current where you have the
12 greatest decaying heat, you know, this essentially
13 guarantees, at least immediately after, that you
14 would have -- maintain coolable geometry.
15 CHAIRMAN ARMIJO: Ken, could you explain
16 this chart that we're looking at here? I'm not
17 familiar with this chart.
18 DR. YUEH: Okay. This is where they
19 have a LOCA integral sample. They take it through a
20 LOCA cycle and then --
21 CHAIRMAN ARMIJO: So, the peak
22 temperatures on the bottom scale?
23 DR. YUEH: That's right. It's inverse.
24 It's one over.

1 CHAIRMAN ARMIJO: Yes.

2 DR. YUEH: So, the higher temperature is

3 on the left-hand side.

4 CHAIRMAN ARMIJO: Yes.

5 DR. YUEH: So, this trend is also

6 consistent with the results Michelle reported about

7 the oxidation has an impact on the quench

8 survivability and the strength.

9 CHAIRMAN ARMIJO: And these are un-

10 irradiated samples?

11 DR. YUEH: Un-irradiated samples.

12 CHAIRMAN ARMIJO: Not pre-charged with

13 hydrogen? They put through it a transient and then

14 there's -- just quenched. And if it fractures or

15 doesn't fracture is there any load on it, or is it

16 just --

17 DR. YUEH: There's no load on it. So,

18 this chart serves to demonstrate that, you know,

19 beyond quench survivability there is still quite a

20 bit of margin.

21 CHAIRMAN ARMIJO: Yes.

22 MR. CLEFTON: And that's with the

23 existing rule.

24 CHAIRMAN ARMIJO: But with where we're

1 going with the hydrogen influence and everything
2 else, that dotted line of the 17 percent boundary
3 would move to the -- that would change with the new
4 rule, or the new criteria.
5 DR. YUEH: Okay. You know, I'm not so
6 sure whether it would move or not. You know, if I
7 can go to the next slide, in the ballooned region,
8 you know, even though the material was not pre-
9 charged with hydrogen they have measured a lot of
10 hydrogen above and below the burst. And in fact,
11 almost the higher ones it's almost close to 2,000
12 ppm hydrogen.
13 And this chart serves to demonstrate
14 samples with different amount of hydrogen in the two
15 rings above and below the burst. And the data is
16 showing that there is no dependence on hydrogen in
17 terms of the energy the sample survived after the
18 test. So, after the test they done a Sharpie impact
19 test. This is the energy absorption shown by the
20 different samples. And the data in color, they all
21 survived 0.3J impact test. But the different colors
22 are showing different hydrogen content. And
23 everything is so intermeshed together, you know,
24 there does not appear to be any dependence on

1 hydrogen.

2 MEMBER CORRADINI: I'm unfamiliar. What

3 is the test being used here in comparison to the

4 test that's being used in the Argonne data? I'm

5 sorry that I don't understand.

6 DR. YUEH: In this test after the

7 integral LOCA cycle they put it on an impact test

8 fixture.

9 MEMBER CORRADINI: You mean a Sharpie

10 test?

11 DR. YUEH: Sharpie test. And then --

12 MEMBER CORRADINI: Is that as definitive

13 as what I thought was the ring test?

14 DR. YUEH: It's a different metric.

15 MEMBER CORRADINI: Well, I'm not a

16 mechanics and materials type of person, so I'm going

17 to turn to --

18 CHAIRMAN ARMIJO: It's another way of

19 breaking things, but --

20 MEMBER CORRADINI: But I thought --

21 CHAIRMAN ARMIJO: But, you know,

22 typically you don't use a round tube on a Sharpie

23 test.

24 MEMBER CORRADINI: Well --

1 DR. YUEH: It is a round, yes.
2 MEMBER SHACK: Sharpie is kind of wrong
3 word. I mean, it's an energy absorption kind of --
4 CHAIRMAN ARMIJO: An energy absorption
5 kind of test, but you know --
6 MEMBER CORRADINI: It's a hammer test.
7 You hold the thing on a pendulum and it goes whack.
8 Isn't that what it is?
9 CHAIRMAN ARMIJO: Correct.
10 MEMBER SHACK: Yes.
11 MEMBER CORRADINI: But the thing is,
12 Ken, you know, here there's no interaction between
13 the hydrogen and the thinning and the oxidation in
14 that thinnest part. I mean, you're getting the
15 hydrogen over there in the peaks, but you're really
16 missing that whole interplay of the hydrogen and
17 oxygen in the thinning.
18 DR. YUEH: I agree this does not have
19 that element in there, but it is -- you know, it's
20 not a pure four-point bend test. When the hammer
21 impact presumably in the ballooned region, it will
22 induce a bending moment as well, but you know, the
23 load should be transmitted to the ring where a lot
24 of hydride is. It's not exact the same geometry,

1 but I think some of the bending moment is still
2 there.
3 DR. BILLONE: But you have no hydrogen
4 in the rupture region.
5 DR. YUEH: That's true. I acknowledge
6 that.
7 MR. ALVIS: Mr. Chairman, can I make a
8 comment?
9 CHAIRMAN ARMIJO: Sure.
10 MR. ALVIS: This is John Alvis from
11 Anatech. And I'm sure Dr. Billone will be able to
12 confirm this, but I believe these tests were
13 actually done in situ. So, they ran the tests, they
14 ran the rod segment through an integral cycle, a
15 LOCA loop. And they would hit -- they had the
16 little -- their hammer in place. And so, no, the
17 samples would never actually balloon in the same
18 location, but the test was conducted in such that
19 the hammer would always hit the same location. So,
20 I don't think you can draw a quantitative -- you
21 know, use these values quantitatively, but
22 qualitatively I think you can. And as Ken
23 was mentioning, I think it shows that for -- you
24 know, because even though some regions in the

1 balloon would have more hydrogen content due to --
2 hydrided than others, the fact is that the load's
3 still going to be transmitted to the weakest point.
4 And you can still see that there's really no trend
5 in the data with the hydrogen increase.
6 MEMBER REMPE: Someone said; I think it
7 was the person on the phone, that there was no
8 hydrogen in the ballooned region?
9 DR. YUEH: There's no hydrogen in the
10 burst region.
11 DR. BILLONE: That's correct. Mike
12 Billone.
13 MEMBER REMPE: Okay. Mike?
14 DR. YUEH: But there will be hydrogen
15 above and below it up to almost 2,000 ppm.
16 MEMBER REMPE: And why was there no
17 hydrogen? What was the phenomenon that made no
18 hydrogen occur in the balloon? Just because it
19 wasn't in contact?
20 DR. YUEH: Because it's a fresh
21 cladding, so there was no hydrogen before the test.
22 The hydrogen was picked up --
23 MEMBER REMPE: Okay.
24 DR. YUEH: -- above and below, picked up

1 during the LOCA --

2 MEMBER REMPE: Okay.

3 DR. YUEH: -- temperature exposure.

4 MEMBER REMPE: Okay.

5 CHAIRMAN ARMIJO: And that's from the

6 hydrogen generated by the reaction during the test?

7 DR. YUEH: Yes.

8 DR. BILLONE: So, Ken, this is Mike

9 Billone. This isn't really different than our data

10 set where we got failure in one of two locations,

11 either the higher hydrogen region or in the zero

12 hydrogen region. It just basically shows a

13 degradation of the material with oxygen.

14 DR. YUEH: Yes, yes. I'm not saying

15 there's an difference, because, you know, I've

16 stated early on that your data is consistent with,

17 you know, other data.

18 DR. BILLONE: But be careful about no

19 hydrogen dependence until you put hydrogen in the

20 ballooned region, which is in your next couple of

21 slides.

22 DR. YUEH: Well, you know, I mean, as I

23 said, we prepare this presentation without seeing

24 your latest two data points with the hydrogen pre-

1 charge. We did not see that in the report that was
2 published.
3 MR. CLEFTON: Last week.
4 DR. YUEH: Yes.
5 MR. CLEFTON: Go ahead.
6 DR. YUEH: This is the same data set,
7 just highlight different tests. Here I think they
8 have also done some tests where the sample was not
9 deformed and the test is showing consistent, you
10 know, with the samples that were deformed. When I
11 say "deformed," you know, ballooned and maybe a
12 burst. Okay. The trend is similar. There's very
13 little difference.
14 And then the other colored data points
15 are these test results from JAEA where they do the
16 quench survivability test with restraint. In this
17 plot they have one data, one sample failed. I think
18 the restraint is up to 500 newtons. Okay. That's
19 what they --
20 DR. BILLONE: Five-hundred and forty.
21 DR. YUEH: Yes.
22 MR. ALVIS: Yes, John Alvis at Anatech.
23 Yes, it's partially restrained. And so, the
24 maximum restraint they get on those tests was 540

1 newtons.

2 CHAIRMAN ARMIJO: Is that the Nagase

3 papers? I've seen a couple of papers, but okay.

4 Then they do an axial restraint?

5 PARTICIPANT: Yes, during the quench.

6 CHAIRMAN ARMIJO: During the quench.

7 Okay.

8 DR. YUEH: Okay. And then there's a

9 whole bunch of -- a series of samples that survive

10 the quench, so certainly within the 17 percent

11 limit.

12 DR. BILLONE: Ken, may I make a comment

13 on that slide?

14 DR. YUEH: Okay.

15 DR. BILLONE: I only want to talk about

16 the JAEA data, which are the triangles. When you

17 impose the 540 newton maximum load, you're doing a

18 pass/fail test.

19 DR. YUEH: Yes.

20 DR. BILLONE: So, the sample that passed

21 may have a strength anywhere from 550 to 10 times

22 that amount. And if you had done what we did, which

23 would have -- I mean, we do a test to failure, not

24 pass/fail tests. And when we do that, we see a

1 significant hydrogen effect. And to say it another
2 way, if we limited our bending to 1 milliliter, all
3 of our samples that Michelle showed would have
4 survived and you would have concluded that there's
5 no oxygen effect because in a pass/fail test all you
6 know is you either passed it or didn't pass the
7 test. So, I'm not sure that you can use a pass/fail
8 test to conclude that there's no hydrogen effect.
9 But keep going.
10 DR. YUEH: Well, yes, but I'm not
11 concluding that there's no hydrogen effect from
12 these tests, right?
13 DR. BILLONE: Okay.
14 DR. YUEH: You know, we came to that
15 conclusion because your original test data -- well,
16 not yours, but Studsvik test results, you know, is
17 sort of in line with your test results.
18 DR. BILLONE: Okay.
19 DR. YUEH: And the Studsvik data had 200
20 ppm of hydrogen and your data had no hydrogen. And
21 then they seemed to have the same capability for
22 energy absorption or, you know, bending moment.
23 DR. BILLONE: No, I understand.
24 DR. YUEH: Yes.

1 DR. BILLONE: Keep going.

2 DR. YUEH: Yes, so we can to --

3 DR. BILLONE: I just wanted to offer

4 some clarification.

5 DR. YUEH: Okay. And also, you know,

6 these early data, I mean, there's a lot of data

7 there even though it's not in the ballooned region,

8 the burst region. But you know, it's in the

9 adjacent area, which, you know, when you impact the

10 sample, will see a load. And that data is showing,

11 you know, a suggestion there is no dependence on

12 hydrogen.

13 Just couple of points on the final

14 slide. You know, from our point of view, because

15 right now the draft rule language is primary based

16 on ductility, maintenance of ductility, and here in

17 the ballooned region clearly there's no ductility.

18 You know, and the justification for that to be

19 covered in a ductility rule is, you know, the

20 argument made is based on strength. And so, I

21 think, you know, it's not consistent with the

22 principles of the intent of the draft rule, the

23 language that it is now. And because, you know, it

24 is in the 10 C.F.R., it is a law. So, we would

1 recommend that maybe the ductility portion of the
2 rule be relocated to the reg guides.
3 MEMBER SHACK: A modest modification.
4 DR. YUEH: Yes, because right now we see
5 that, you know, it's an exemption, right? It's an
6 exception to the rule --
7 CHAIRMAN ARMIJO: The balloon, even
8 though it's not ductile, it's exempted on the basis
9 of strength?
10 DR. YUEH: Yes, so it's not meeting the
11 ductility requirement. It's just by based on
12 strength.
13 Okay. And the last point is that as,
14 you know, the Chairman brought up earlier, you know,
15 the key is coolability, and obviously the ballooned
16 and burst region is more limiting. And if the same
17 thing can be applied there, why can it not be
18 applied to the rest of the rod? Now, we, you know,
19 came up with this point because the data, initial
20 data is just in that
21 -- the energy absorption in the bending moment is,
22 you know, independent of hydrogen. Okay. So, we
23 did not see those two data points before we draft
24 this.

1 And I think it's still -- the two data
2 points, I think it's not enough to say definitively
3 how much dependence there is on hydrogen, especially
4 given the irradiated material with 200 ppm of
5 hydrogen behaved almost the same as the as-received
6 material.
7 MEMBER ABDEL-KHALIK: Certainly two data
8 points is better than none.
9 DR. YUEH: Yes, but we still -- there
10 are other data points out there suggesting that if
11 there is a dependence, it's not very strong. And
12 certainly when people do tensile tests with
13 hydrogen-charged material, the strength does not
14 decrease very much.
15 I think that's all the slides I have.
16 CHAIRMAN ARMIJO: Yes, well, the issue
17 there of the inconsistency with finding the
18 ballooned region to be okay based on a strength
19 criteria and the -- but requiring that the non-
20 ballooned region be accepted on a ductility
21 criterion is not consistent. And you're saying why
22 not do it all on strength? Is that what you're
23 second bullet said?
24 DR. YUEH: Well, as an alternative.

