Official Transcript of Proceedings

NUCLEAR REGULATORY COMMISSION

Title: ACRS Materials, Metallurgy & Reactor Fuels Subcommittee

Docket Number: n/a

Location: Rockville, Maryland

Date: June 23, 2011

Work Order No.: NRC-970 Pages 1-114

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

DISCLAIMER

UNITED STATES NUCLEAR REGULATORY COMMISSION'S

ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

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

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

UNITED STATES OF AMERICA

NUCLEAR REGULATORY COMMISSION

+ + + + +

ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

(ACRS)

+ + + + +

MATERIALS, METALLURGY, AND REACTOR FUELS

SUBCOMMITTEE

+ + + + +

THURSDAY

JUNE 23, 2011

+ + + + +

ROCKVILLE, MARYLAND

+ + + + +

The Advisory Committee met at the Nuclear Regulatory Commission, Two White Flint North, Room T2B1, 11545 Rockville Pike, at 8:30 a.m., J. Sam Armijo, Chairman, presiding.

COMMITTEE MEMBERS PRESENT:

J. SAM ARMIJO, Chairman

SAID ABDEL-KHALIK, Member

CHARLES H. BROWN, Member

MICHAEL L. CORRADINI, Member

JOY REMPE, Member

WILLIAM J. SHACK, Member

NRC STAFF PRESENT:

CHRISTOPHER BROWN, Designated Federal Official

PAUL CLIFFORD, NRR

MICHELLE FLANAGAN, RES

KATHY GIBSON, RES

MICHELLE HAYES, NRO/DSRA

SHANA HELTON, NRR

TARA INVERSO, NRR

RALPH LANDRY, NRO/DSRA

RICHARD LEE, RES/DSA

PATRICK RAYNAUD, RES/DSA

HAROLD SCOTT, RES

JOHN VOGLEWEDE, RES

SUNIL WEERAKKODY, NRR/DSA

ALSO PRESENT:

JOHN ALVIS, Anatech/EPRI

MIKE BILLONE, ANL*

GORDON CLEFTON, NEI

BERT DUNN, AREVA NP

TOM EICHENBERG, TVA/EPRI

YANG-FI LIN, GNF/GEH

ERIK MADER, EPRI

ROBERT MONTGOMERY, PNNL*

KURSHAD MUFTUOGLU, GEH

KEN YUEH, EPRI

*Participating via telephone

T-A-B-L-E O-F C-O-N-T-E-N-T-S

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

8:30 a.m.

CHAIRMAN ARMIJO: Good morning. The meeting will now come to order. This is a meeting of the Materials, Metallurgy, and Reactor Fuels Subcommittee. I'm Sam Armijo, chairman of the subcommittee. ACRS members in attendance are Charles Brown. We're missing a few people here. Joy Rempe. I thought I saw Mike Corradini here.

PARTICIPANT: Yes, he's here.

CHAIRMAN ARMIJO: Is he here? Showing up, Dr. Corradini. Michael Ryan, Said Abdel-Khalik and perhaps we'll see Mr. Jack Sieber shortly.

The purpose of this meeting is to receive a briefing on the expanded technical basis for 50.46b rulemaking. In particular, a briefing will be given on the mechanical behavior of ballooned and ruptured cladding. We will hear presentations from representatives of the Office of

Nuclear Reactor Regulation and Nuclear Regulatory Research. In addition, a presentation will be heard from the Electric Power Research Institute, EPRI. The subcommittee will gather information, analyze relevant issues and facts and formulate proposed positions and actions as appropriate for deliberation by the full committee.

The rules for participation in today's meeting were announced as part of the notice of this meeting previously published in the *Federal Register* on June 14, 2011. We have received no written comments or requests for time to make oral statements from members of the public regarding today's meeting.

A transcript of the meeting is being kept and will be made available as stated in the *Federal Register* notice. Therefore, we request that participants in this meeting use the microphones located throughout the meeting room when addressing the subcommittee. Participants should first identify themselves and speak with sufficient clarity and volume so that they can be readily heard.

I'd like to ask everyone here to silence all phones and we can now proceed with the meeting. But I do understand we have people on the bridge line. And if they're on the bridge line, I would appreciate if you keep your phones on mute until we're ready to hear from you.

I'd like to turn the meeting over to Ms. Kathy Gibson of the Office of Research to make introductory remarks.

MS. GIBSON: Thank you. I'm Kathy Gibson, the director of the Division of Systems Analysis. We're here as a part of the continuing saga of the 50-46 rulemaking effort. We briefed you most recently on the three regulatory guides that Michelle put together with the working group.

Just to go back, bring everybody up to where we started and where we are now, in May of 2008 we issued a Research Information Letter titled, "Technical Basis for Revision of Embrittlement Criteria in 10 C.F.R. 50.46." It was RIL 0801. And in that RIL we recommended that the experimental results from our LOCA research program be used as the basis for rulemaking to revise the cladding embrittlement criteria in 10 C.F.R. 50.46.

And then in December of that year we

briefed you on the LOCA research program findings and the rulemaking strategy for the ECCS requirements.

Since then, as you know, we have an interoffice working group that has been working on the rulemaking revisions. In developing the rule language the working group discussed the treatment of the portion of the fuel rod predicted to balloon and rupture during a LOCA.

In RIL 0801 we acknowledged that no criteria have been found that would ensure ductility in the cladding balloon. However, loss of ductility in the 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. So, the staff discussion regarding this in the working group focused on how to document and support the statement in the Statements of Consideration for the current rulemaking.

At the same time we were completing an ongoing research program at Studsvik specifically designed to investigate the mechanical behavior of the ballooned and ruptured region that had been interrupted by the closure of the hot cell facilities at Argonne.

So, today's briefing is on the results and conclusions of this research program that supports the treatment of the ballooned and ruptured region in the Proposed Rule Statements of Consideration.

The report documenting these results and conclusions along with necessary updates to the RIL will be provided as enclosures to the proposed rule package that we're scheduled to brief you on in December and then the full committee in February 2012.

So, the briefing today is intended to familiarize you with this material in anticipation of these future briefings. A formal review of the information presented today will be part of the proposed rule package and no letter on this subject is being requested at this time. However, as always, the feedback and discussion of this subcommittee is welcomed, encouraged and helpful to us as we develop a strong and thorough regulatory product.

So, let me introduce the staff that's

here today to brief you. Tara Inverso of the Office of Nuclear Reactor Regulation, Division of Policy and Rulemaking will begin today's briefing with a status of the cladding embrittlement rulemaking project.

Let me acknowledge that Paul Clifford is also here from NRR.

Following Tara, Michelle Flanagan of my staff will present the briefing on the results and conclusions of the research program and discuss how these results and conclusions are being used to support the treatment of the ballooned and ruptured regions in the proposed rule.

John Voglewede, our senior level advisor for fuels, is also here to answer questions as need, as well as Mike Billone, our contractor from Argonne is also on the phone.

So, I would like to turn the floor over to Tara.

MS. INVERSO: Thank you, Kathy.

As Kathy mentioned, my name is Tara Inverso and I'm the project manager for the 50.46c rulemaking activities, and I'll begin today's meeting with an overview of the rulemaking project.

As Kathy also mentioned, the purpose of today's meeting is to present the expanded regulatory basis which confirms regulatory treatment of the ballooned and ruptured region within the 50.46c rulemaking. And as she also mentioned, the purpose of this is to provide familiarization to the ACRS Subcommittee members in anticipation of a formal review of the proposed rule package later this calendar year.

CHAIRMAN ARMIJO: Tara, as it's currently written, does the 50.46c rule language deal with a balloon, or is it implied that it's dealt with, or are you going to have to add language?

MS. INVERSO: As the rule is currently and the version that was released in anticipation of the May 10 ACRS Subcommittee meeting, the ballooned region is not specifically called out. And in that regard, the presentation that Michelle is about to give would not alter the rule language. Michelle will talk that the recommendation through this research and the report is that the same cladding, the brittle-to- ductile transition zone will apply to the ballooned region also. So, there would be no changes, no specific call out.

CHAIRMAN ARMIJO: Okay. So, that's really the bottom line?

MS. INVERSO: Yes.

CHAIRMAN ARMIJO: Okay. So, I'll wait to hear what you have to say.

MS. INVERSO: Today's meeting will begin with this overview presentation. It will then move directly into Michelle's technical discussion. EPRI will then lead a discussion of their remarks on the mechanical behaviors of the balloon document, and the meeting will wrap up with a discussion led by the ACRS members.

There are four main objectives of this rulemaking. The first objective is to revise the acceptance criteria based on recent research findings. This research focused on high burnup fuel rods after accident conditions and they identified some previously unknown embrittlement mechanisms, specifically how hydrogen interacts in the embrittlement process and then also shed some more light on previously known embrittlement mechanisms.

The Commission also provided direction

in this rulemaking through SECY-02-0057, and that was released on March 3, 2003. And the Commission directed us to rewrite the acceptance criteria such that they are more performance-based in nature. And they also directed us to expand applicability to all fuel designs and cladding materials. In other words, the current regulation applies to just zircaloy and ZIRLO, and this regulation would be expanded.

MEMBER CORRADINI: And just remind me; and if an applicant came in as all this was transpiring, they'd have to come in on a case-by-case basis for different cladding and make a case for it?