1 CHAIRMAN ARMIJO: I'd like to hear from
2 the staff on that. What are your thoughts?
3 MR. CLIFFORD: If I may? This is Paul
4 Clifford, NRR. The way the draft rule has been
5 formulated is consistent with the way the rule
6 exists today, and that is the preservation of
7 ductility. Now, the performance-based metric will
8 be maintained as that of demonstrating that you have
9 ductility.
10 But the area of confusion I think that's
11 being alluded to in this bullet is that in fact
12 there will not be a specific performance-based
13 requirement inside the burst region. Instead, we
14 attempted to demonstrate that by preserving
15 ductility outside. In other words, by limiting the
16 time and temperature that a fuel rod can undergo
17 during a LOCA, that by limiting that time and
18 temperature based upon the ductility, you are in
19 fact maintaining a reasonable degree of strength
20 inside the burst region. So, you do not need a
21 separate independent performance-based metric.
22 But, there is some concern in how we
23 write the language, because if we were to specify
24 that you need to maintain ductility, then it could

1 be argued that even though there is an implicit
2 degree of strength being maintained, and we feel
3 that's adequate, that we're not physically
4 maintaining ductility. So, that's something that we
5 were going to have to deal with as we move forward
6 and formulate the actual rule language.
7 CHAIRMAN ARMIJO: Yes, it's tricky,
8 because effectively it's an argument that says if we
9 protect the non-ballooned region and demonstrate
10 ductility there, here are a bunch of arguments that
11 says we don't have to measure or confirm ductility
12 in the ballooned region. But it's arguments based
13 on strength --
14 MR. CLIFFORD: Right.
15 CHAIRMAN ARMIJO: -- these other tests.
16 Wasn't quite clean, but --
17 MR. CLIFFORD: We will need to rely upon
18 our Office of General Counsel to make sure that we
19 get it right when we write the rule language.
20 CHAIRMAN ARMIJO: Yes, that everybody
21 understands it. Yes.
22 MEMBER BROWN: I was just curious as to
23 why the OGC is going to make that as opposed to
24 making the technical argument as to how the language

1 ought to be.

2 CHAIRMAN ARMIJO: Well, they'll make the

3 technical argument. And the issue is whether that

4 language conforms with the ductility requirement in

5 the rule.

6 MR. CLIFFORD: Right, we need to make

7 sure that we have a level of detail so that it can

8 be enforceable and, you know, specifically

9 calculated and applied without interpretation.

10 CHAIRMAN ARMIJO: Well, you bring up a

11 good point, Ken, there is an inconsistency that's

12 going to have to be addressed and worked out.

13 Okay. Do you have anything --

14 MEMBER SHACK: You mentioned these

15 tensile tests. Now, are these tensile tests with

16 hydrogen and then subjected to a LOCA cycle and

17 oxidation --

18 DR. YUEH: No.

19 MEMBER SHACK: -- or just hydrogen and -

20 - so you're saying if I just put hydrogen in and I

21 don't bother to oxidize, then it doesn't make any

22 effect on strength?

23 DR. YUEH: That's right, there's no

24 effect.

1 MEMBER SHACK: Okay. But it's a very
2 different kind of --
3 CHAIRMAN ARMIJO: But that's a different
4 thing, yes.
5 DR. YUEH: You know, it is. I think I
6 don't have the data, you know, with me because we
7 didn't have a lot of time to prepare this, because
8 as I said, we discovered this document accidently
9 last week. I think some other people may have done
10 something with hydrogen pre-charge. And I think I
11 heard, you know; I don't have the data with me, as I
12 said, that the strength even after the LOCA cycle is
13 not very significantly impacted by hydrogen.
14 CHAIRMAN ARMIJO: Even after the LOCA?
15 DR. YUEH: After the LOCA. It's not as
16 strongly dependent as ductility is.
17 CHAIRMAN ARMIJO: Right. Well, that's
18 really what the Argonne tests -- you know, if they
19 could have measured ductility, they would have
20 measured ductility. But they couldn't, so they
21 measured strength.
22 Any other comments or questions from the
23 members?
24 (No audible response.)

1 CHAIRMAN ARMIJO: Okay. We have people
2 on the bridge line, quite a few people. So, if
3 there's any questions or comments from people on the
4 bridge line, now's a good --
5 PARTICIPANT: Make sure they're open.
6 CHAIRMAN ARMIJO: Chris? Where did
7 Chris go?
8 MEMBER CORRADINI: He went to make sure
9 it's open.
10 CHAIRMAN ARMIJO: The bridge line's
11 open. And if you're on the line and you wish to
12 make a comment, please identify yourself.
13 MR. MONTGOMERY: Mr. Chairman, this is
14 Robert Montgomery.
15 CHAIRMAN ARMIJO: Hello, Robbie.
16 MR. MONTGOMERY: How are you?
17 CHAIRMAN ARMIJO: Very well, thank you.
18 MR. MONTGOMERY: Thank you for giving me
19 the opportunity to speak. I'll note my new
20 affiliation. I'm currently employed at Pacific
21 Northwest National Labs.
22 I just wanted to note a point that Mike
23 Billone made regarding the Japanese data on quench
24 and axial force and load. Their data set is quite

1 comprehensive and it was not developed just purely
2 on a pass/fail basis. There is a significant amount
3 of data that was taken prior to the development of
4 the 540-newton limit that includes tests ran with
5 unrestrained or unlimited load. And they developed
6 basically a load versus hydrogen dependency for pre-
7 hydrided samples oxidized at various level of
8 oxidation. So, I just wanted to make that point
9 clear. The 540-newton limit came after that data
10 set was developed based on other structural analyses
11 to determine a load limit on the assembly based on a
12 load calculation and defined at the maximum
13 foreseeable load on the fuel rods due to quenching.
14 The axial load would be limited to about 540
15 newtons. It would be actually a little lower than
16 that -- a little higher than that and they --
17 CHAIRMAN ARMIJO: Yes, so --
18 MR. MONTGOMERY: So, I want to make sure
19 that that data is represented fairly in this
20 presentation.
21 CHAIRMAN ARMIJO: Now, is that published
22 work, Rob?
23 MR. MONTGOMERY: Yes, it is. Yes, it
24 is. Nagase from JAEA has published that work and I

1 believe I've shown those in the past, that data, at
2 some of the previous ACRS meetings.
3 CHAIRMAN ARMIJO: Yes.
4 MR. MONTGOMERY: They show the fracture
5 load as a function of hydrogen --
6 CHAIRMAN ARMIJO: And they ran a lot of
7 those tests to failure? They didn't just stop at
8 the 540?
9 MR. MONTGOMERY: That is correct.
10 CHAIRMAN ARMIJO: Okay. And the other
11 thing, were all of them just a simple axial loading?
12 Was there any kind of bend testing going on in
13 those programs?
14 MR. MONTGOMERY: No, there were not.
15 CHAIRMAN ARMIJO: Okay.
16 MR. MONTGOMERY: Those programs all
17 focused on the axial load.
18 CHAIRMAN ARMIJO: Okay. Well, look, I
19 appreciate that point and maybe, Chris, we can dig
20 up some of those papers. Members may want to take a
21 look at them. I do.
22 Okay. Thank you, Rob.
23 Anyone else on the bridge line wishes to
24 make a comment?

1 (No audible response.)

2 CHAIRMAN ARMIJO: Okay. Anyone within

3 the room? Do you wish to make a comment?

4 (No audible response.)

5 CHAIRMAN ARMIJO: No? Okay.

6 Okay. Well, look, with that, I don't

7 think we have any more business.

8 Committee members, one last chance?

9 (No audible response.)

10 CHAIRMAN ARMIJO: Okay. Well, I'd like

11 to thank the staff and EPRI for their presentations.

12 We have a pretty complicated set of rule. We have

13 a pretty complicated set of reg guides and issues.

14 And I think it's going to take a lot of

15 communication to sort out all these things out.

16 Things are going out for public comment now. That's

17 a time for everyone to get their views on the

18 record. And we will be reviewing the reg guides

19 after the public comment period, and as well as the

20 draft rule language before and after. So, we've got

21 quite a bit of work ahead of us, and I hope

22 everybody sticks with it.

23 With that, I'll adjourn the meeting.

24 Thank you.

1 (Whereupon, the meeting was adjourned at
2 11:02 a.m.)
3
4
5
6

U.S.NRC

UNITED STATES NUCLEAR REGULATORY COMMISSION

Protecting People and the Environment

Overview of the 10 CFR 50.46c Rulemaking and Recent Activities

June 23, 2011

Tara Inverso
Division of Policy and Rulemaking
Office of Nuclear Reactor Regulation

Meeting Purpose

- Present the expanded regulatory basis on regulatory treatment of the balloon region to ACRS

Meeting Agenda

1. Overview of 50.46c rulemaking activities

2. Additional research into mechanical behavior of the balloon

3. Industry remarks

4. ACRS discussion

Rulemaking Purpose

- Revise ECCS acceptance criteria to reflect recent research findings
- SECY-02-0057
  - Replace prescriptive analytical requirements with performance-based requirements
  - Expand applicability to all fuel designs and cladding materials
- Address concerns raised in two PRMs: PRM-50-71 and PRM-50-84

Recent Developments

- Draft regulatory guidance developed
  - Presented to ACRS on May 10, 2011 (sub-committee) and June 8, 2011 (full committee)
- Staff continues to evaluate results of fuel fragmentation/dispersion research
- **"Mechanical Behavior of Ballooned and Ruptured Cladding"**

Rulemaking Schedule

- Anticipated ACRS Meetings on Proposed Rule:
  - Sub-committee: December 2011
  - Full committee: February 2012

- Proposed Rule Due to the Executive Director for Operations:
  - February 29, 2012

Questions?

Tara Inverso, Project Manager

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U.S.NRC

UNITED STATES NUCLEAR REGULATORY COMMISSION

Protecting People and the Environment

10 CFR 50.46c ECCS Rulemaking: Mechanical Behavior of the Balloon

Materials, Metallurgy, and Reactor Fuels Subcommittee
Advisory Committee on Reactor Safeguards
June 23, 2011

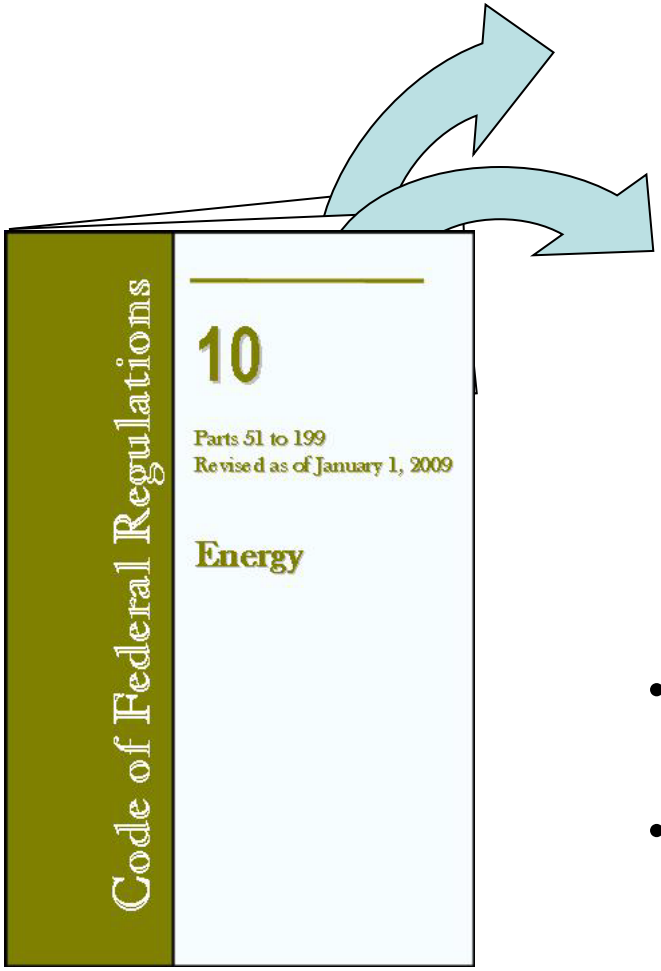
Michelle Flanagan
Michelle.Flanagan@nrc.gov
Division of Systems Analysis
Office of Nuclear Regulatory Research

Overview

Contents of *"Mechanical Behavior of Ballooned and Ruptured Cladding"*:

- Begins with a review of the regulatory history of the balloon region
- Presents the results of the NRC's integral LOCA research program
- Supports the treatment of the ballooned region within the rulemaking to revise 10 CFR 50.46(b).

Regulatory History



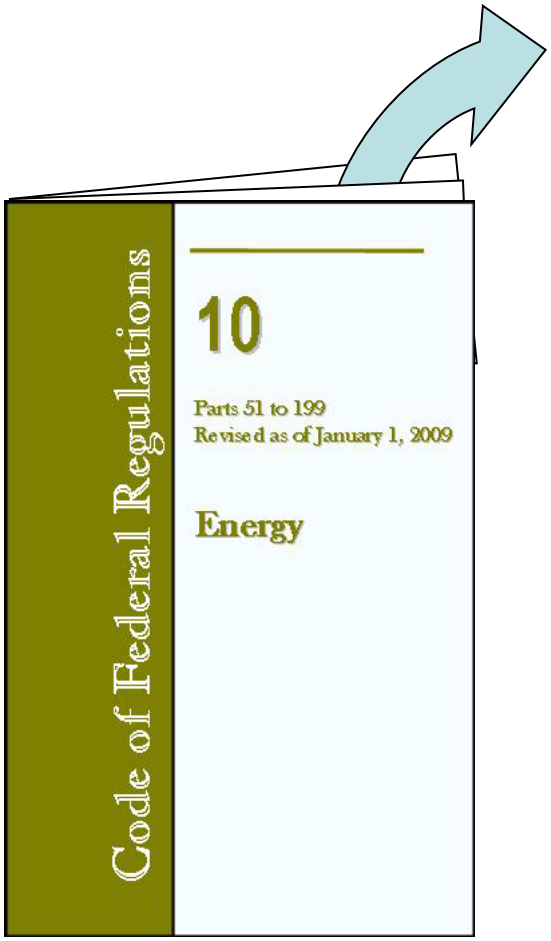
10CFR 50.46 Acceptance criteria for emergency core cooling systems for light-water nuclear power reactors.

Appendix A of 10CFR Part 50, General Design Criteria 35 Emergency Core Cooling

Regulation requires that an emergency core cooling system is available to ensure that if a loss-of-coolant accident took place:

- The core remains amenable to cooling. **(Coolable geometry)**
- Decay heat is removed for the extended period of time required by the long-lived radioactivity remaining in the core (**Long-term cooling**)

Regulatory History



§ 50.46 Acceptance criteria for emergency core cooling systems for light-water nuclear power reactors.

Commission hearings in the 1970's established that coolable geometry could be maintained if the fuel **cladding remained ductile.**

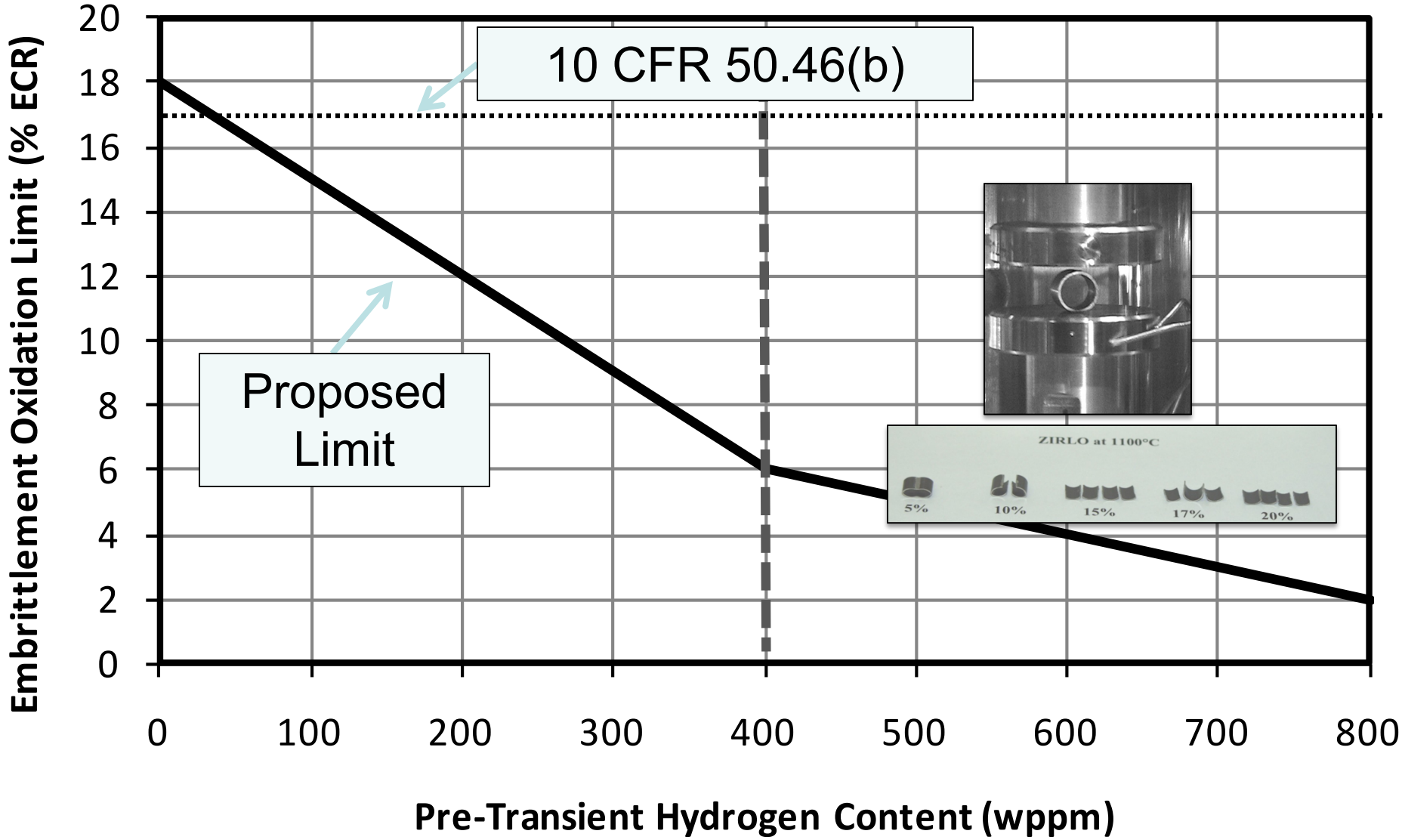
Therefore criteria were established, largely based on ring compression data, to ensure ductility, and these criteria are specified in the rule. The criteria state:

- The calculated maximum fuel element cladding temperature **shall not exceed 2200º F**.
- The calculated **total oxidation** of the cladding **shall nowhere exceed 0.17** times the total cladding thickness before oxidation.

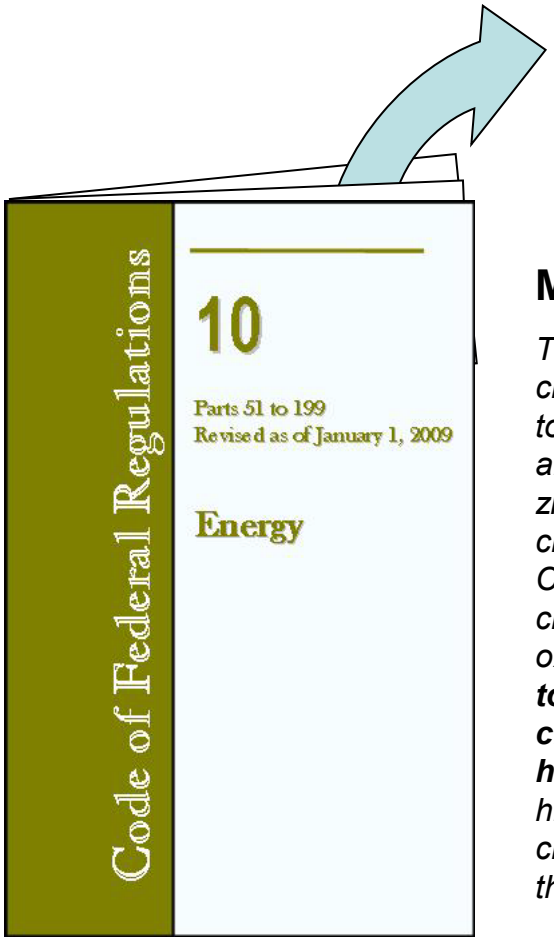
Completed Investigation: Are these criteria still appropriate for high burnup cladding?

Finding: Completed embrittlement program indicated the oxidation criterion is not sufficient for high burnup cladding

Research Findings



Existing treatment of the Balloon



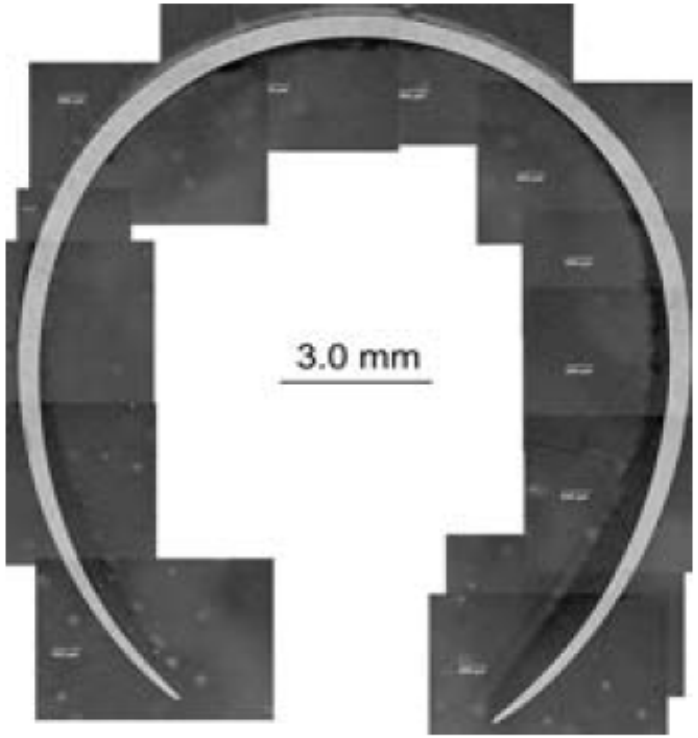
§ 50.46, "Acceptance criteria for emergency core cooling systems for light-water nuclear power reactors"

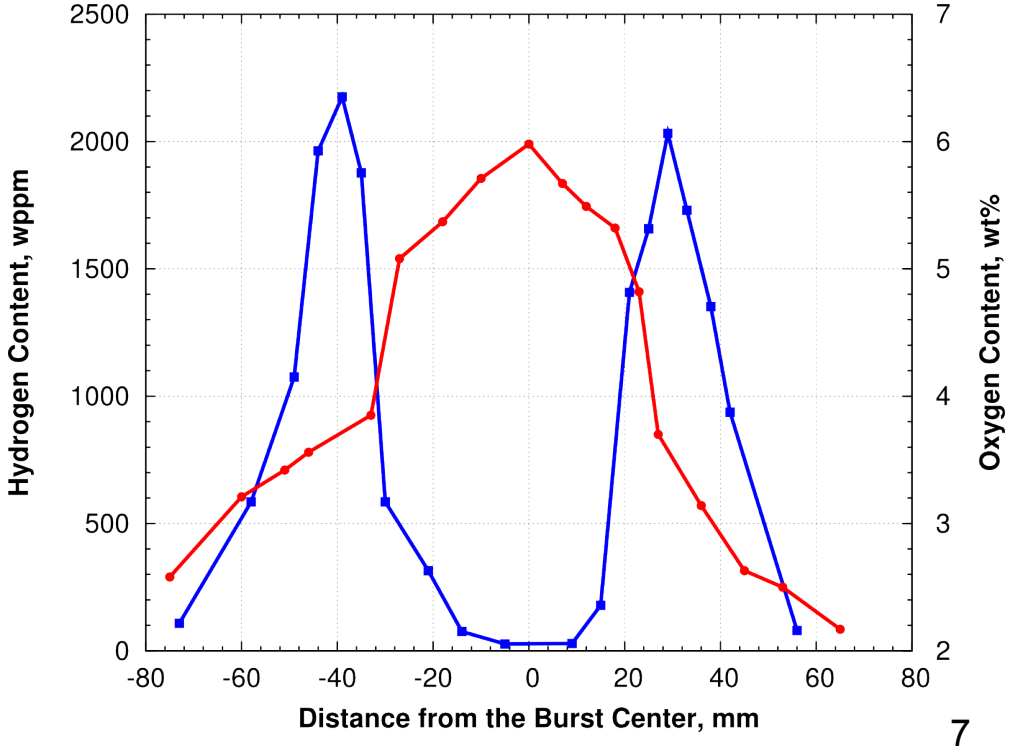
Maximum cladding oxidation is defined within the regulations:

The calculated total oxidation of the cladding shall nowhere exceed 0.17 times the total cladding thickness before oxidation. As used in this subparagraph total oxidation means the total thickness of cladding metal that would be locally converted to oxide if all the oxygen absorbed by and reacted with the cladding locally were converted to stoichiometric zirconium dioxide. If cladding rupture is calculated to occur, the inside surfaces of the cladding shall be included in the oxidation, beginning at the calculated time of rupture. Cladding thickness before oxidation means the radial distance from inside to outside the cladding, after any calculated rupture or swelling has occurred but before significant oxidation. ***Where the calculated conditions of transient pressure and temperature lead to a prediction of cladding swelling, with or without cladding rupture, the unoxidized cladding thickness shall be defined as the cladding cross-sectional area, taken at a horizontal plane at the elevation of the rupture****, if it occurs, or at the elevation of the highest cladding temperature if no rupture is calculated to occur, divided by the average circumference at that elevation. For ruptured cladding the circumference does not include the rupture opening.*

Is this approach still valid for the balloon node, with the new understanding of the effect of hydrogen?