MS. INVERSO: Correct. As this is transpiring before the rule language is released and implemented; and as Paul mentioned in the last presentation, we're proposing a staged implementation, so there will be a point where some licensees fall under the current regulations and some will be adopting the new. And while the current regulations are in place, they will still need to go through with the exception procedure that they have been using to use alternate cladding materials. When the proposed rule language, if it is adopted, the cladding would have to meet the acceptance criteria and that would have to be proven to us before it could be loaded into the reactor.

MEMBER CORRADINI: And currently how many licensees have used the exemption path to have alternative cladding than the two that are in the rule?

MS. INVERSO: I think I'll turn that one over to Paul. If you --

MR. CLIFFORD: Okay. Yes, since the rule is specific to zircaloy and ZIRLO, there's many. The exact number, I would say around 20.

MEMBER CORRADINI: So significant?

MR. CLIFFORD: Yes, we've issued exemptions for all plants that have gone to M5 cladding alloy, which is an AREVA proprietary alloy. And we've also issued exemptions for optimized ZIRLO, which is a Westinghouse cladding allow.

MEMBER CORRADINI: And then just so I get it clear in this transition, so then with those exemptions they have to show that they meet the current rule. But the way you described it to me, if this is being implemented, would they have to then -- how does it happen in this transition for those exemptions? They just meet the current rule period until the new rule comes in? I'm trying to specific the transition.

MR. CLIFFORD: Yes.

MEMBER CORRADINI: I'm a bit cloudy as how all this transpires. That is, does everybody meet the current rule whether it be by exemption or by directly applying to the rule and then the new rule, assuming it's in in the current form, comes into play and then everybody gets reevaluated?

MR. CLIFFORD: Correct.

MEMBER CORRADINI: Okay.

MR. CLIFFORD: Each applicant, each licensee would need to at some staged scheduled implementation date be in compliance with the new requirements.

MEMBER CORRADINI: And I'm sorry, again from an impact standpoint, that would then potentially limit the burnup they can go to? I mean, I'm trying to figure it out from the standpoint of now this current rule is fine. I go to this sort of burnup running the fuel. Life is good. Now, the new rule is implemented. To meet the new rule they would probably have to roll back, potentially roll back the burnup.

MR. CLIFFORD: Based upon the information that's been provided to the owners groups on a plant-by-plant basis we don't expect that any plants, when they implement the new requirements, would need to make significant changes to either tech specs or licensed burnup plants.

MEMBER CORRADINI: Okay. Thank you.

MS. INVERSO: This rulemaking would also address concerns raised in two Petitions for Rulemaking. The first is PRM-50-71 that was received in March of 2000 on behalf of the Nuclear Energy Institute and it requested that we rewrite the regulation to expand its applicability to all fuel designs and cladding materials, well specifically cladding materials, which, as we just mentioned, was also a Commission direction.

The second PRM is PRM-50-84, and that was submitted by Mr. Mark Leyse on March 15, 2007, and he requested that the licensees operate in such a manner that they minimize the build of crud of oxide.

Recent developments. The Office of

Nuclear Regulatory Research has drafted three regulatory guides. The first was to establish a test procedure for measuring post-quench ductility. The second, Draft Guide 1262, was a test procedure for measuring breakaway oxidation. And the third, Draft Guide 1263, was a method for establishing analytical limits.

Michelle presented those three draft guides to the ACRS Subcommittee on May 10, 2011 and the full committee on June 8, 2011. And at those meetings we presented our plan to publish those draft guides along with the proposed rule such that when the public comments, they can comment on both the rule and the draft guides and be able to see how the two interact with each other.

The staff mentioned at the full committee meeting on June 8, 2011 that we're evaluating results of the fuel fragmentation dispersion research in parallel with this rulemaking. We have nothing new to update on that phenomenon today besides what we stated at the June 8 meeting. And the purpose of today's meeting is Michelle's presentation on the mechanical behavior of the ballooned and ruptured cladding, which was a document that the Office of Nuclear Regulatory Research has drafted.

CHAIRMAN ARMIJO: Okay. Well, I just want to make sure I understand the fuel fragmentation dispersion issue. Is that or is that not going to be treated in the 50.46c rule?

MS. INVERSO: This is a phenomenon that we are at the beginning stages of evaluating research results. I would like to be able to tell you exactly how everything will evolve, but it will continue to evolve as we go on in parallel. Our goal is to continue with this embrittlement rule. And as of today I would say it would not be included in the proposed rule language. We will provide that proposed rule based on embrittlement to the Commission by the established due date. Whether or not we will be at a point that we can provide a discussion of the evaluation within the SECY paper, we'll have to see as the evaluation continues.

CHAIRMAN ARMIJO: Well, if you were going to have fuel fragmentation language in the rule, I would expect that you would brief the ACRS on that matter before you do it.

MS. INVERSO: We will note that and

we'll keep the ACRS updated as we progress through our evaluation.

CHAIRMAN ARMIJO: All right. Thank you.

MEMBER CORRADINI: But, I mean, I'm kind of with Sam on this. The way you answered it before he asked the question was there will be nothing in the rule about fuel fragmentation dispersion. There might be discussion in the reg guide at best.

MS. INVERSO: Probably the SECY paper.

MEMBER CORRADINI: Or the SECY paper; excuse me.

CHAIRMAN ARMIJO: Yes, and then so --

MEMBER CORRADINI: I'm sorry.

CHAIRMAN ARMIJO: -- if it's in the SECY paper, what does that mean and --

MEMBER CORRADINI: Nothing as far as I can tell.

CHAIRMAN ARMIJO: Well --

MEMBER SHACK: Well, as I recall from the previous meeting, there was a somewhat stronger statement that they might include a recommendation that you hold off.

MR. CLIFFORD: At this time we may have a discussion. It's not final, but there may be a discussion in the SECY paper that identifies the phenomenon, identifies the potential impact, and then there would be a recommendation from the staff. We haven't solidified what that recommendation will be.

MEMBER CORRADINI: But, not to pin you down, but to pin you down, that means the rule will -- I mean, the way at least I heard it described, the rule will proceed forward on the timeline as you currently have regardless of what might appear in the SECY paper?

MR. CLIFFORD: Correct. The rule will be complete and the rule will be ready to be published for public comment --

MEMBER CORRADINI: Okay.

MR. CLIFFORD: -- at the Commission's discretion.

CHAIRMAN ARMIJO: Okay. Let's move on. I have to think about it.

MS. INVERSO: The rulemaking schedule. We expect to come back to the ACRS Subcommittee on December 15, 2011 and then again to the full committee on February 9, 2012. And our ultimate due date to the Executive Director for Operations is

February 29, 2012.

And that concludes the overview, unless there are questions.

(No audible response.)

MS. INVERSO: Okay. With that, I will turn it over to Michelle.

MS. FLANAGAN: Thank you. My name is Michelle Flanagan and I am in the Division of Safety Systems Analysis in the Office of Nuclear Regulatory Research. And my presentation today will review the contents of the technical report titled, "Mechanical Behavior of Ballooned and Ruptured Cladding." And the purpose of this document is to serve as the technical basis for the treatment of ballooned and ruptured cladding in the proposed rule.

The presentation today will for the most part follow along with the contents of this report. And so, that begins with a review of the regulatory history of the ballooned region and then presents the results of NRC's integral LOCA research program, and then finally describes how these research results will be used to support the treatment of ballooned and ruptured cladding within the rulemaking to revise 50.46c.

So, if we look for the overarching requirements for ECCS systems, we see that general design criteria and 50.46 require that an ECCS system is available to ensure that if a loss of coolant accident took place that the core remains amenable to cooling and that decay heat is removed to ensure long-term cooling.

And in 1973, the Commission hearings established that coolable geometry could be maintained if the cladding remained ductile. This position falls out of the belief that specific prediction and quantification of LOCA loads isn't possible or wasn't possible at that time to a satisfactory extent and that maintaining ductility is the best approach to preserving coolable geometry. And at that time ring compression test data, among other experimental observations, were used to establish ductility thresholds and those ductility thresholds were written and codified in the regulation.

And over 10 years ago the question was first posed are these criteria still appropriate for high burnup cladding? And like the program that defined the LOCA acceptance criteria in 1973, this new program particularly targeted at high burnup cladding also used ring compression tests to assess the oxidation and temperature limits at which embrittlement occurs. And staying close to the existing basis an emergency core cooling system computations was an important regulatory consideration.

NRC's test program concluded with the finding that the oxidation criteria was not sufficient for high burnup cladding. And specifically what was found was that hydrogen content had a significant impact on cladding embrittlement. The greater the hydrogen content, the less oxidation was required to embrittle the cladding material. And as Kathy mentioned, the Office of Nuclear Regulatory Research issued Research Information Letter 0801, which recommended that the experimental results from this program be considered as the basis for rulemaking and then an interoffice working group was formed to develop rule language.

And in developing rule language for revision to 50.46b, the staff discussion focused on how to treat the ballooned region. And in particular, the staff discussed whether the hydrogen-based embrittlement correlation derived from ring compression tests as shown on the previous slide was the appropriate limit to apply in the ballooned region, and particularly in the way that the current regulations would dictate.

So, on this slide it's awfully small text, but I'll read what is described for how to apply the oxidation criteria in the ballooned region, and this is codified language.

Where the calculated conditions of transient pressure and temperature lead to a prediction of cladding swelling, with our without rupture, the unoxidized cladding thickness shall be defined as the cladding cross-sectional area taken at the horizontal plane of elevation.

So, basically where there is ballooning and rupture, the regulations specify that the average wall thickness should be used in the oxidation calculation, and that upon rupture double-sided oxidation should be assumed. And so, the question that the staff was looking at was whether this approach to calculating oxidation should continue to apply with the hydrogen-based limit.

CHAIRMAN ARMIJO: Okay. I want to understand that.

MS. FLANAGAN: Yes?

CHAIRMAN ARMIJO: If you have some pre-transient hydrogen pickup --

MS. FLANAGAN: Yes?

CHAIRMAN ARMIJO: -- maybe 200, 300 ppm in cladding of a certain thickness, and you balloon and you thin the cladding by a factor of 2, does that put you into effectively the 600 ppm hydrogen concentration in the ballooned region?

MS. FLANAGAN: No, it's a weight percentage, weight ppm of hydrogen.

MEMBER SHACK: But it changes your ECR calculation?

MS. FLANAGAN: Right.

CHAIRMAN ARMIJO: It does change something.

MEMBER SHACK: Yes.

MS. FLANAGAN: Yes, the denominator of the --

CHAIRMAN ARMIJO: Yes, I'm just trying to find out what's really the limiting mechanical -- the weak point is the hydrogen-enriched oxidized thinnest wall.

MS. FLANAGAN: Yes.

CHAIRMAN ARMIJO: That's the ballooned region, I think. So, what is the limiting mechanical portion of the fuel?

MS. FLANAGAN: So, I'll start out an explanation and I think Mike Billone might be able to describe this in a more precise way.

CHAIRMAN ARMIJO: Okay.

MS. FLANAGAN: But what we're measuring is the strength, the properties of the residual beta layer, which is influenced -- or it degrades with oxidation and oxygen ingress, and that oxygen ingress is enhanced by hydrogen. And so, it's not necessarily the oxide thickness that's creeping into the thickness of the cladding as much as it is how much oxygen is absorbed in the base metal.

Mike, do you have anything that would be even more precise?

DR. BILLONE: I'm not sure the question is for ballooned and ruptured cladding. What is the weak point? Is that the question?

CHAIRMAN ARMIJO: Yes, that's basically it, Mike.

DR. BILLONE: There are three weak points. One is -- are you on slide 7 yet, Michelle?

MS. FLANAGAN: Yes.

DR. BILLONE: Oh, okay. I don't know, the red curve is oxygen and weight percent. And you'll see at the center of the ruptured node or the burst area you have the maximum oxygen content which causes embrittlement. And then as you move away from the rupture zone, in between the peak of the red curve and the peak of the blue curves your combination of hydrogen and oxygen also favors possible failure at those locations. So, just to the left and just to the right are possible failure locations, and also the center of the rupture region. And then it gets into how big is your rupture, what is the balloon strain, how weak is that region compared to the higher hydrogen region.

CHAIRMAN ARMIJO: Now, where is the thickest alpha layer on this same curve? Would it be where you have your peak hydrogen?

DR. BILLONE: Well, basically where your peak hydrogen is you basically have one-sided oxidation on the surface of the cladding. And it's 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 was real or not. Now, nobody disputes two-sided oxidation in a ballooned region, so my question is whether you get ballooning depends on the internal pressure in the rod presumably, and I calculate it from 06-30. Is it going to really turn out in practice that it's always the ballooned region that controls whether I'm going to hit my oxidation limit? That is, I'm really always going to have two-sided oxidation to consider because in my susceptible rod I'm always going to have ballooning. Or am I simplifying it too much?

DR. BILLONE: No, I think people at NRC could answer that better. And I think the answer depends on whether you do an Appendix A conservative thermohydraulics calculation or you do a best estimate as to whether your limiting oxidation is in the balloon, where I believe it is if you do the calculation right, or if it's somewhere above.

MEMBER SHACK: Can I make sure I understand you passing it back to the staff? Are you saying that if you did an Appendix A calculation you'd get higher temperatures and put the location in a different non-physical place?

DR. BILLONE: That is my understanding

from Harold Scott. And I'm quoting thermohydraulics experts who have been RES when I make that statement.

MR. CLIFFORD: This is Paul Clifford from NRR. I would say you're right, first of all. Yes, when you have ballooning and bursting, you introduce double-sided oxidation. Also, the wall thinning goes into the equation. So, if you have a balloon and burst, that will generally be the location, the node of peak calculated oxidation. However, there is some effects, cooling effects due to the changes in the hydraulic conditions around the ballooned region that can cause the temperatures to be a little lower. But that's usually overshadowed by the double-sided --

PARTICIPANT: (Off microphone.)

MR. CLIFFORD: Yes. So, that won't be the location of peak cladding temperature, but it will probably be the location of --

MEMBER SHACK: Because of the way they shuffle the fuel around, will the rod be likely to balloon? The hot rod, will it be also likely to balloon, or will there be such low burnup that maybe you won't have enough pressure to balloon?

MR. CLIFFORD: Well, there's competing effects.

MEMBER SHACK: Yes.

MR. CLIFFORD: The rod internal pressure increases with burnup, but power, rod power decreases with burnup.

MEMBER SHACK: Right.

MR. CLIFFORD: So, you'd have competing effects and both will be taken into account in predicting whether or not the rod will balloon and burst.

MEMBER SHACK: But, just in experience does it turn out that the critical rod is usually a ballooned rod? I guess that's my real question.

MR. CLIFFORD: It depends on the methodology that's being applied in some ways, but in general, yes, the hottest rod will balloon and burst, certainly for a large break as break size diminishes and the rate of RCS depressurization changes.

MEMBER CORRADINI: Then it could move around?

MR. CLIFFORD: It could depend on where the steam water interface is.

MEMBER SHACK: But doesn't that make this other argument about two-sided oxidation where there's no ballooning somewhat moot? Right. Yes, that was sort of where I was getting at, that, you know, if the critical region is always the ballooned one and everybody agrees there's two-sided oxidation --

MR. CLIFFORD: Right.

MEMBER SHACK: -- then I'm not sure why there was such a dispute over two-sided oxidation when it wasn't likely to be ballooned in this situation.

MR. CLIFFORD: The other issue was a high burnup phenomenon.

MEMBER SHACK: Right.

MR. CLIFFORD: You're talking about the oxygen ingress from the cladding ID surface. The issue there is you could have a location that had a higher peak cladding temperature, which means it didn't have the beneficial hydraulic effects of the balloon, but now would have to be penalized with a double-sided oxidation calculation.

MEMBER SHACK: Okay. So, I really do have to look at these beneficial effects of the cooling associated with the turbulence around the balloon?

MR. CLIFFORD: Correct.

MEMBER CORRADINI: Can you say that again what you just said at the end? I didn't catch it. Can you repeat it, please?

MR. CLIFFORD: If you had an un-ballooned un-deformed rod, at high burnups you would have -- because of the fuel bonding layer you could have a source of oxygen on the cladding ID surface so that you would in a sense have double-sided oxidation even though you didn't have a balloon and burst. So, at the location of peak cladding temperature, which is generally outside the ballooned region, you would now have to do double-sided oxidation. So, it would be somewhat of a penalty on that calculation, which today you wouldn't have that effect.

MEMBER CORRADINI: Okay. So, there'd be a penalty, but would that change Bill's conclusion about for a large break where it would matter? It might, or --

MR. CLIFFORD: No, not really, because that's a high burnup effect, so it's only going to be on the really high burnup fuel, which is operating at lower initial powers, which is going to have a lower cladding temperature than the fresh fuel.

MEMBER CORRADINI: So --

MR. CLIFFORD: I mean, there's many competing effects that are our all accounted for in the model.

MEMBER CORRADINI: Right, right. Right. Okay.

MEMBER BROWN: How are you getting oxygen if you don't have a --

CHAIRMAN ARMIJO: What was that, Charlie?

MEMBER BROWN: How do you get the oxygen? CHAIRMAN ARMIJO: In from the --

MEMBER BROWN: If you don't have a rupture, how do you get it on the --

CHAIRMAN ARMIJO: The contention is that when you have U-02 bonded to the zirconium oxide, that you basically have a large source of oxygen to pump into the cladding.

MEMBER BROWN: Okay. All right. I got

it.

CHAIRMAN ARMIJO: And that's the argument --

MEMBER CORRADINI: Basically it's not U-02 anymore. You steal some of the oxygen from the U-02.

CHAIRMAN ARMIJO: Well, they're just saying that if it's bonded to the zirc oxide, it's effectively oxygen. Now, that's a contingent. There's a dispute on whether that oxygen is truly available to --

MEMBER BROWN: So, it's not necessarily released. It's a matter of --

CHAIRMAN ARMIJO: Well, it has to --

MEMBER BROWN: -- transferring from the U-02, from the uranium --

CHAIRMAN ARMIJO: Right, it has diffused from the U-02 into the zirc and stabilized.

MEMBER BROWN: But there may not -- there's still a boundary? It's just got to diffuse?

CHAIRMAN ARMIJO: Right.

MEMBER BROWN: Okay. Interesting.

MS. FLANAGAN: Okay. So, on --

CHAIRMAN ARMIJO: That being said --

MS. FLANAGAN: On slide 7; I think we've talked a little bit about what these two images are really depicting, but just to complete the picture here, on the left-hand side what we're noticing is non-uniformity in the thickness of the cladding, and this was known in 1973 when the rule was written. What it leads to is very thin-walled cladding very near the rupture and a thicker area towards the back. So, the very thin regions near the rupture opening are all in all likelihood brittle, even if the back region is ductile.