Balloon Region Phenomenon



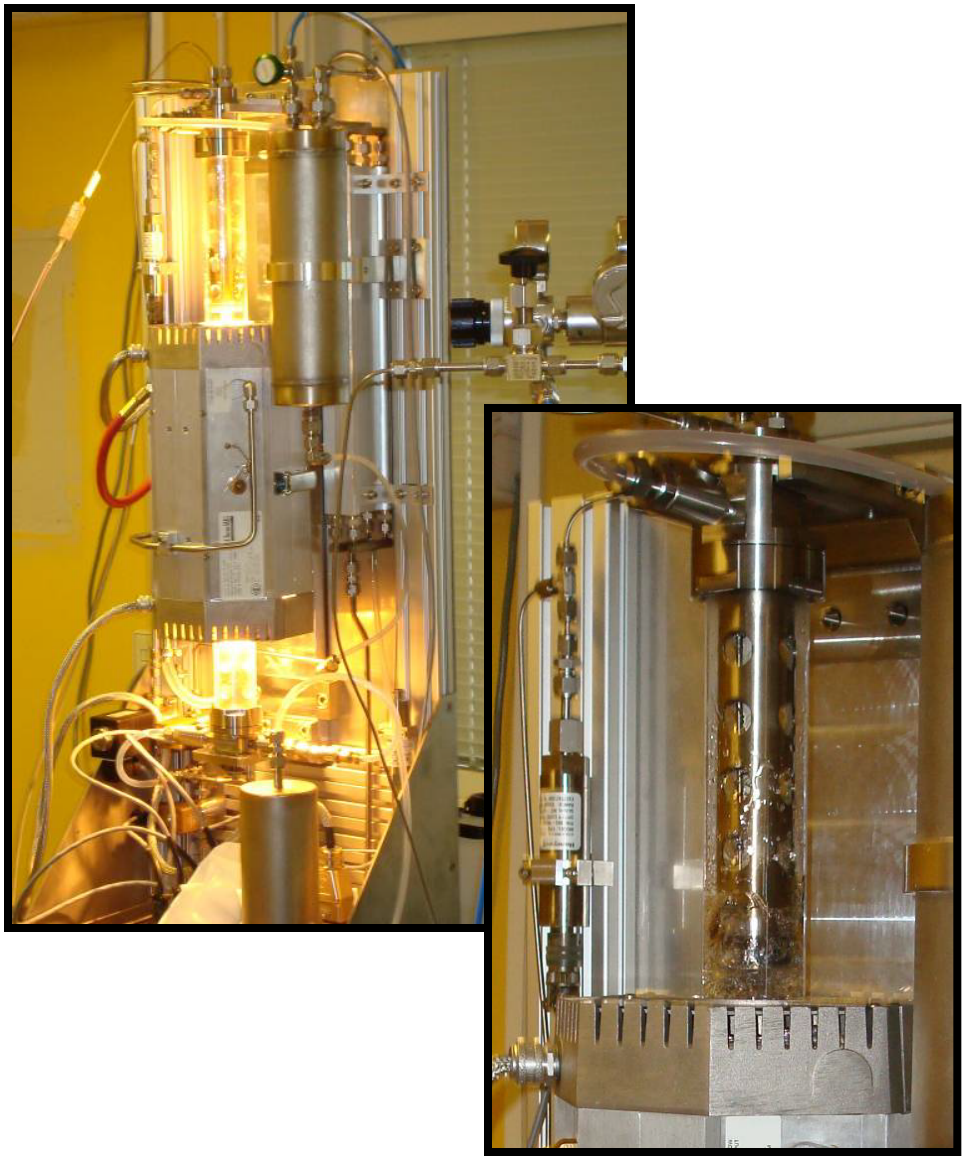


Proposed Treatment of the Balloon Region in RIL-0801

Research Information Letter-0801, *Technical Basis for Revision of Embrittlement Criteria in 10 CFR 50.46*

"Finally, no criteria have been found that would ensure ductility in the cladding balloon. However, loss of ductility in this short portion of a fuel rod should not lead to an uncoolable geometry as long as the amount of oxidation in the ballooned region remains limited in the current manner."

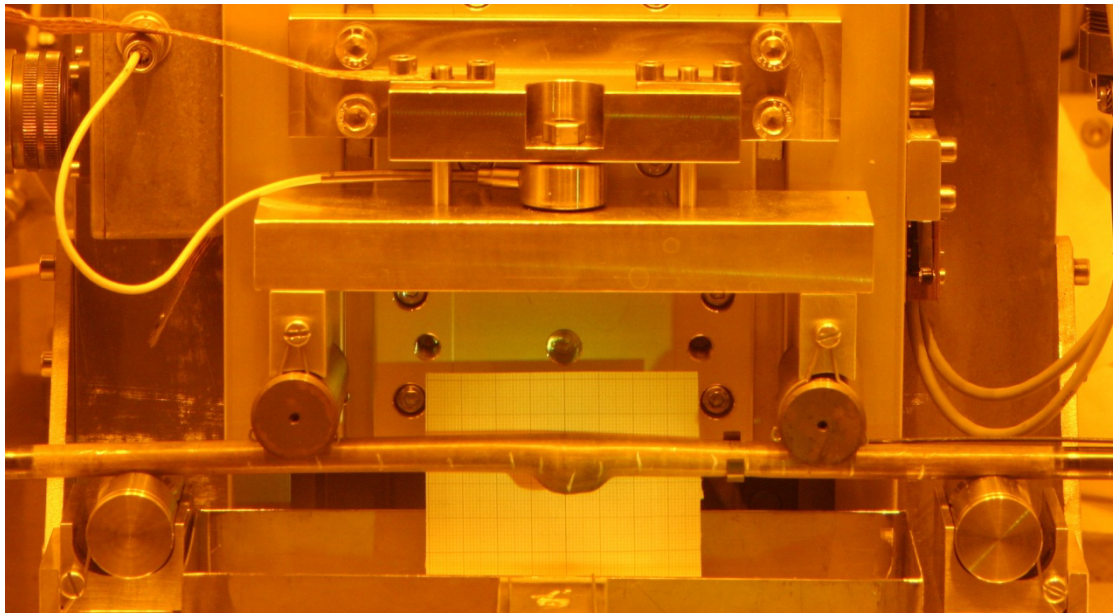
Investigation on Balloon Mechanical Behavior



Sections of pressurized, as-received, prehydrided and irradiated cladding, approximately 300 mm in length, were ramped from 300°C at a rate of 5°C/sec. They were pressurized to induce ballooning and burst and to target balloon sizes within the range of 30% - 70% strain. They were oxidized in steam to target oxidation levels (ECR), with consideration of the strain and hydrogen content.

The sections of cladding underwent ballooning, burst and oxidation in a test train shown to the left.

Investigation on Balloon Mechanical Behavior

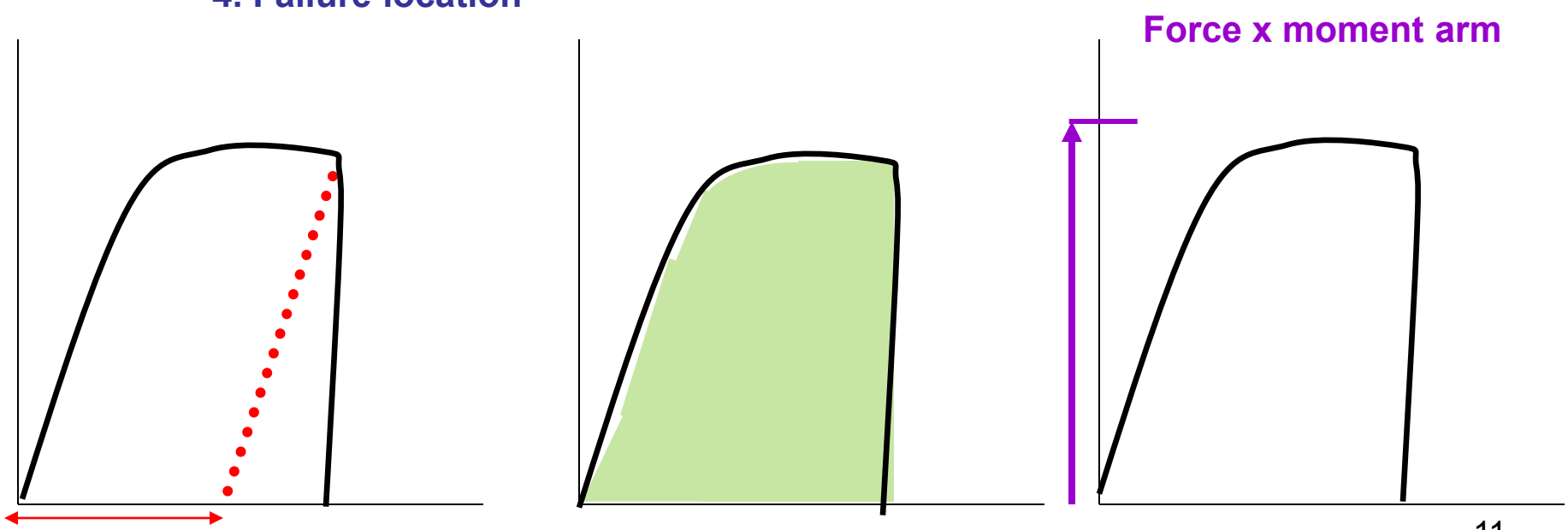


Bend tests were used to evaluate the balloon mechanical behavior ***in a mechanical test that applies a uniform bending moment to the ballooned region***. The axial location and nature of fracture was recorded. The observations of bend tests on irradiated material were compared to bend test results on as-received and pre-hydrided ballooned and burst integral samples run at ANL.

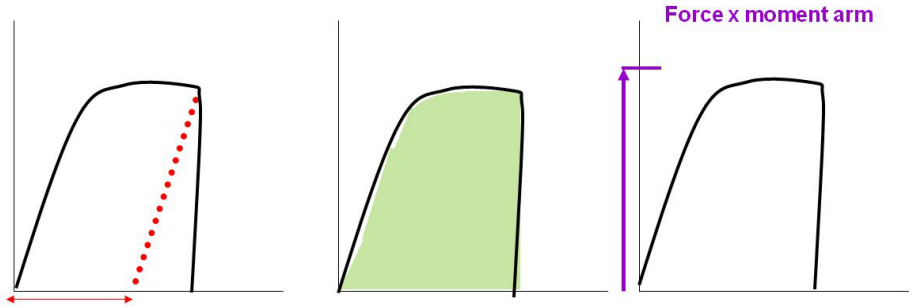
Investigation on Balloon Mechanical Behavior

Bend tests provide a variety of quantitative information, and are relatively sensitive to changing material properties

1. Maximum plastic displacement (measure of ductility)
2. Maximum applied energy (measure of toughness)
3. Maximum bending moment (measure of strength)
4. Failure location



Investigation on Balloon Mechanical Behavior



Investigate influence of:

- ✓ Oxidation
- ✓ Irradiation
- ✓ Balloon size
- ✓ Bend test temperature
- ✓ Hydrogen content

ANL

Studsvik

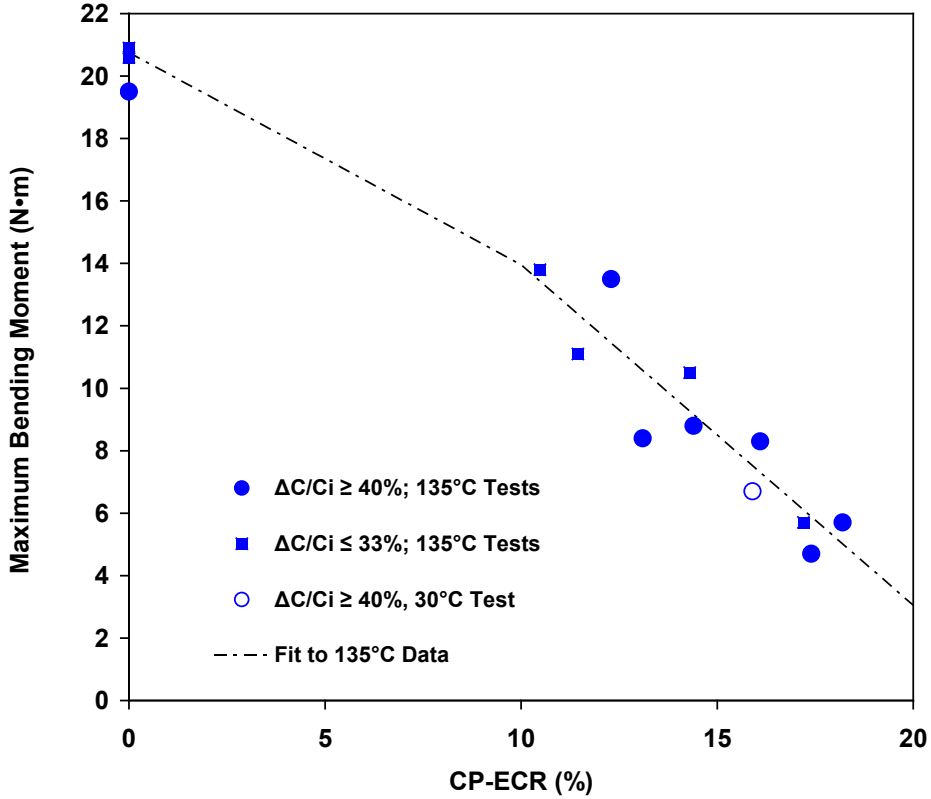
Results – As-Fabricated

Test ID OCZL#	Fill Pressure, psig	Rupture Strain, % (T_R, °C)	CP-ECR %	Quench at 800°C	Stress in Rupture Node	Failure Location	Maximum Bending Moment N•m	Maximum Energy J	Plastic Displace. mm
8	600	21 (845±25)	0	No	Maximum tension	No cracking	20.9	>8.4	>7.7
9	400	33 (875±15)	0	No	Maximum tension	No cracking	20.6	>8.3	>7.7
10	1600	69 (715±10)	0	No	Maximum tension	No cracking	19.5	>7.7	>7.1
12	1000	32 (805±20)	14	No	Maximum compression	-40 mm +33 mm	10.5	0.78	0
13	1200	41 (741±15)	14	No	Maximum tension	Rupture opening	8.8	0.58	0
14	1200	47 (735±6)	18	Yes	Maximum tension	Rupture opening	5.7	0.24	0
15	1200	51 (755±23)	18	Yes	Maximum compression	Cracking; no failure	8.9	>2.3	>13
17	1200	49 (750±17)	13	Yes	Maximum tension	Rupture opening	8.4	0.71	>0.5
18	1200	43 (748±4)	12	Yes	Maximum tension	Rupture opening	13.5	1.29	0
19	600	24 (840±12)	17	Yes	Maximum tension	+23 mm -23 mm	5.7	0.23	0
21	600	27 (850±10)	10	Yes	Maximum tension	+33 mm -29 mm	13.8	1.17	0
22[a]	600	22 (837±12)	11	Yes	Maximum tension	+25 mm -27 mm	11.1	0.83	0
25[a]	1200	42 (757±21)	16	Yes	Maximum tension	-26 mm +26 mm	8.3	0.50	0
29[a]	1200	49 (746±19)	17	Yes	Maximum tension	Rupture opening	4.7	0.40	>8.5
32[a,b]	1200	49 (748±8)	17	Yes	Maximum tension	Rupture opening	6.7	0.26	0

[a] Displacement rate lowered to 1 mm/s to get better agreement between bend and ring-compression tests for the maximum elastic strain rate.
[b] 4 -PBT conducted at 30°C.