And on the right-hand side we see locations of peak oxidation and peak hydrogen. And in both of these situations we notice that there are locations of brittle material and these can occur even if you're below the criteria that are established in the rule.

And so, both of these observations were understood around 1980. And nevertheless, the U.S. -- and some of this work was also done in Japan to identify these high-hydrogen regions. They also noticed this. And despite these findings, the oxidation limits in 50.46 were maintained and weren't adjusted. And this was based on two findings: One is that the ballooned specimens survived quenching even with high oxidation levels, and that the quench specimens didn't fracture following the loss of coolant accident conditions even when modest loads were applied as long as the oxidation level was less than the regulatory limit. And so, as I said, with these findings in hand, NRC made no changes to the LOCA acceptance criteria.

So, reflecting this historical treatment, RIL 0801 stated that no criteria have been found which would ensure ductility in the cladding balloon. However, loss of ductility in the short portion of the fuel shouldn't lead to an uncoolable geometry as long as the amount of oxidation in the ballooned region remains limited in the current manner. And then the current manner in this case referred to the text and the approach that's in 50.46 right now.

And so, in an effort to support the staff discussion about the treatment of the ballooned region, the working group staff turned to the results coming out of NRC's integral LOCA research program. This integral LOCA research program was designed to measure the mechanical behavior of ballooned and ruptured cladding following LOCA conditions.

And in the images here a single rod was exposed to LOCA conditions in a test train. This particular one is the test train at Studsvik and it was designed and fabricated to replicate the equipment that's at Argonne. And so, companion tests were run at Argonne and Studsvik.

And then following the LOCA simulation bend tests were conducted. And the best test is a test that applies a uniform bending moment to the entire ballooned region.

CHAIRMAN ARMIJO: Michelle, in all of these tests you took them up to the 1,200, or 2,200 F for what, how many --

MS. FLANAGAN: For varying amounts of time depending on the target oxidation level.

CHAIRMAN ARMIJO: Okay.

MS. FLANAGAN: But, yes, the oxidation was accumulated at 1,200.

CHAIRMAN ARMIJO: Okay.

MS. FLANAGAN: Sometimes only for a couple of seconds, but yes, that's where the tests were conducted.

CHAIRMAN ARMIJO: All right.

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

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

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

CHAIRMAN ARMIJO: Yes. Okay.

MS. FLANAGAN: Relative to the loading.

CHAIRMAN ARMIJO: And the four points are where?

MS. FLANAGAN: Oh, sorry. Here.

CHAIRMAN ARMIJO: Okay. There?

MS. FLANAGAN: Here.

CHAIRMAN ARMIJO: Okay.

MS. FLANAGAN: Here and there.

CHAIRMAN ARMIJO: All right. Thank you.

MS. FLANAGAN: As I mentioned, the failure location was significant. And so, during these tests the failure location was recorded and the observations of bend tests in irradiated material tested at Studsvik were compared to the results of as-received and pre-hydrided material that was tested at Argonne. And in the tests what we looked at was the load displacement curve. And from the load displacement curve the bending moment, failure energy and offset strain were determined, and also, as I mentioned, the failure location was recorded. And then by comparing the parameters that we can derive from the load displacement curve, we can investigate the relative influence of oxidation, irradiation, balloon size, bend test temperature, as well as hydrogen content.

So, these are the results from the as-fabricated test series. And my intention isn't to go through them on this graph, because later I have plots which do a better job of reviewing what these results show, but one thing I want to point out is the range of rupture strains that are a part of this test matrix. They range from 21 percent strain all the way up to almost 70 percent strain. So, we have a large range of balloon strain.

In addition, all of the samples here, and actually all of the ones that we tested in our program, did survive quench, the actual quench process. And this is significant, because for unrestrained as-fabricated cladding quench will induce a sharp thermal gradient across the cladding wall in both hoop and axial thermal stresses induced in the cladding lead to the cladding surface being in tension on the inner surface and compression -- oh, sorry, tension on the outer surface and compression on the inner surface. And regardless of the stress and magnitude of these quench stresses, all the samples shown here and in the remainder of the program did survive quench itself and had some residual properties that were observed in the bend tests.

MEMBER SHACK: Michelle, are these 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.

MEMBER SHACK: Okay. So, that's really the bottom?

MR. CLIFFORD: Right, that's the bottom. And then towards the end of life that could get up to 20 -- well, worst case calculations, it could get up to 3,000 psi. But best estimate calculations are more around 2,000 psi.

CHAIRMAN ARMIJO: Now, Michelle, was there any pre-hydriding of these samples? Are these just as-fabricated?

MS. FLANAGAN: All of the results on this slide are as-fabricated.

CHAIRMAN ARMIJO: Okay.

MS. FLANAGAN: Later when I show the plots, there are two points that were recently generated that are for pre-hydrided material. But a lot of the work that was done at Argonne was on as-fabricated cladding in this campaign with bend tests.

CHAIRMAN ARMIJO: So, I guess I'm missing the point. If there's survival of a quench and they're high-ductility, it's really not relevant to something that's been in the reactor for a few years and has a few hundred ppm of hydrogen. So, what am I missing?

MS. FLANAGAN: At this point, this set of data is really to observe the impact of oxidation. And so, we're looking at how much oxidation is required to degrade properties. On the next slide I think --

CHAIRMAN ARMIJO: Okay. I'll wait.

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

MEMBER CORRADINI: So, this is a set of baseline experiments with no preexisting hydrogen?

MS. FLANAGAN: That's correct. But during the ballooning and rupture process there will be the secondary hydriding developed.

MEMBER CORRADINI: Right.

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

MEMBER CORRADINI: But, I mean, to get to Sam's -- I mean, I'm a novice at this, so I'll only ask questions after an expert asks it. But I guess to Sam's point, if I went -- all right. I guess it's on this one. If I went back to your qualitative graph of 5, all this data is sitting to the left-hand side where there's no preexistent hydrogen.

MS. FLANAGAN: Right, it would be on the

y-axis itself.

MEMBER CORRADINI: And it would be in the survive region? Essentially it's created a database that says -- that's my interpretation of what you just said.

MS. FLANAGAN: Yes.

MEMBER CORRADINI: Am I misinterpreting?

MS. FLANAGAN: No, the only part that I'm hesitating about is when you said it's in the survive region, because this is a different -- this is more to look at the qualitative -- quantitative -- sorry, no, qualitative impact of oxidation. And I think this will make more sense --

MEMBER CORRADINI: Okay. So, the answer is I should wait? That's what you're telling me and I'll wait.

MS. FLANAGAN: Yes, and if your question isn't answered, then let's return to --

MEMBER CORRADINI: Yes, that's fine. You can tell us to wait. That's allowed.

MS. FLANAGAN: Oh, okay.

MEMBER CORRADINI: It's a very acceptable answer: Wait.

MS. FLANAGAN: I know, but I just love

answering questions.

MEMBER CORRADINI: You don't have to be so nice to us. You don't have to. It's not required.

MS. FLANAGAN: Okay. So, what I'd like to show from this slide is that this is the bending moment that was observed in the load displacement curve for the tests that were shown on the previous slide. And so, the main thing we noticed from this is as oxidation increases, the bending moment decreases. The more oxidation you have, the less bending moment you have.

And I want to point out, as I said before, there was a large range of ballooning strains that were part of this test matrix. And despite the fact that there was a large range of balloon strains, we seen the general dominating trend as oxidation. And if you look at the two shapes, circles on this plot represent ballooning strains above 40 percent and the squares represent ballooning strains 33. So, you have a differentiation on the figure of large balloons and small balloons, and we don't see a separation of the results based on that finding.

And on the next slide I'm going to point out there's two different failure locations that we saw in these tests. And what I'll say while on this slide is despite the fact that in some cases we saw failure taking place in the center of the rupture opening at the location of maximum oxidation, and then sometimes in the region of highest hydrogen content, we don't see a separation of data points still. It's still dominating by oxidation.

MEMBER SHACK: But you've scaled your ECR here by the --

MS. FLANAGAN: Yes, that's a good point actually, and it's written here and I just forgot to say it. The x-axis is a calculated value. And in this case it was calculated with the approach to oxidation and ECR that defined in the current rule, so it's scaled in that sense by the wall thickness and the strain. Thank you for reminding me to say that.

So as I said, we observed two failure locations during these bend tests. One on the left-hand side is where a combination of high hydrogen content and oxidation was observed. I tried to scale this figure to kind of orient relative to the hydrogen plot above. The location of failure wasn't at the maximum hydrogen at about 40 millimeters away from the burst center, but about 24 millimeters below at a location where there is high hydrogen content, but we also have high oxygen content as well.

The other type of failure location that we observed was failure right in the center of the rupture. And as I mentioned in the previous slide, even when we see these two different failure locations, the conclusion that we can draw from this is that you still need oxidation in order to cause failure. The more oxidation you have, the lower the bending moment. And we saw the same trend when we observed the maximum energy of failure in these bend tests.

So, after the as-fabricated test series was complete, four tests on irradiated material were conducted at Studsvik. And I want to point out that prior to the testing at Studsvik there was a lot of work that was done to compare the apparatus, the LOCA heating apparatus, as well as the bend apparatus between Studsvik and Argonne so that we 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

case, should the test procedures be modified to limit the extent of deformation in the ballooning region as if there's a neighboring rod that would limit?

MS. FLANAGAN: Well, we don't see a large impact from the strain on the results, but I agree with you that there is some non-prototypicality in this large balloon strain. We don't see that it impacts the conclusions that we can draw from these particular tests. And the test procedures that you're referring to are our internal procedures for -- this isn't combined with the regulatory guide test procedures.

MEMBER ABDEL-KHALIK: I'm just trying to understand the prototypicality of the results. And if the geometry of the ballooned region in the tests is nowhere near what you would expect in reality, I'm just wondering how you can justify this.

MS. FLANAGAN: I would agree, but we don't see a large influence of the ballooning strain. So what I'm saying is that even though these balloon strains are very large, I don't think that that invalidates the conclusions that you draw from comparing two rods and looking at the influence of oxidation.

CHAIRMAN ARMIJO: But if you didn't have as much strain wouldn't you expect that the maximum energy would be greater than something that had a lot of strain in your mechanical test?

DR. BILLONE: No.

MS. FLANAGAN: Yes, maybe Mike can interject.

Mike, I have slide 16 up, and I can go back to slide 14 where we were looking at the plots of the values that were measured. And they include balloon strains of 70 percent all the way down to 20 percent.

DR. BILLONE: Right, so then there's two different issues here. Relative to Michelle's slides, because we don't see a significant difference in strain, which is maximum bending energy -- I mean, maximum bending moment, or maximum energy, you just look at the square points versus the circular points. And the square points are as low as 20 percent circumferential strain, which is certainly well within the ability of the cladding to deform in an array. As you get to higher strains, you've got possibly balloon cladding pushing against other cladding and you vary the shape.

But the reason we went for the higher strains is we wanted to also look at fuel relocation, kind of a maximum upper bound on fuel relocation and possibly fuel dispersion through the rupture opening. And that historically has been the way we've conducted the program since 1998.

My last comment is that when vendors use Appendix A, for example, to do some hydraulics analysis, they have ballooning strains, and it could be as high as 100 percent, you know, as high as 20 percent, regardless of whether it's typically realistic or not.

MS. FLANAGAN: Does that answer that question?

MEMBER ABDEL-KHALIK: No, but that's okay.

MS. FLANAGAN: Let me try one more thing and --

MEMBER ABDEL-KHALIK: I'm just trying to understand how these results can actually be invariant, and I can't convince myself that they can ever be invariant.

MEMBER SHACK: But they've stilled over

a range of a strains that exceed what they expect to find, which I think is sort of her point, is that clearly if you're not getting too much scatter over this range of strains, over the real range of strains it's going to be even less. And so, you know, they're trying to sort of -- because in reality they don't know this average strain all that well. It's something they compute. So, you'd like to show that it's relatively insensitive to that, and that's sort of what the results are showing here.

MS. FLANAGAN: Of the four tests that were run at Studsvik here's a couple parameters of the tests. I'm going to go right into a plot which has the Studsvik values along with the as-fabricated values.

So, on this plot the Studsvick high burnup tests are indicated with open red triangles. And those points as well as the as-fabricated points were all documented in the report that was provided a couple weeks ago.

MEMBER SHACK: Where are the triangles?

DR. BILLONE: The diamonds.

MS. FLANAGAN: Diamonds; sorry.

MEMBER SHACK: Diamonds?

MS. FLANAGAN: Yes.

MEMBER SHACK: Okay. All right.

MS. FLANAGAN: Here, here, here and then there's one up here.

And then since the report was provided to the ACRS a couple weeks ago, two pre-hydrided results were produced. And so, I'm putting them on here to make a point in a second about the effect of hydrogen. But what I'd like to point out in this figure are that the values of bending moment, as I said before, decrease with increasing oxidation and therefore limiting oxidation in ballooned and ruptured cladding we determined is appropriate and the ballooned region should have an oxidation limit applied.

The values of bending moment for irradiated fuel have been shown to be reduced relative to as-fabricated cladding with the same oxidation level. And in addition, recent pre-hydrided data has shown that the bending moment of pre-hydrided material is also reduced from as-fabricated cladding for the same oxidation level. And taken together this data suggests that there is a hydrogen effect for the mechanical behavior of the balloon that should be accounted for.

Applying the proposed hydrogen-dependent oxidation limit in the balloon preserves favorable mechanical properties. And I say this -- recall that the tests at Studsvik had a pre-transient hydrogen content of around 200 weight ppm, and so therefore their oxidation limit would be around 12 percent. And so, if we assume that this trend is depicting a value around here for 12 percent, we see that the bending moment value is higher than the as-fabricated cladding at 17 percent. And we also see the same general trends when we examine the failure energy.

DR. BILLONE: Michelle, may I make a small point?

MS. FLANAGAN: Yes.

DR. BILLONE: Argonne is just showing two data points for pre-hydrided cladding and we have four more tests we're in the middle of. So, we'll be able to populate this data with lower hydrogen contents comparable to Studsvik. Currently we're testing at 200 to 250 weight parts per million. So, we'll have four more data points on this plot.

CHAIRMAN ARMIJO: Okay. That's in the pipeline, or is already done?

DR. BILLONE: We're in the process of completing those tests.

CHAIRMAN ARMIJO: Yes, okay. Back on that same chart, so just let me get this straight: The blue data points have some level of hydrogen, but less than 200 ppm?

MS. FLANAGAN: The blue dots are as-fabricated cladding.

CHAIRMAN ARMIJO: Okay.

MS. FLANAGAN: So, they began with no hydrogen.

DR. BILLONE: Five to ten weight parts per million.

MS. FLANAGAN: Oh, sorry. Right.

CHAIRMAN ARMIJO: So, it's only whatever hydrogen that they picked up during the test?

MS. FLANAGAN: Yes.

CHAIRMAN ARMIJO: And the 200 ppm is for the HB Robinson cladding that was irradiated and you had measured that before. And then the new --

DR. BILLONE: It's not HB Robinson.

It's --

PARTICIPANT: High burnup.

CHAIRMAN ARMIJO: High burnup? Oh, okay.

DR. BILLONE: -- high burnup from North Anna.

CHAIRMAN ARMIJO: Okay.

MS. FLANAGAN: Yes.

CHAIRMAN ARMIJO: High burnup.

DR. BILLONE: But HB means high burnup.

CHAIRMAN ARMIJO: Okay. So, you're just saying here's your hydrogen effect demonstrated in this curve and we can account for that by the same oxidation limits that we're going to apply in other parts of the cladding?

MS. FLANAGAN: Yes.

CHAIRMAN ARMIJO: Is that basically what you're saying?

MS. FLANAGAN: That's --

CHAIRMAN ARMIJO: Even for balloon stuff.

MS. FLANAGAN: Yes, it's saying that if you apply the hydrogen-based oxidation limit, you will preserve balloon properties.

CHAIRMAN ARMIJO: And you'll maintain a sufficient level of ductility even in the ballooned region? I'm just trying to get to --

MS. FLANAGAN: Yes.

CHAIRMAN ARMIJO: -- the conclusion of --

MS. FLANAGAN: I think if we wanted to say a lot more, we would really need a lot more data points. So, we're kind of struggling to say what we can conclude. The data that we have confirms that applying the oxidation limit in the balloon is appropriate. Applying a hydrogen-based limit is also appropriate.

CHAIRMAN ARMIJO: Okay. Well, I'll let you finish then. See where you're going.

MS. FLANAGAN: I'm not going too much further.

CHAIRMAN ARMIJO: That's it.

MS. FLANAGAN: Now, I'm going to state the program conclusions.

MEMBER BROWN: Go back. You said you had a dearth of data points.

MS. FLANAGAN: I did? For as-fabricated cladding we have a large number of data points. For irradiated material we have four.

MEMBER BROWN: Yes, you didn't have much. And so, we're going to set a rule based on a limited data set as opposed to -- I'm just trying to understand. I'm a neophyte also; as Mike commented, and I would have thought that on the material standpoint we'd want a wider range and a more populated data set for the irradiated material as opposed to just as-fabricated material, which is not totally representative, at least in my own mind, of what you experience under the actual LOCA conditions that we're projecting to try to protect against.

MS. FLANAGAN: I think if we started to see trends that we didn't expect, we would want a lot more data. There was nothing that we saw that we weren't expecting. And so then as a confirmatory research program we're comfortable with the amount of data that we have to make our decisions.

MEMBER BROWN: How much data do you have, these three data points? Is that --

MS. FLANAGAN: For irradiated material we have four tests that were integral, LOCA, bend test.

MEMBER BROWN: Okay. Four data points.

MS. FLANAGAN: For these -- I mean, yes, this is in addition to a large amount of work that was completed to just look at the effect of oxygen and hydrogen through the ring compression tests. So, this is kind of a targeted program specifically on the balloon properties. And in that case we did four integral LOCA tests.

MEMBER BROWN: I'm not a metallurgist, so I'm not going to sit here and -- it just seems like that -- for a major rule change that just seems like a low amount of data in order to draw a conclusion for a rule change that's been in place for --

MS. FLANAGAN: Well, I should say that the existing basis that was established in 1973 looked at this also. And what I'm saying is that now our question was is there a hydrogen effect in the balloon? And for that we did a number of tests and we didn't see anything that we didn't expect. And so as a confirmatory program, that was satisfying. As establishing a new understanding of new phenomenon that would probably not be sufficient. Does that make sense?

MEMBER BROWN: Sort of. I'll continue

to listen.