Results – As-Fabricated

Bending Moment

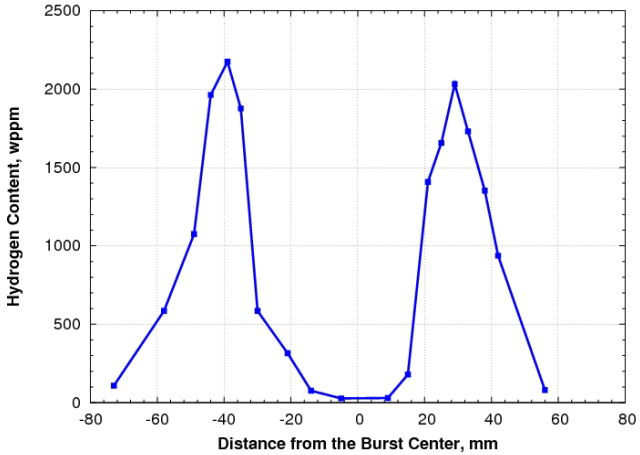


Maximum bending moment as a function of maximum oxidation level (CP-ECR) for post-LOCA samples subjected to 4-PBTs with the rupture region in tension for all tests but one. Bend tests were performed at 135°C and 2 or 1 mm/s to 14-mm maximum displacement. One bend test was performed at 30°C and 1 mm/s.

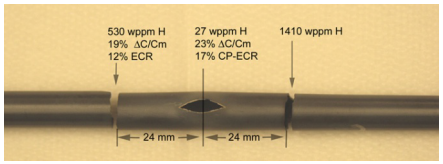
For ECR > 10%; M_{max} = 13.96 – 1.090 (CP-ECR – 10%), N•m

Results – As-Fabricated

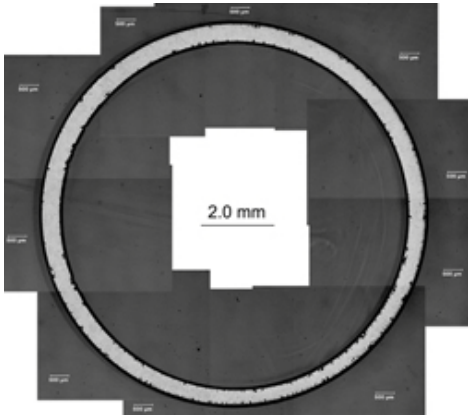
Failure Location



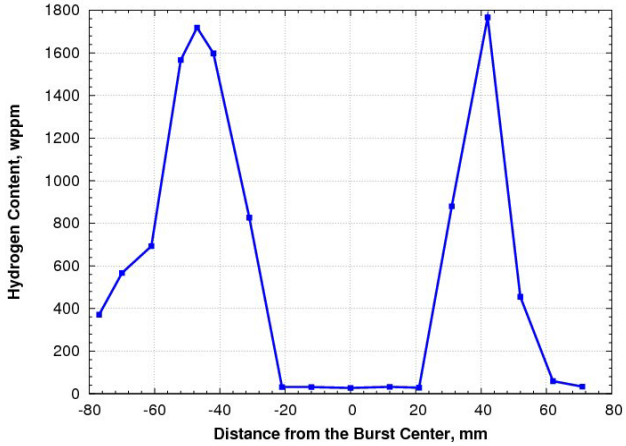
(a) Hydrogen-content profile



b) Measured values at failure locations

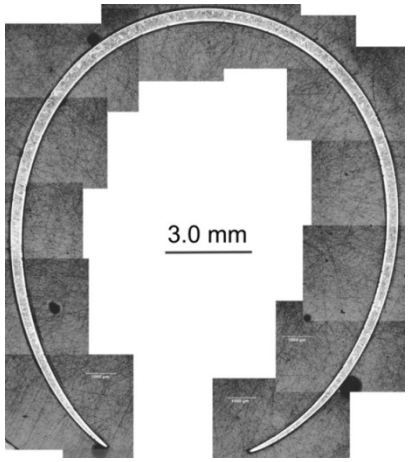


(c) Low-magnification image of severed cross section at -24 mm



(a) Hydrogen-content profile

(b) Failure location



(c) Low-magnification image of severed cross section

Results – As-Fabricated

Failure Energy

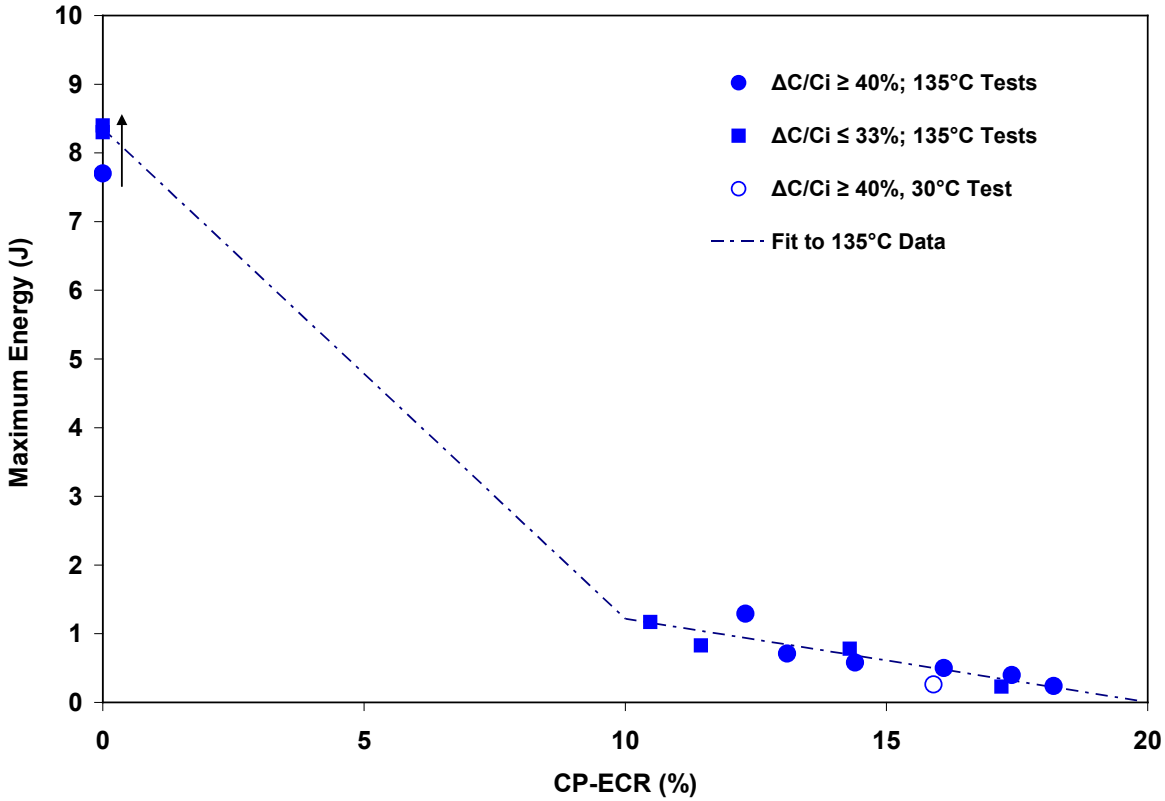
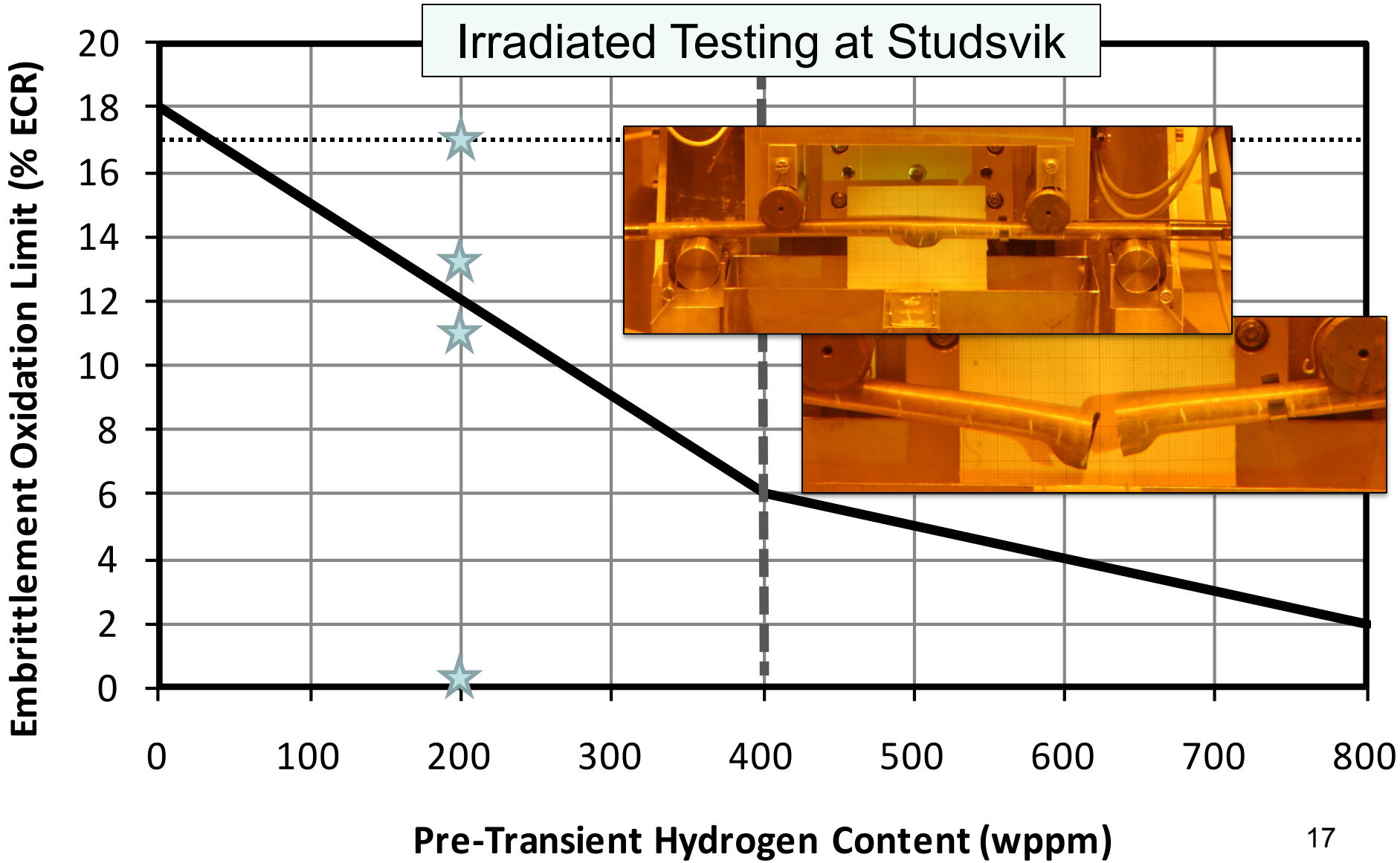


Figure 4. Maximum (for 0% CP-ECR) and failure (for ≥10% CP-ECR) energy as a function of oxidation level (CP-ECR) for post-LOCA samples subjected to four-point bending with the rupture region in tension for all tests but one. Bend tests were performed at 135°C and 2 or 1 mm/s to 14-mm maximum displacement. One bend test was conducted at 30°C and 1 mm/s.

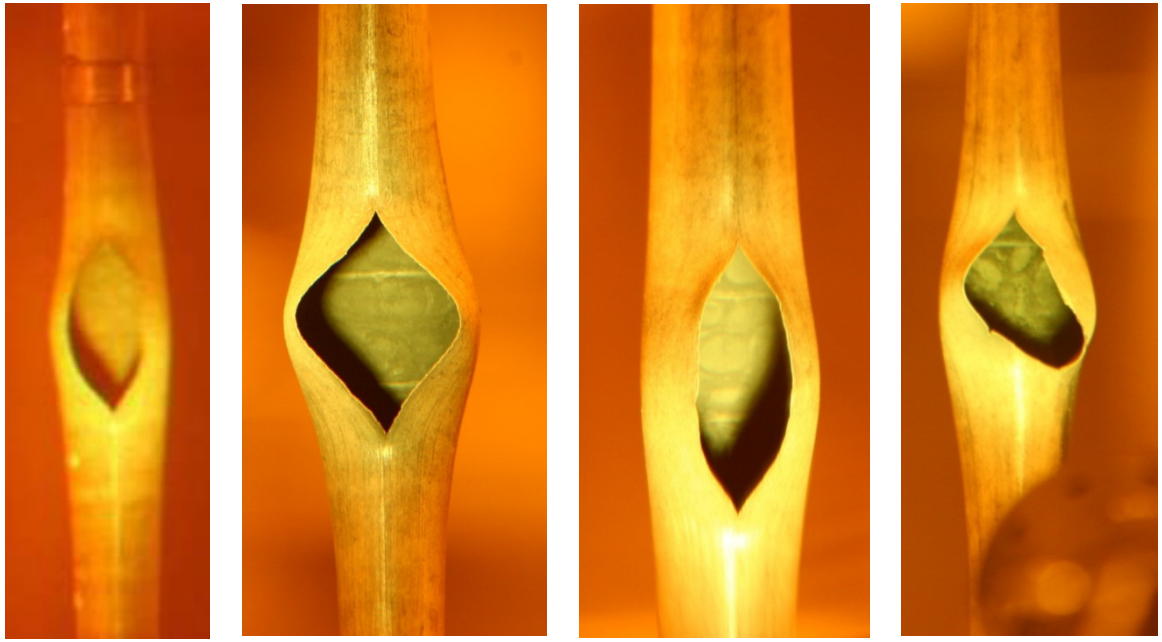
For ECR > 10%; E_{max} = 1.22 – 0.121 (CP-ECR – 10%), J