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

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

So, then when we look at the program

conclusions within the regulatory context, we look at three aspects: One is how can we use these results to address the treatment of the ballooned region within the rulemaking to revise the embrittlement criteria of 50.46? Another aspect is to address the extrapolation of these research findings to new cladding alloys and lower oxidation temperatures. And then finally, we addressed the regulatory question of alternate performance metrics for the ballooned and ruptured region of the fuel.

And these are topics that are elaborated on in the report, and I'm just going to give some highlights of what this report concludes within this regulatory context. So, regarding --

CHAIRMAN ARMIJO: Michelle, before you --

MS. FLANAGAN: Yes?

CHAIRMAN ARMIJO: Go back to that slide 21.

MS. FLANAGAN: Yes. Oh, yes.

CHAIRMAN ARMIJO: You say all samples survived the quench, and that included the irradiated high burnup cladding?

MS. FLANAGAN: Correct.

CHAIRMAN ARMIJO: It included the as-fabricated low-hydrogen cladding, and it included the pre-hydrided cladding, the 400 to 700 ppm hydrogen. The ballooned regions in all of those samples survived this quench in your test. So, then the question I have is if this ballooned region under all of these conditions has sufficient ductility to survive the quench, why is there any concern that a non-ballooned region -- hasn't been deformed, doesn't have any more hydrogen, is no more irradiated. Why would we have any concern about the non-ballooned region? Why wouldn't we just say, hey, if the ballooned region which is already fractured, thin, loaded with irradiation, loaded with hydrogen survives a quench, why do we worry about the non-ballooned region?

MS. FLANAGAN: Let me make sure I understand the question. When I say that the sample survived quench, what I mean is that after the transient and the apparatus is disassembled, the rod was in one piece, and then we did a mechanical test to see what was left.

CHAIRMAN ARMIJO: Well, that's my point.

MS. FLANAGAN: Right.

CHAIRMAN ARMIJO: It survived the quench, you know?

MS. FLANAGAN: Right.

CHAIRMAN ARMIJO: Whatever loading was in that apparatus, it did survive it. And so, if something that is clearly thinner wall, obviously more fragile than the un-deformed portion of a fuel rod, can survive that, why wouldn't we focus all our concerns strictly on the ballooned region as a limiting region and not spend a lot of time worrying about the un-deformed cladding?

DR. BILLONE: Michelle, may I try that one?

MS. FLANAGAN: Sure.

DR. BILLONE: These samples that we're testing, they're segments, they're not full fuel rods, but they're free to expand in the axial direction and contract in the axial direction. So, basically surviving quench means surviving the thermal stresses induced by quench. However, you know there's additional stresses on the cladding to the extent that it's not free to contract during a quench and it may get hung up at grid spacers or what not. So, we know there are loads above and beyond -- in particular there are axial loads due to partial constraint above and beyond what we call quench loads or when we talk bout thermal stresses. So, that's the whole point of this program is what do you have left in the cladding above and beyond surviving thermal loads, not counting the partial constraint-type thermal loads, just the temperature gradient to the cladding-type thermal loads.

CHAIRMAN ARMIJO: Yes, I hear you, Mike, but you know, if we're measuring fracture toughness or we're looking for something to retain ductility, it would seem to me that if you've demonstrated sufficient ductility in a region that has half the wall thickness --

DR. BILLONE: I'm sorry, where are you getting the impression that we've demonstrated ductility? I'm missing that.

CHAIRMAN ARMIJO: Well, if --

MEMBER SHACK: Demonstrated sort of strength to survive quench. There may be no ductility left at that point.

CHAIRMAN ARMIJO: Well, then if there's --

DR. BILLONE: We're maintaining

ductility in the majority of the --

CHAIRMAN ARMIJO: Well, I thought all your measurements here showed you measured the strain energies, you measured offset strains in these four-point bend tests.

DR. BILLONE: Right.

CHAIRMAN ARMIJO: And if that doesn't give you some information on ductility, I don't know what --

DR. BILLONE: Well, in general we didn't measure any offset strain for most of our tests. Particularly if you fail in higher hydrogen regions the material is brittle, but it has strength. And most of our failures in the rupture region, when you subject the rupture opening, detention failed with no offset strain. So, I mean, I hesitate to use the word "ductility" to include the whole ballooned region with everything from the hydrogen peak all the way to the oxygen peak.

CHAIRMAN ARMIJO: So, where is the limiting region? What part of the fuel rod should we be worried about?

MS. FLANAGAN: I think we're getting back to the question that Dr. Shack asked earlier.

I mean, in some cases you're right that we may be limited in the ballooned region, but I'm not sure that that leads to the conclusion that we should not have any limit in other areas. Because depending on the conditions and the large break versus small break and the different transient history there's still a need to have a limit for other areas. And I think it gets back to the particular transient of interest where you're going to identify your worst case.

MEMBER SHACK: But I think you can also make the argument that maintaining the ductility with the criteria they have for the un-deformed ring seems to give you results for the balloon that assure that it's got some sort of integral strength. Even if you can't sort of talk about ductility in a meaningful way, that it doesn't -- you know, if you follow those rules, at least you're with something that looks reasonable in the ballooned region even though you're sort of basing that largely on engineering judgment. Because as Michelle says, you really can't calculate all the loads it has to take. And then you're going come back to the argument, okay, it's only a ballooned region. A failure there doesn't mean you've lost coolable geometry. But it's --

CHAIRMAN ARMIJO: Well, I --

MEMBER SHACK: You know, the criterion they're imposing seemed to give you --

CHAIRMAN ARMIJO: I see the argument starting with the un-ballooned region saying if we can protect it there, it turns out that the ballooned region isn't catastrophic. But it still --

MEMBER SHACK: Yes, there's something a little less than totally satisfying.

CHAIRMAN ARMIJO: Yes, there you go.

MEMBER SHACK: But I think that comes back to the fact that as she comes to her alternate metric she's going to say she doesn't really know what they could be, because you can't really -- we don't -- we're not really smart enough to calculate all the loads.

CHAIRMAN ARMIJO: Yes, but I'm just trying -- getting back at the coolable geometry, I'm looking at these pictures of these fractured ballooned regions and a fracture in a ballooned region, I can see where you could have actual relocation of fuel, stuff falling out of that. I think it's still coolable, but compare what would happen in a fractured un-deformed, relatively un-deformed region, I'd say that's a non-event. Unless it fractures in many places, I don't see why that wouldn't be a priori coolable. I'm just trying to get back to our fundamental goal of assuring coolable geometry. And any way you look at it, the fracture in the ballooned region would be less coolable than fracture in the un-ballooned region. And so, why don't we concentrate on the ballooned region. I guess that's where I'm at.

MS. FLANAGAN: And in practice that may be how the calculations turn out, that that's the focus and that's the limiting region. So, I don't know if -- I think --

CHAIRMAN ARMIJO: Okay. Well, maybe --

MS. FLANAGAN: -- that might be how it is.

CHAIRMAN ARMIJO: When we get to the point of how do we treat it and what does somebody that has to assure they have adequate ductility and compliance with the rule, what do they have to do in the ballooned region as compared to the un-ballooned region to meet the requirements?

MEMBER CORRADINI: And in the rule. I view all of this as --

MEMBER SHACK: You have to compute your ECR for the ballooned region and make sure it meets the rule. You're going to go back to that diagram.

MEMBER CORRADINI: But, yes, I'm -- I should be --

MEMBER SHACK: So, they're --

MEMBER CORRADINI: I'm still confused. I'm still confused. It seems to me that the ballooned region would still dominate because any non-ballooned region, if it could dominate, would probably be in a low-power region, therefore it wouldn't -- I'm still missing something. Your original question to Paul still is in my mind.

MEMBER SHACK: Yes, but then it comes back to this peak clad temperature is likely to be something other place because I'm going to get cooling. And so, I have a whole bunch of competing effects going on here. I mean, I think we'd actually need to see some calculations to really understand what's happening. Bert's going to say something.

CHAIRMAN ARMIJO: Well, the peak clad temperature can't move too far away from the balloon because that's where it was the hottest originally. That was where --

MEMBER SHACK: Well, it balloons at 800 C, so I mean, you know --

CHAIRMAN ARMIJO: I understand, but that was the first part that got hot.

MEMBER SHACK: Yes, but then it cools off.

CHAIRMAN ARMIJO: Locally, but as far as the decay heat and the source of heat and the things that caused it to get hot, it's still in that same nodal region. So, it's not going to be far away.

MEMBER CORRADINI: Yes, it's not going to be a foot up or a foot down. It might be a few inches up or down.

CHAIRMAN ARMIJO: Yes. Yes.

MR. DUNN: Dr. Armijo?

CHAIRMAN ARMIJO: Yes?

MR. DUNN: Bert Dunn, AREVA. Could I could enter the conversation?

CHAIRMAN ARMIJO: Sure.

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

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 region would seem to me to be more severe than a fracture of a un-deformed tube in which it would be very difficult for pellets to come out of a simple cracked round tube.

MR. DUNN: Well, except that you will have ruptures in that assembly all the way around. The pins will kind of locked into a position, whether or not they rupture or not. I mean, not whether -- whether they crack or not.

CHAIRMAN ARMIJO: Well, you know, the issue is if they cracked, have you lost coolable geometry? And the answer I'd have is I don't see how that's lost coolable geometry. If you break a balloon and fuel spills out, that's probably still pretty coolable, but seems to me that it's worse. But, I think we can go on and see where the staff is headed.

MEMBER CORRADINI: But, can I ask a question? I mean, maybe I'm missing it, but all of these experiments are single rod experiments, right?

MS. FLANAGAN: Yes.

MEMBER CORRADINI: It would never expand like this in a rod bundle. So, I'm missing something here that maybe has been discussed and I was not at that subcommittee meeting. But the P over D of these things is like 1.3, 1.25. These things have gone to like 2, right? So, what am I missing in terms of the reality of how this would occur within a rod bundle? Somebody help me here.

MR. DUNN: I think in terms of my response to that is the rods, if they expand as a circle with the same degree of expansion all the way around, which they never do, but -- that they will touch an adjacent rod at about 30 percent strain. So past 30 percent strain you have stopped your circular expansion and you've moved into something that might look like a cloverleaf or a child's jack, or something, and that they will wrap around the adjacent rod. You'll provide some additional strength to stop the tertiary expansion at that point, the tertiary strain, and you'll probably wind up with slightly lower strains for the rods.

MEMBER CORRADINI: So, let me ask my next question.

MR. DUNN: But I think largely strain will be preserved.

MEMBER CORRADINI: Okay. All right. So, that makes some -- qualitatively that makes sense to me. So, then why is the cooling better? It seems to me I would get contact to contact and all of a sudden things would get ugly circumferentially.

MR. DUNN: Well, one thing --

MEMBER CORRADINI: Where is that computed?

MR. DUNN: One thing is that an azimuthal gradient through the cladding doesn't have to be very strong to move the power to another location. The second thing is that you have direct droplet enhancement. You're in re-flood probably. You're carrying water droplets up with the steam. They're interacting directly with that cladding expansion. And that's occurring throughout the entire bundle. And the rupture distribution axially has a variation to it so that you --

MEMBER CORRADINI: Well, I mean, okay, I hear what you're saying, but I guess I don't want to take us off track because there's a whole lot more to go over.

MR. DUNN: We are. I'm sorry.

MEMBER CORRADINI: But I guess my only point is that -- I was holding this one until later, but it's just striking me that I understand how the cooling would be initially enhanced, but if anything, if I start touching I would get some circumferential heating issues that -- and I'd get a blockage. And I'm back to Sam. This is still the limiting location. I mean, I was letting him go with this because I figured it would have to be the limiting location just because eventually you're going to run into the next rod.

MR. DUNN: I think my expectations are -- you're talking about something on the order of coplanar blockage where we get a lot of coolant up to that rod --

MEMBER CORRADINI: Yes.

MR. DUNN: -- and the energy can't be transported out of that rod to adjacent rods.

MEMBER CORRADINI: Yes.

MR. DUNN: If we got something on the order of 5 by 5 or 7 by 7 coplanar blockage within a fuel bundle, that would be difficult to cool. But if you look at the axial distribution at rupture, it's up here, down here. And so, the coolant varies around like that, like a snake through a path.

MEMBER CORRADINI: Okay. All right.

MR. DUNN: And there are tests --

MEMBER CORRADINI: I'll be quiet.

MR. DUNN: -- though not many bundle tests --

CHAIRMAN ARMIJO: Well, once it ruptures, you got direct cooling of the fuel.

MEMBER CORRADINI: Okay. So, now we're getting to my point. So, repeat your last point?

MR. DUNN: My last point?

MEMBER CORRADINI: About there's not many bundle tests.

MR. DUNN: That's true. There's not very many bundle tests with characteristic cooling measurable.

MEMBER CORRADINI: Okay.

MR. DUNN: Okay? There are FLECHT tests in which coplanar blockage has been put in place, and distributed blockage. There's FEBA tests in which that's been done. What's missing today would be bundle tests with the possibility of fuel relocation.

MEMBER REMPE: What was the second, sir? He said FLECHT. And what was the second?

PARTICIPANT: PHOEBUS.

MEMBER REMPE: PHOEBUS? It's PHOEBUS is what you're talking about over in France, or --

MR. DUNN: What? Did I mis --

MEMBER REMPE: Was it PHOEBUS was the second place that you mentioned where they did --

MR. DUNN: F-E-B-A.

MEMBER REMPE: FEBA? Okay.

MR. DUNN: I'm sorry, ma'am. I couldn't hear you very well.

MEMBER REMPE: Oh, sorry.

CHAIRMAN ARMIJO: Okay. Let's move on.

MEMBER SHACK: Sorry, Sam.

CHAIRMAN ARMIJO: Oh, that's all right.

MEMBER SHACK: Well, just to close it, it is interesting to note that in the RIL the last paragraph sort of addresses these issues on the ballooning and the blockage and it sends us off to Grandjean's review where he says that our current ballooning models underestimate potential blockage which would contribute to -- and I was going to ask whether -- the RIL sort of indicated we were going to go off and work with the French on this, and then is there any progress on that?

MS. FLANAGAN: I certainly don't have any information on that in this presentation, but I can make a note to get back on that.

MEMBER SHACK: Okay. You're not off the top of your head aware of efforts?

MS. FLANAGAN: To redo calculations or to revisit conclusions?

CHAIRMAN ARMIJO: Experiments.

MEMBER SHACK: Well, either conclusions, experiments, to address the criticism that our current estimates of coolant flow blockage are un-conservative, which is Grandjean's conclusion about the way we do it now.

MS. FLANAGAN: Okay. I'll make a note of that. And like I said, I don't have material here.

CHAIRMAN ARMIJO: Okay. Michelle, just keep going.

MS. FLANAGAN: Okay. So, as I mentioned, the program conclusions and the results of the experimental program were then used to reference a regulatory context. And so, regarding the treatment of the ballooned region within the rulemaking to revise 50.46, the report that was provided and is the subject of this briefing uses the observations of the test program to support the position that the time and temperature limit that was developed based on ring compression data to limit oxidation should be applied uniformly into the entire rod and that the provisions within the guidance that were outlined in the existing rule that used average wall thicknesses and double-sided oxidation should continue to apply in the rupture region to calculate the ECR value.

MEMBER SHACK: I had a question on this one. You used an average wall thickness. That was a measured average wall thickness, or was that computed the way we would do it if we were doing a calculation?

MS. FLANAGAN: Measured.

CHAIRMAN ARMIJO: So, do you have to do a ballooning test to come up with that measured average wall thickness, or is that something that you can calculate?

MS. FLANAGAN: It is a calculation, and there's models that predict the ballooning strain given pressure and temperature conditions. And what we did in this program was look at what the actual experiments measurements were and then plotted the values relative to the actual observed measurements. Did that answer --

DR. BILLONE: There are two reasons we did that. One is this is all ZIRLO you're looking at, and the ballooning strain correlation for ZIRLO is proprietary and wasn't really available to us. We wouldn't be able to publish those results.

Secondly is we wanted to take that large scatter in the correlation prediction out of this particular database so we could specifically look at the effects of oxidation. So, we literally measured the outer circumference of the post-balloon sample and post-oxidized sample and had models to convert that into a circumferential strain.

CHAIRMAN ARMIJO: Okay.

MS. FLANAGAN: So, the next way that we used the next regulatory statement or the regulatory conclusion that's in the document is looking at the extrapolation of these research findings to new cladding alloys and lower oxidation temperatures. So as you recall, our test procedures and the regulatory guides, which we came earlier this month with the full committee and in May to the subcommittee, presented test procedures to do ring compression tests that could be used to develop oxidation limits. And when we look at -- the subject report discusses and supports a position that the embrittlements developed for new cladding alloys and at lower oxidation temperatures based on ring compression tests may be applied uniformly in the entire rod with the provisions of the balloon outlined in the existing rule.

The results of this program didn't reveal any reason that oxidation embrittlement limits developed from ring compression tests on non-deformed cladding material should not be indicative of trends in the degradation of ballooned and ruptured regions. So, said in another way, the results of this program did not reveal any reason that materials which demonstrate improved embrittlement performance in ring compression tests wouldn't also demonstrate improved performance in the ballooned region. And then new cladding alloys therefore would not be required to conduct an integral LOCA test program like that which was done here to specifically characterize the balloon region properties.

So, another sort of regulatory conclusion, or a description that was in the document was looking at alternate performance metrics for the ballooned and ruptured region. And this is really because there's been a lot of discussion of alternate metrics for fuel rod performance under LOCA conditions within the international community. And these alternate performance metrics for the most part rely on detailed knowledge of LOCA loads, are complex, experimental and modeling research programs. And so, the statement that's expanded on in this report is that the state of the art doesn't support a regulatory position based on these proposals in the near term. And therefore, pursuing more complex performance metrics, more complex modeling approaches for the ballooned and ruptured region isn't recommended at this time.

Now, earlier in the presentation I had the text that referred to the ballooned region from RIL 0801. And given that now we have additional information, we've made experimental observations and we have a more specific conclusion about the balloon, it would be appropriate to revisit the RIL and update this statement and possibly expand on it. So, in preparation for this meeting, we transmitted a draft update to the RIL. Now, by the time we're here in December maybe this would be expanded, but the one I want to point out here is an additional two sentences which could be added to the RIL to restate the conclusion that this report finishes with, and then this RIL would reference the subject report of this meeting as a point or two a part of the technical basis.