Investigation on Balloon Mechanical Behavior



Results – Irradiated Tests

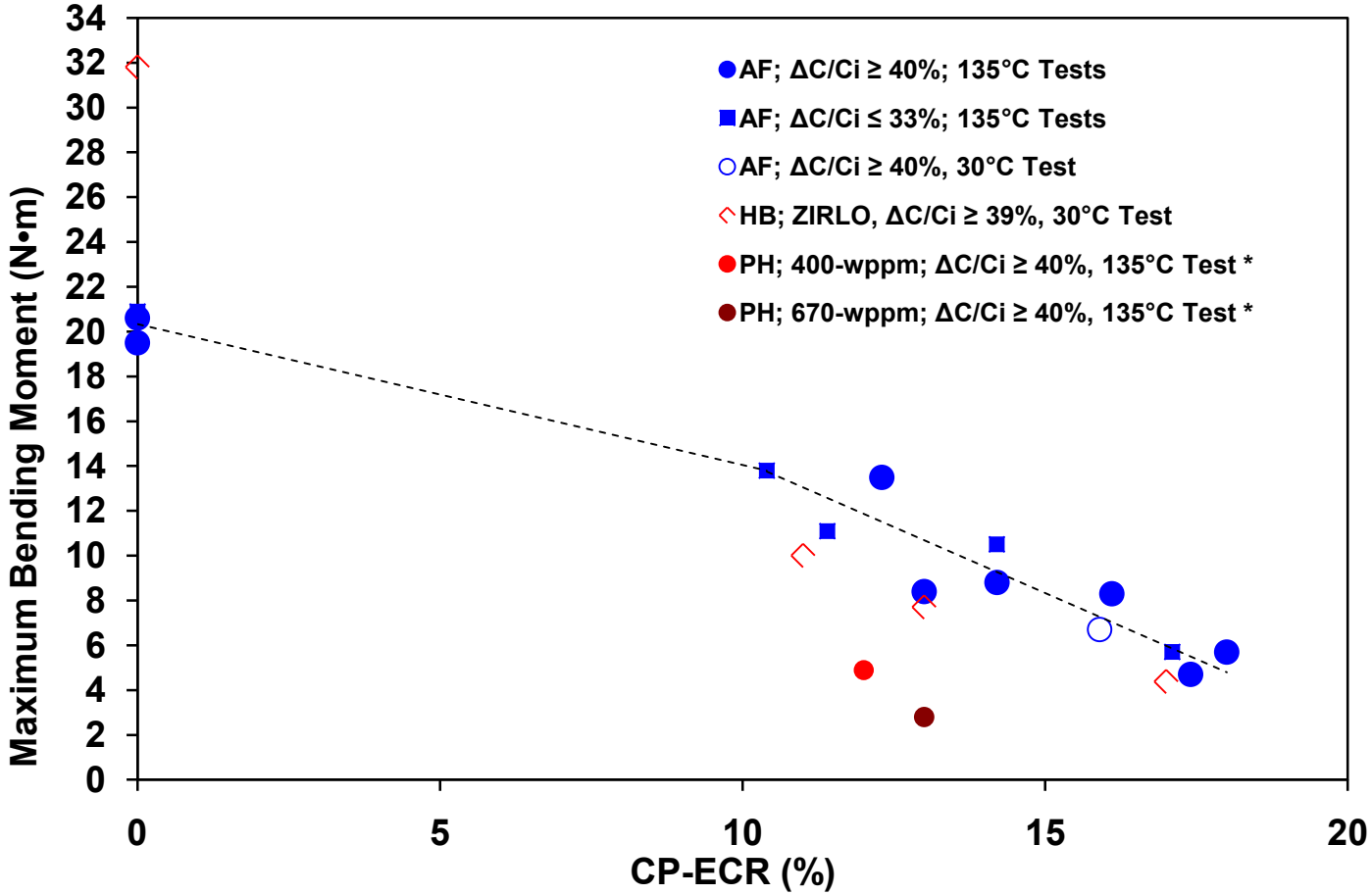
	189	191	192	193
Comments	Ramp to rutpure test	Ramp to PCT, held for 25s at PCT	Ramp to PCT, held for 5s at PCT	Ramp to PCT, held for 85s at PCT
Burnup	≈ 72 GWD/MTU	≈ 71 GWD/MTU	≈ 72 GWD/MTU	≈ 72 GWD/MTU
PCT	950 ± 20°C	1185 ± 20°C	1185 ± 20°C	1185 ± 20°C
Measured Strain	48%	50%	56%	50%
Calculated ECR	≈ 0%	13%	11%	17%
Fill Pressure	110	110	82	82
Burst Pressure	113	104	77	77
Burst Temperaure	700	680	700	728
Rupture Width	10.5	17.5	9.0	13.8
Rupture Length	23.9	21.6	22.7	17.8



(a) (b) (c) (d)

A close up of the rupture opening after the transient on rod segment from test (a) 189 (b) 191 (c) 192 and (d) 193

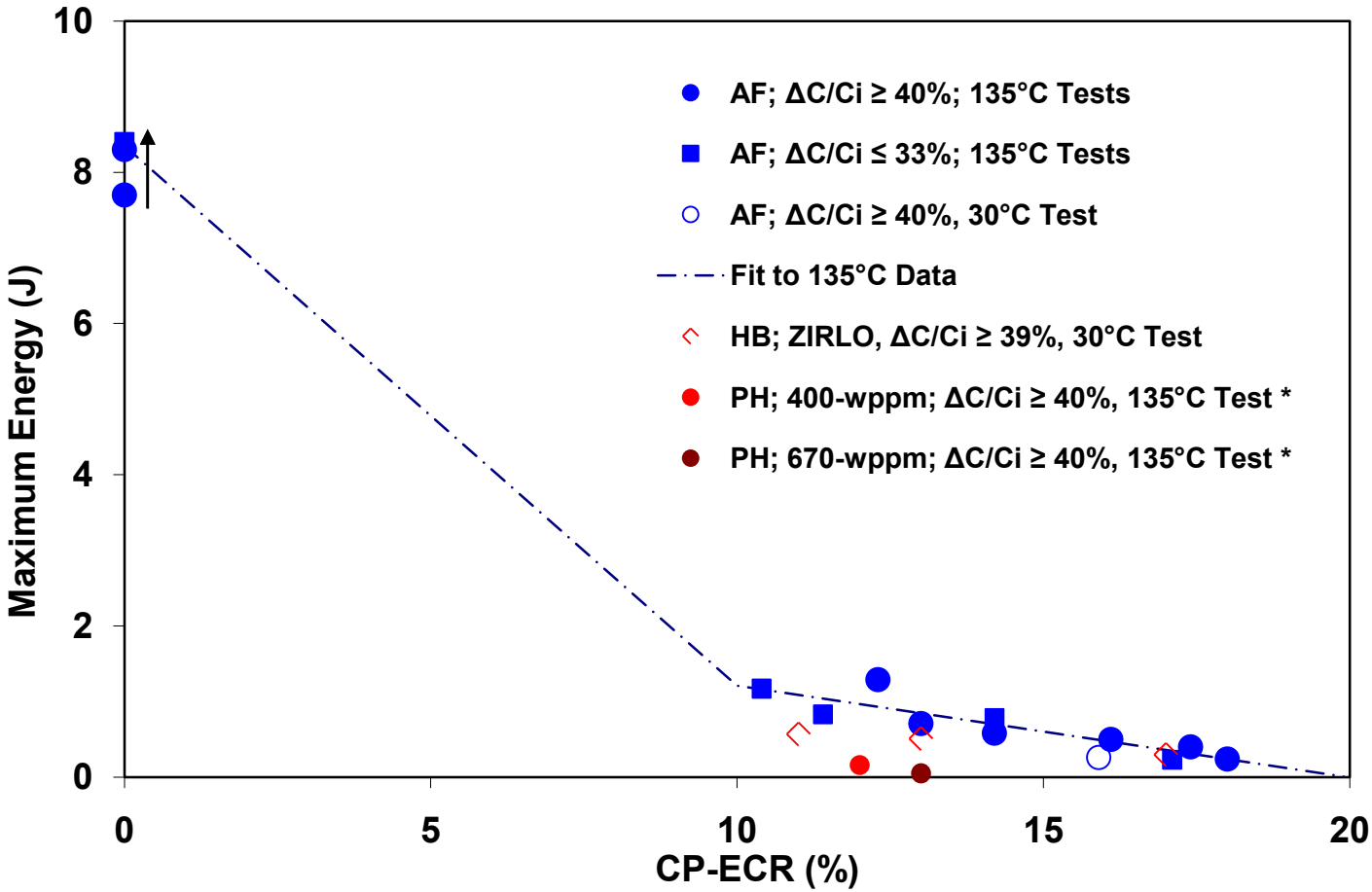
Results – Comparing AF, PH & Irradiated data



Maximum bending moment as a function of oxidation level for post-LOCA-oxidation samples subjected to 4PBTs at 1-2 mm/s and either 135°C or RT (30°C). For samples at 0% CP-ECR, which did not fail, values are plotted for 14-mm displacement. The trend line is a best fit to Argonne 4PBT data at 135°C.

*** NOTE:** The values for pre-hydrided material have become available since the DRAFT "Mechanical Behavior of Ballooned and Ruptured Cladding" report was transmitted to ACRS in support of this briefing.

Results – Comparing AF, PH & Irradiated data



Maximum energy as a function of oxidation level for post-LOCA-oxidation samples subjected to 4PBTs at 1-2 mm/s and either 135°C or RT (30°C). For samples at 0% CP-ECR, which did not fail, maximum energies through 14-mm displacement are plotted. For samples with >10% CP-ECR, data points represent failure energy. The trend line is a best fit to Argonne 4PBT data at 135°C.

*** NOTE:** The values for pre-hydrided material have become available since the DRAFT "Mechanical Behavior of Ballooned and Ruptured Cladding" report was transmitted to ACRS in support of this briefing.

Program Conclusions

- All samples survived quench
- The values of bending moment and failure energy have been shown to decrease with increasing oxidation, even through a wide range of values for balloon strain
- Even though very high values of hydrogen content were observed within the balloon region for the as-fabricated samples, no matter where the failure was observed, the residual bending moment remained a function of the oxidation
- The values of bending moment and failure energy reveal a hydrogen effect on the mechanical behavior of the balloon region that should be accounted for
- When the new proposed hydrogen-based criteria is applied in the rupture region, mechanical properties in this region are maintained to at least that of fresh cladding

Program Conclusions
within the Regulatory Context

Addressed in three aspects

- Treatment of the ballooned region within the rulemaking to revise the embrittlement criteria in 10 CFR 50.46
- Extrapolation of research findings to new cladding alloys and lower oxidation temperatures
- Alternate performance metrics for the ballooned and ruptured region of a fuel rod

Program Conclusions

Within the Regulatory Context: Treatment of the Ballooned Region within the Rulemaking To Revise 10 CFR 50.46(b)

The time-at-temperature limit developed based on ring-compression data to limit oxidation should be applied uniformly to the entire rod, with the provisions for the balloon outlined in the existing rule to use the average wall thickness in the rupture region to calculate the CP-ECR.

Program Conclusions

Within the Regulatory Context: Extrapolation of Research Findings to New Cladding Alloys and Lower Oxidation Temperatures

- Embrittlement limits developed for *new cladding alloys or at lower oxidation temperatures* based on RCTs may be applied uniformly to the entire rod, with the provisions for the balloon outlined in the existing rule to use the average wall thickness in the rupture region to calculate the CP-ECR.

- Results did not reveal any reason that materials which demonstrate improved embrittlement performance in RCTs should not apply measured improvement in the balloon region
  - Yield properties and fuel rod dimensions considered in the conclusion

Program Conclusions

Within the Regulatory Context: Alternate Performance Metrics for the Ballooned and Ruptured Region of a Fuel Rod

- There has been longstanding discussion of alternate metrics for fuel rod performance under LOCA conditions within the international community.
- Alternate approaches rely on detailed knowledge of LOCA loads or complex experimental and modeling research programs.
- The state-of-the art does not support regulatory positions based on these proposals in the near term and therefore, pursuing more complex performance metrics for ballooned and ruptured regions is not recommended at this time.

Proposed Update to RIL-0801

Research Information Letter-0801, *Technical Basis for Revision of Embrittlement Criteria in 10 CFR 50.46*

Finally, no criteria have been found that would ensure ductility in the cladding balloon. However, loss of ductility in this short portion of a fuel rod should not lead to an uncoolable geometry as long as the amount of oxidation in the ballooned region remains limited in the current manner. Bending moment and failure energy have been measured using the 4-PBT for as-received, pre-hydrided and irradiated samples to determine the resistance to fracturing and fragmentation of ballooned cladding during a LOCA. Values comparable to those determined for as-fabricated cladding at 17% CP-ECR have been found when oxidation is limited in accordance with embrittlement threshold shown in Figure 1.

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Protecting People and the Environment

Conclusion

- Completed integral LOCA test program has generated new data and understanding of the mechanical behavior of ballooned and ruptured fuel rods
- Results indicate that limiting oxidation in the balloon region continues to be appropriate
- Results indicate that applying the hydrogen-based embrittlement limit in the balloon region preserves mechanical behavior to that of as-fabricated rods at 17%
- A technical basis document has been written to supplement the treatment of the balloon within the proposed rulemaking
- Updates to RIL-0801 have been proposed which incorporate the findings of the recent research

BACKUP MATERIAL

Program Conclusions

Within the Regulatory Context: Extrapolation of Research Findings to New Cladding Alloys and Lower Oxidation Temperatures

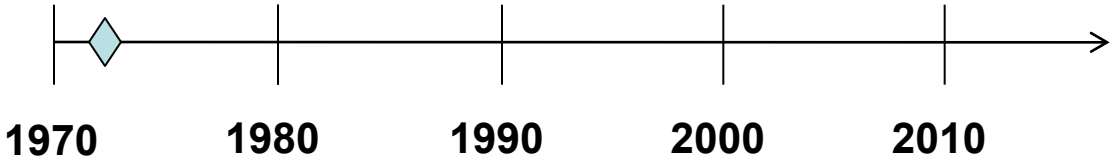
- RECALL: Original approach to embrittlement criteria falls out of the belief that specific prediction and quantification of LOCA loads is not possible
- A more extensive program could have been conducted and/or mechanical testing of ballooned and ruptured cladding could be required in order to license any embrittlement analytical limits other than that recommended in Regulatory Guidance.
- Additional data still may not be enough to ***guarantee*** that fuel-rod cladding would maintain its geometry during and following LOCA quench due to uncertainties in calculated LOCA loads.
- Therefore, the recommendation for treatment of the balloon region can apply even as new cladding alloy limits and lower temperature oxidation limits are developed

Program Conclusions

Within the Regulatory Context: Alternate Performance Metrics for the Ballooned and Ruptured Region of a Fuel Rod

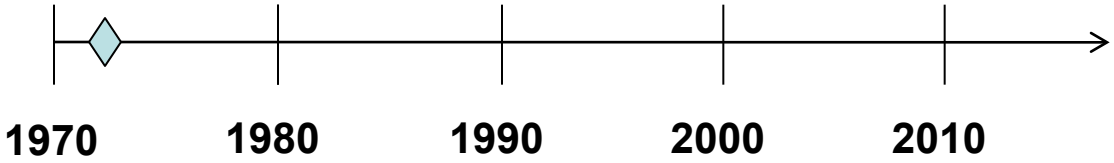
- RECALL: Original approach to embrittlement criteria falls out of the belief that specific prediction and quantification of LOCA loads is not possible
- A more extensive program could have been conducted to generate an acceptance criteria which is more mechanistic.
- Additional data still may not be enough to ***guarantee*** that fuel-rod cladding would maintain its geometry during and following LOCA quench due to uncertainties in calculated LOCA loads.
- Therefore, pursing an alternative metric in the ballooned and ruptured region is not recommended at this time.

Regulatory History of the Balloon



The LOCA rule adopted in 1973 included acceptance criteria for peak cladding temperature (2200 F) and maximum cladding oxidation (17%). In its final opinion statement, the Atomic Energy Commission said that "***the purpose of these first two criteria is to ensure that … the cladding would remain in one piece if it were not too heavily oxidized, and would still restrain the $U0_2$ pellets***" (p. 1095). The testimony in the rulemaking hearing placed considerable reliance on the demonstrated survival of specimens in quench tests. Strength and loads arguments were also made. In summary, however, the Commission stated that "***retention of ductility in the zircaloy is the best guarantee of its remaining intact during the hypothetical LOCA***" (p. 1098).

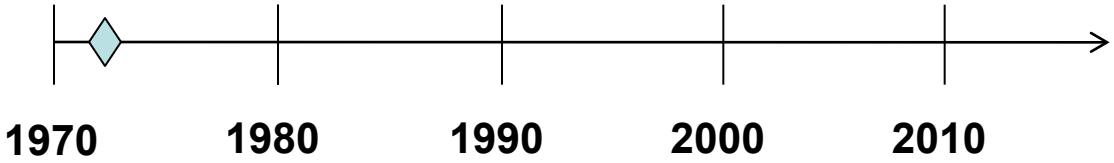
Regulatory History of the Balloon



Although it was not discussed in the Commission's opinion statement, retention of ductility in the cladding has inherent benefits. Even minimal ductility ensures that cladding will have high strength and toughness and therefore high resistance to fracturing. Fully brittle cladding, on the other hand, might fail at low strength and shatter particularly if it were scratched or contained flaws.

Also ***not apparent in the historical record is any discussion of complications associated with applying the ductility-based criteria to the ballooned region***. ***Average values were simply assumed.*** Discussions of such complications could have (and may have) taken place during or after the 1973 rulemaking hearing, but the discussion arose again when more recent efforts were underway to revise the rule to accommodate burnup effects.

Regulatory History of the Balloon



Complications in the balloon arise from several sources. The first is the cladding wall in the ballooned region, which is neither contiguous nor of constant thickness. This is illustrated in the cross section shown in Figure 1 with the rupture opening at the bottom of the figure.

It is apparent that some of the cladding near the rupture opening is very thin and will in all likelihood be brittle even though the material opposite the rupture may be ductile.

10 CFR 50.46(b)(2)specifies a method of using average wall thickness for oxidation calculations.

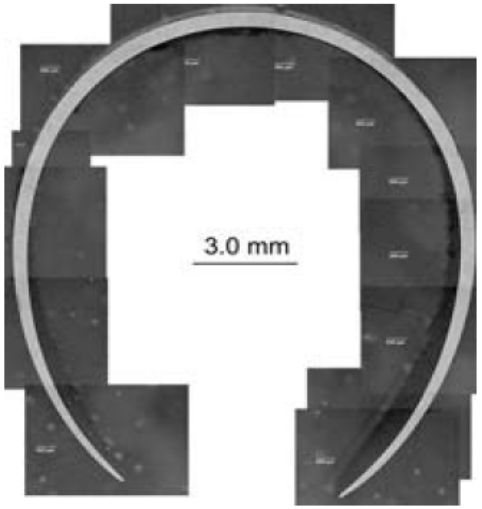
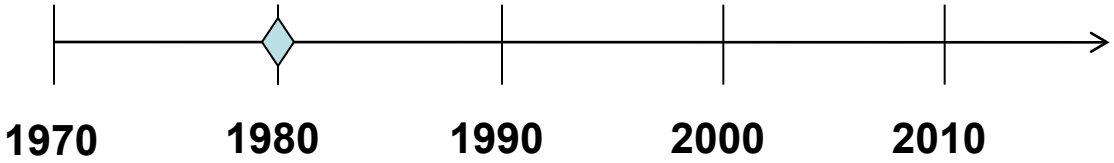


Fig. 1. Ballooned and ruptured ZIRLO cladding (ANL)

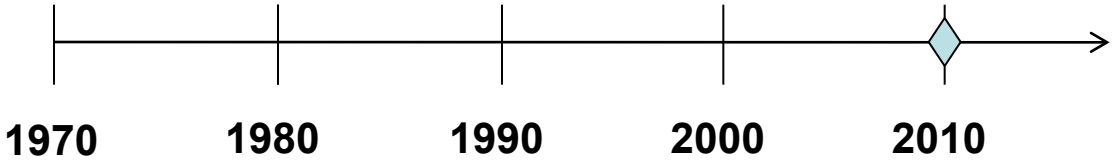
Regulatory History of the Balloon

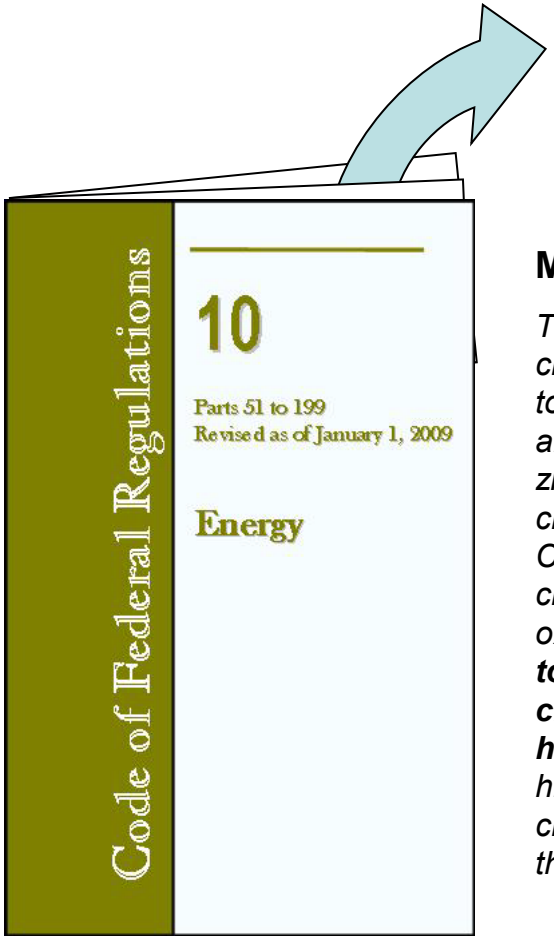


A second complication was discovered after the rulemaking was completed. Research reported in the early 1980's in both the U.S. (NRC) and Japan (JAERI) found regions of high hydrogen concentration just above and below the rupture location. This was a consequence of oxidation of the inside cladding surface by steam, which enters through the rupture opening. Research in both countries found that these neck regions in the balloon could be brittle. ***As a consequence, there are several regions in a balloon in which ductility may not be maintained even if the acceptance criteria in 10 CFR 50.46 are satisfied.***

Nevertheless, the U.S. and Japanese researchers in 1980 concluded that the current oxidation limits were conservative based on two findings: (1) ballooned specimens survived quenching with very high oxidation levels, and (2) quenched specimens did not fracture when modest loads were applied as long as the oxidation level was less than the regulatory limit. ***With these findings in hand, no change was made by NRC in the LOCA acceptance criteria***.

Regulatory History of the Balloon



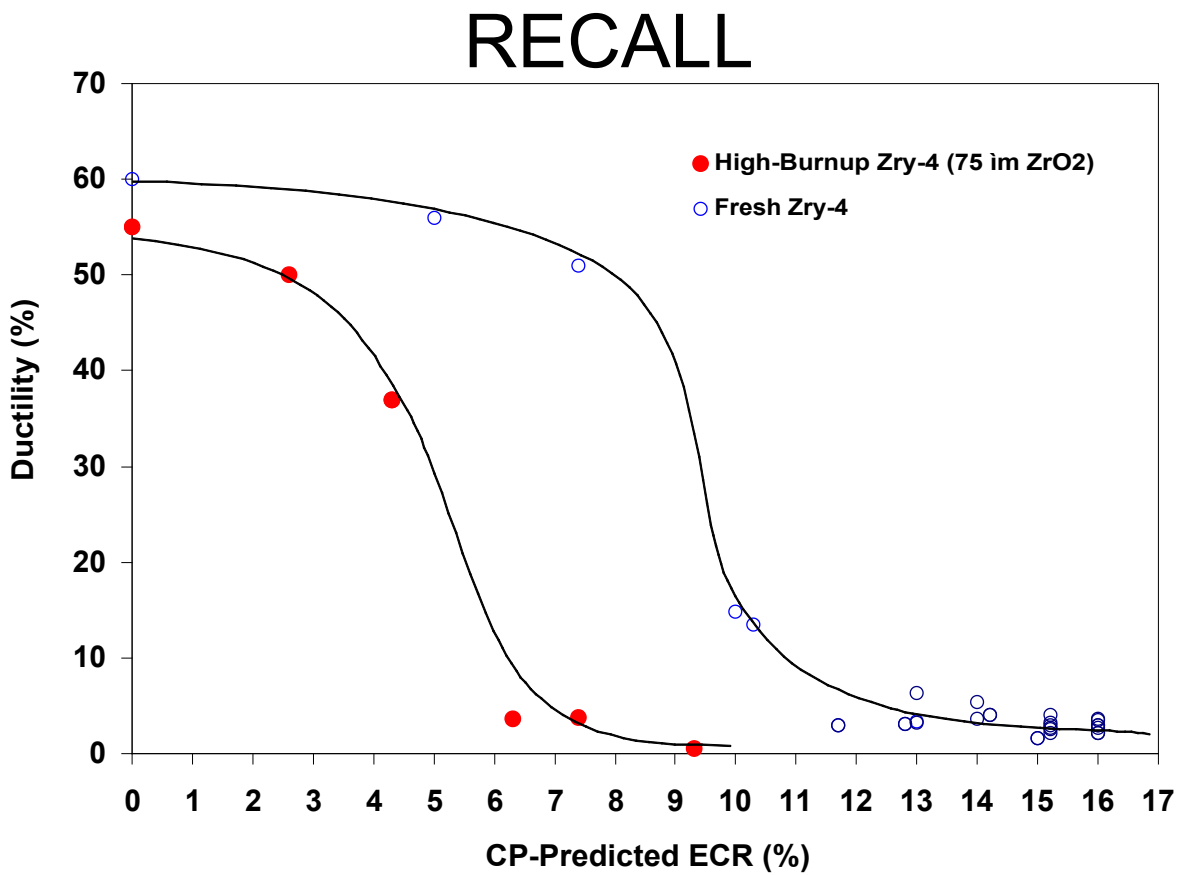


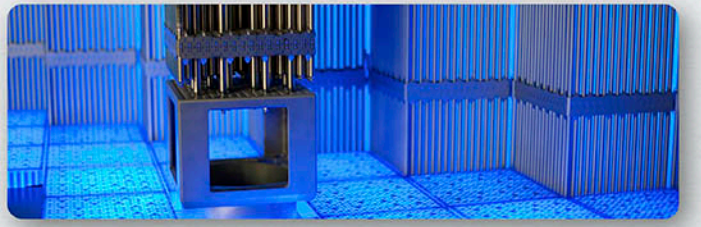
50.46 Acceptance criteria for emergency core cooling systems for light-water nuclear power reactors.

Maximum cladding oxidation is defined within the regulations:

The calculated total oxidation of the cladding shall nowhere exceed 0.17 times the total cladding thickness before oxidation. As used in this subparagraph total oxidation means the total thickness of cladding metal that would be locally converted to oxide if all the oxygen absorbed by and reacted with the cladding locally were converted to stoichiometric zirconium dioxide. If cladding rupture is calculated to occur, the inside surfaces of the cladding shall be included in the oxidation, beginning at the calculated time of rupture. Cladding thickness before oxidation means the radial distance from inside to outside the cladding, after any calculated rupture or swelling has occurred but before significant oxidation. ***Where the calculated conditions of transient pressure and temperature lead to a prediction of cladding swelling, with or without cladding rupture, the unoxidized cladding thickness shall be defined as the cladding cross-sectional area, taken at a horizontal plane at the elevation of the rupture****, if it occurs, or at the elevation of the highest cladding temperature if no rupture is calculated to occur, divided by the average circumference at that elevation. For ruptured cladding the circumference does not include the rupture opening.*

Results of balloon region research program





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Comments on Mechanical Behavior of Ballooned and Ruptured Cladding

Ken Yueh
Senior Project Manager

ACRS Subcommittee on Materials, Metallurgy & Reactor Fuels

June 23, 2011

Feedback

- The industry is supportive of the NRC's research efforts on the mechanical behavior of the ballooned and ruptured cladding region
- The test results reported in ML111370032 are consistent with other international test results
  - Quench survivability with and without restraint
  - Mechanical strength and impact resistance are independent of hydrogen concentration in the hydrogen range of interest
  - International research efforts are focused on generating data to support alternative acceptance criteria not tied to ductility

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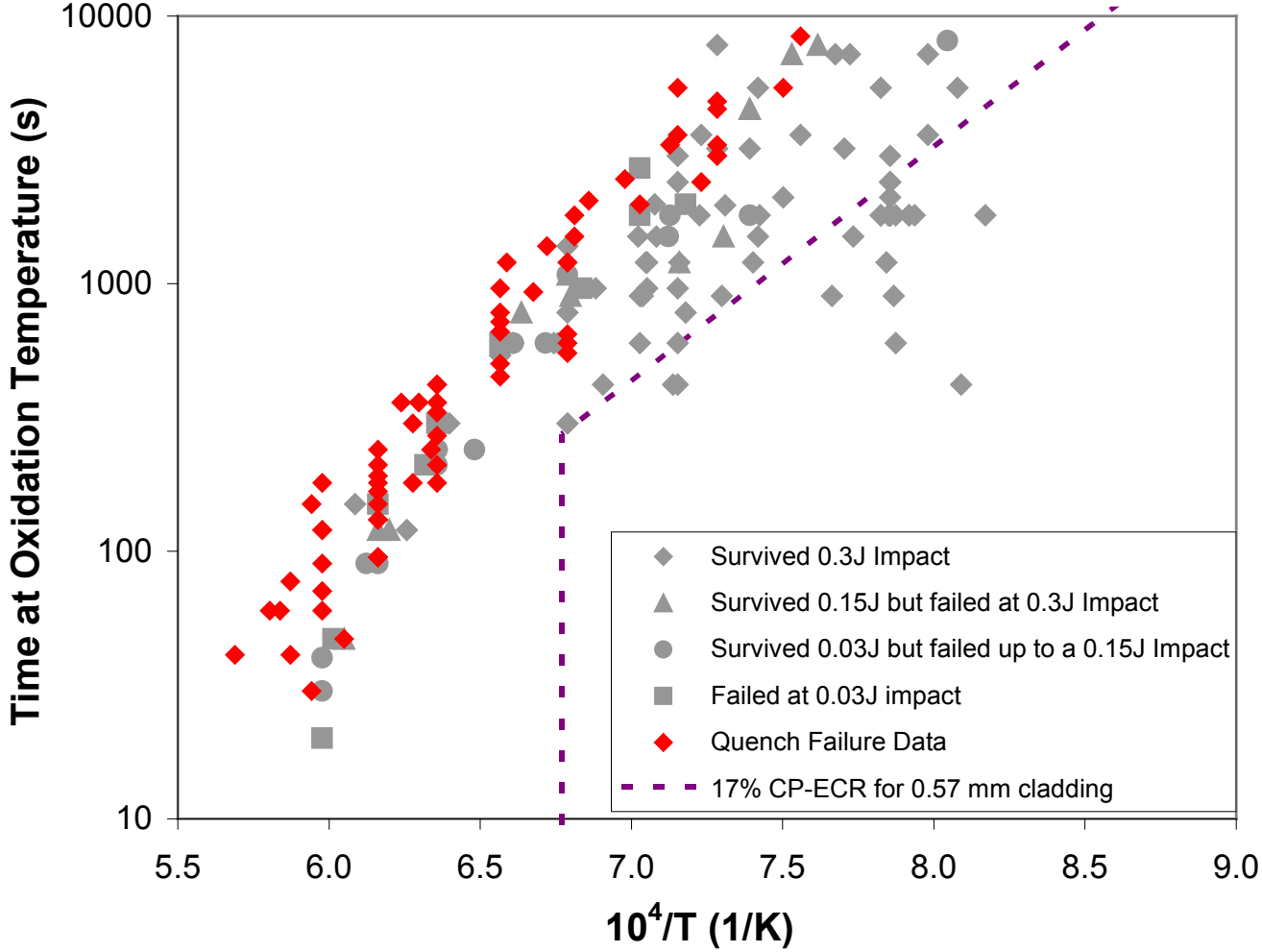
Published Test Results Review

- 17% limit has a lot of margin to quench failure



* Chung and Kassner, NUREG/CR-1344

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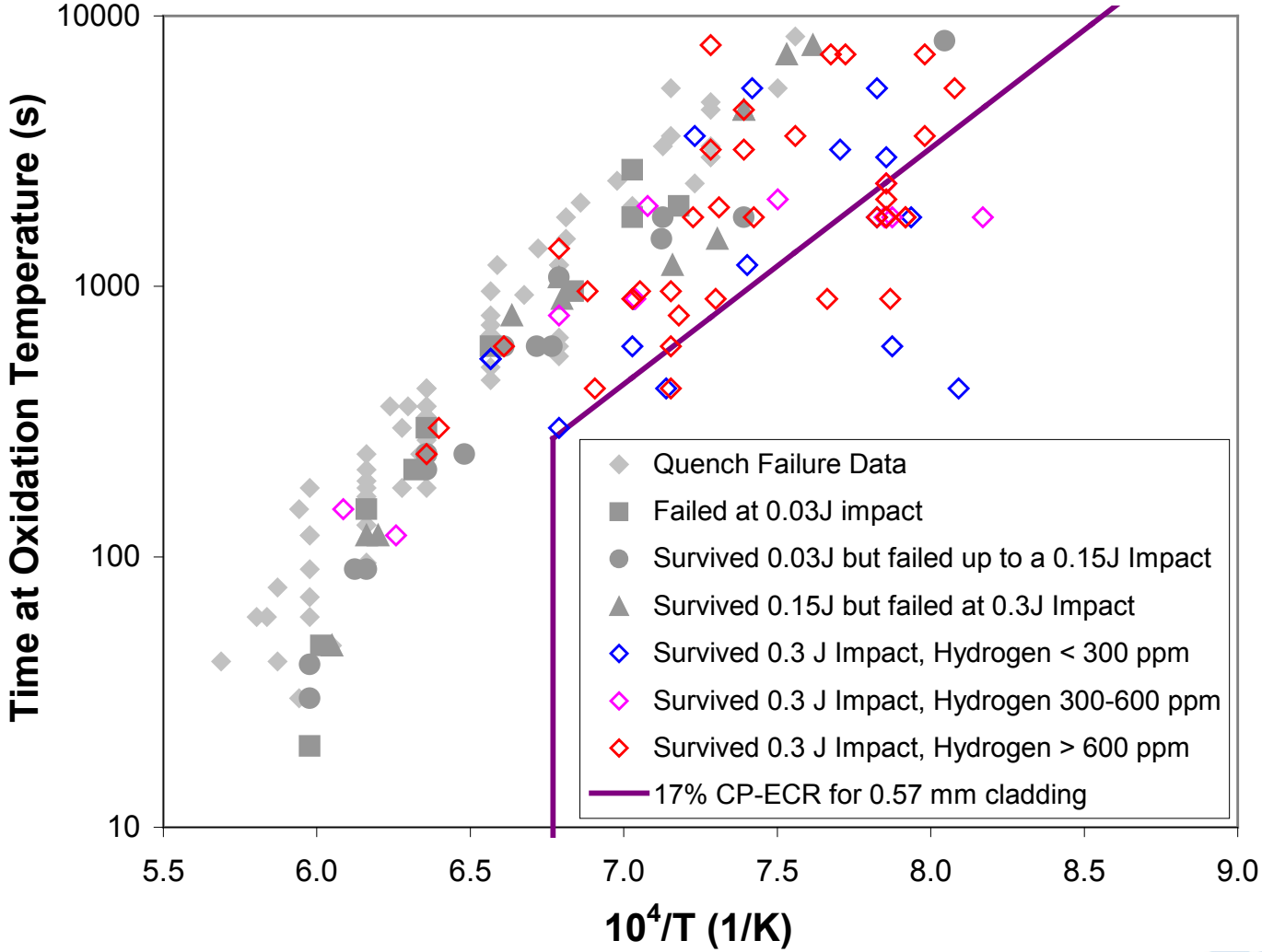
Published Test Results Review

- No hydrogen dependence



* Chung and Kassner, NUREG/CR-1344

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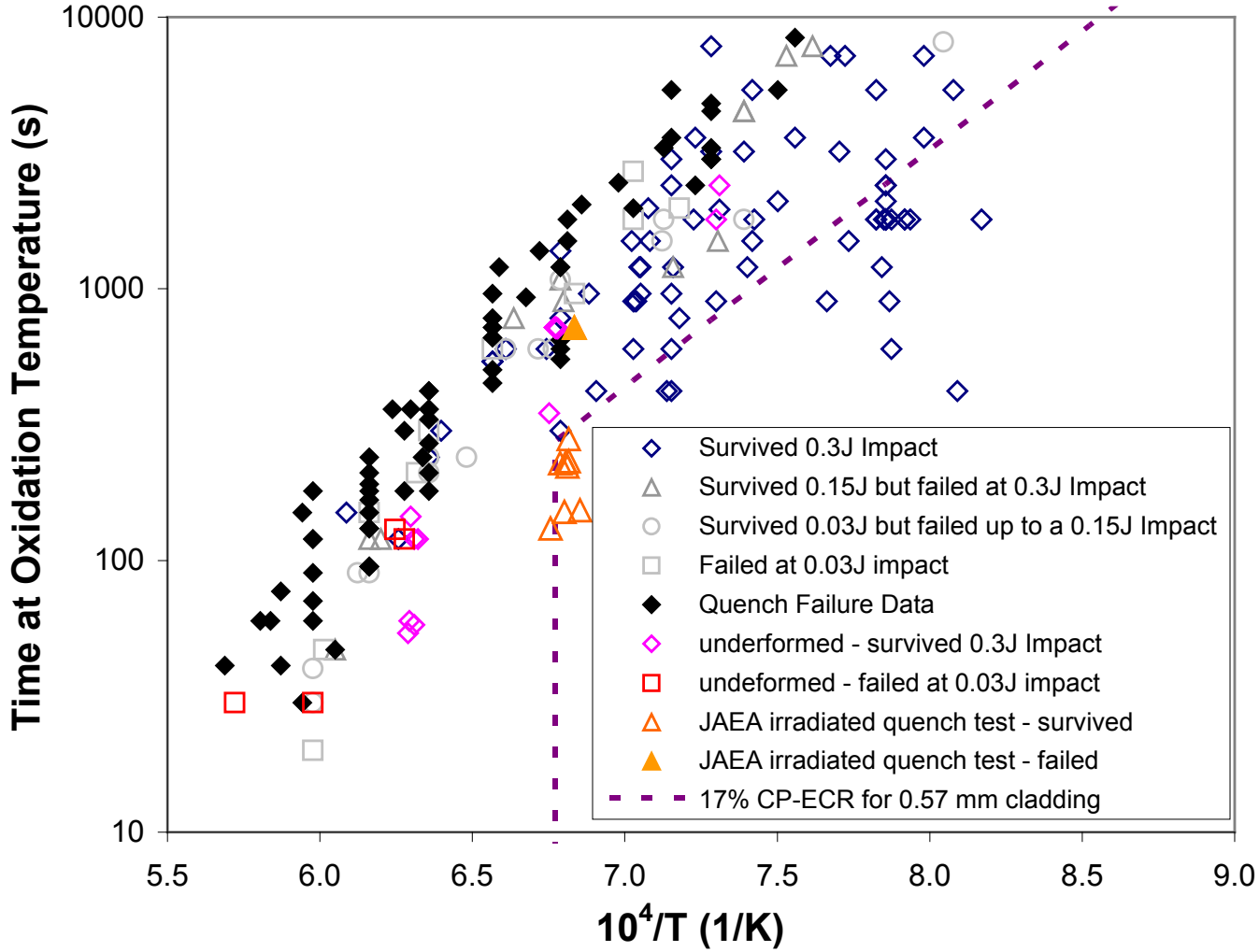
Published Test Results Review

- Similar behavior with irradiated and non-deformed regions



* Chung and Kassner, NUREG/CR-1344 and JAERI

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Feedback

- The application of the test results is not consistent with the principles of the proposed rule, which predicates on the maintenance of ductility
  - Seems like an “exemption” is granted for the ballooned and ruptured region
  - Recommend the “ductility” requirement be placed in a lower level regulatory guide
- If the acceptance of the ballooned and ruptured region condition can be made on the basis of results documented in ML111370032, then the same standard should be allowed for the balance of the fuel rod
  - Data support a hydrogen independent application

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