And so, in this case the statement that was there in the original RIL would remain. We still have no criteria that would ensure cladding ductility in the balloon. And we'd note that the bending moment and failure energy were measured using four-point bend tests or as-received pre-hydrided and irradiated material in order to determine the resistance to fracturing. I don't know if I need to read this, but basically what I want to point out here is that given this new information, it would be appropriate to make an update to the RIL that would revisit the conclusion and reference the report.

MEMBER SHACK: Now, this revision is a

little different than the one you submitted to us in the previous revision.

MS. FLANAGAN: It is. That might be an accident on my part in preparing the slides, because do you mean that it's different language --

CHAIRMAN ARMIJO: The language --

MEMBER SHACK: The wording's different.

CHAIRMAN ARMIJO: Yes.

MS. FLANAGAN: Oh, it is?

MEMBER SHACK: Yes, the context is roughly the same.

MS. FLANAGAN: Okay.

MEMBER SHACK: But, you know, somebody's been editing.

MS. FLANAGAN: Yes.

MEMBER SHACK: One way or another.

MS. FLANAGAN: We do revisit this a lot. And I think that's why there was a draft on what was submitted. And that wasn't part of the public -- it's very pre-decisional. But the main point that I want to make is that it would be appropriate to update the RIL based on this new information considering that we are calling it the Technical Basis to Apply the Criterion No. 1.

So, I'm at the end of my presentation. And the conclusions that I want to end with are to point out or to state that a completed integral LOCA test program has generated new data and understanding of the mechanical behavior of ballooned and ruptured fuel rods. These results indicate that limiting oxidation in the ballooned region continues to be appropriate. And the results also indicate that applying the hydrogen-based embrittlement limit in the ballooned region preserves mechanical behavior to that of as-fabricated rods at 17 percent.

And a technical basis document has been drafted which would be a supplement to the technical basis, and particularly focus on treating the ballooned region within the proposed rulemaking. And then updates to RIL 0801 have been proposed which incorporate the findings of this recent research into that document.

MEMBER BROWN: Does that mean that -- your third bullet?

MS. FLANAGAN: Yes.

MEMBER BROWN: The way I read that and what they seem to have said is that the 17 percent criteria satisfies the thing regardless of whether you do the new rule or not; in the 17 percent, the old rule?

MS. FLANAGAN: Seventeen percent is the old rule for as-fabricated cladding and it would be the limit for the new rule as well for as-fabricated cladding.

MEMBER BROWN: Okay. I guess I've missed, I've forgotten what's --

MEMBER CORRADINI: Yes, I think what she's saying is --

CHAIRMAN ARMIJO: But the criteria for irradiated stuff would follow the same criteria that the un-ballooned region would have to meet.

MS. FLANAGAN: The old criteria said that any fuel no matter what its burnup, no matter what its hydrogen content should be subject to 17 percent. And this new rule says that as you increase your hydrogen content you should reduce that limit. And so, what I mean when I say as-fabricated rises at 17 percent is that we continue to find that 17 percent is appropriate around -- that value is appropriate for actuation system cladding. And the only thing that's new is what's going on with irradiated material.

MEMBER BROWN: Okay. I'm trying to understand. If you start out with 17 percent as-fabricated, that changes as you irradiate and operate, but it's going to -- I mean, you've got what you've got when you start out with 17 percent. I guess I've lost the bubble somewhere between the first meetings and this meeting as to what the new rule is going to accomplish. Does that mean you're going to put additional limits on the total fuel burnup based on hydrogen?

MS. FLANAGAN: The 17 percent is a value that's accumulated during the accident, so it's not something that accumulates during operation. It's where when I start an accident I have certain properties and I have certain characteristics of each fuel rod, and in the new regulation where I start the accident. The properties of that fuel dictate how much oxidation I can subject that particular rod to during the accident.

MEMBER CORRADINI: Would slide 5 be a good graphic to help him? It's qualitative, but isn't that the criteria?

MS. FLANAGAN: Right. Yes. So, what

this -- here, the y-axis, the oxidation limit is referring to something that takes place during the transient. And then the x-axis could be considered for a particular rod where am I starting into the transient, and therefore what should I limit that particular rod to?

MEMBER SHACK: Let me try a different explanation, Charlie. This way with burnup it'll be at least as good as fresh fuel would be.

CHAIRMAN ARMIJO: Can you repeat that, Bill? I was talking.

MEMBER SHACK: With their current way, the way they're going to treat burnup and accumulate it from hydrogen, they'll at least assure that they have performance equivalent to fresh as-fabricated stuff at 17 percent. So, you know, we don't really know that that's good enough, because we don't really have metrics that tell us that, but we know that it's going to be as good as that.

MEMBER CORRADINI: The last part -- I was with you all the way until that last -- you were doing very well. Then you --

MEMBER SHACK: The question always is how do I know what is good enough in the ballooned region? And since I don't know all the loads and everything -- and it makes it difficult to provide complete assurance, but --

MEMBER CORRADINI: But the way the rule is -- the way I interpret it was, the reason I asked them to go back to No. 5 is they are essentially degrading, they are essentially being more restrictive as the burnup goes up so that it would behave no worse than fresh fuels.

MEMBER SHACK: Right.

MEMBER CORRADINI: Then you added that sentence that got me --

MEMBER SHACK: Well, should have stopped. Like Michelle, I should learn not to answer when I don't have to.

MS. FLANAGAN: So, I've covered all of the slides. And I know that we have additional time on the schedule. I think I have until 11:00?

CHAIRMAN ARMIJO: 11:00, yes. But you're moving right along, unless you have another handout.

MS. FLANAGAN: I do not.

CHAIRMAN ARMIJO: Well then, you know what I suggest we do? Unless there's questions from members, I think we can take a 15-minute break. And why don't we reconvene at 10:20?

MS. FLANAGAN: And then should we be back up here or are we going on to the --

CHAIRMAN ARMIJO: Well, I think we're finished with your presentation, and we could move right into industry remarks.

MS. FLANAGAN: Okay.

CHAIRMAN ARMIJO: And, but I'd appreciate it if you'd obviously stick around.

MS. FLANAGAN: Oh, of course. Yes. I just wanted to know if I needed to be here, or over there.

CHAIRMAN ARMIJO: No, I think you've covered your presentation very well.

MS. FLANAGAN: Okay.

CHAIRMAN ARMIJO: Thank you very much. And so, let's -- Well, we got a little more time. Yes, let's get back at 10:25. Give ourselves another few minutes here. 10:25, please.

(Whereupon, at 10:04 a.m. off the record until 10:25 a.m.)

CHAIRMAN ARMIJO: Let's reconvene. Okay. EPRI?

DR. YUEH: I think Gordon from NEI is going to make a brief statement first.

CHAIRMAN ARMIJO: All right. We'll have Mr. Clefton from NEI, and then Dr. Yueh.

MR. CLEFTON: We good to go?

CHAIRMAN ARMIJO: Go ahead.

MR. CLEFTON: Okay. My name's Gordon Clefton. I'm with NEI. I'm representing consensus standpoint from the industry. We've had a cooperative effort of the vendors, the fuel vendors, utilities, owners' groups, and cooperation that's been very good supporting this rulemaking.

What we wanted to do is complement the fact that we are supportive of the laboratory work that -- Ken's going to be talking about that quite a bit here, and very supportive of the idea that the Chairman's offered that we'll have multiple meetings in the future to address the details of where we're going with this rulemaking, that we think that there's an opportunity for the industry to provide resources and assistance in optimizing the rule so it's useable and that we have the best industry input that we can put into it. And that comes with communications, either with the ACRS, with work shops, or with public meetings that we have. Certainly encourage that.

We didn't bring any slides today as we know we were on a tight schedule for the agenda of this, and we'll just go right into Ken's presentation. If we do have more opportunity to talk afterwards, I'd be happy to address. And we've got Tom, our chairman, from the reg tech from EPRI to address some language issues, a quick summary of where we are with 50.46 Charlie aspects. And of course we have the staff from AREVA, General Electric and Anatech to answer questions; if you come up with us. So, we have resources in the audience, not just Ken up here on the table.

MEMBER SHACK: But I take it you have specific problems with some of the language in 50.46c?

MR. CLEFTON: In quick summary, we think that we're supportive of the concept of bringing it back to coolable geometry in the rule and putting the details in the regulatory guides underneath, which is the direction that we've been progressing over the years since the ANPR comments and suggestions gone in. So, we have some specific comments addressing that. And then we'd certainly like to talk about the implementation plan for it because of the resources available at the NRC and the resources available in the industry. We think that deserves some attention so that we don't get into a position that we collectively set a schedule that's not attainable because of resource limitations.

Ken?

DR. YUEH: Thank you for the opportunity to present our view. We only notice this document availability last week, although it was issued I think the end of May. We didn't see this, notice it. It was accidently discovered by one of our members, and so we didn't have a lot of time to through the document. I will only be providing almost a first impression of, you know, what we think of the argument presented in the document.

As Gordon Clefton stated, the industry is supportive of this type of research. I think, you know, this type of research being conducted by other research organizations and I think the data reported in the mechanical property of the, you know, ballooned and ruptured region in some ways is very similar to what other people have observed, including earlier studies conducted at ANL. And it's specifically a lot of quench survivability tests, and more recently Japanese work with restraint.

You know, we made this slide up before we saw the latest presentation which included several more data points, hydrogen pre-charge. I think there's still some questions I think need to be answered with the data. You know, so far we have two data points, but we're seeing a substantial difference with, you know, hydrogen pre-charge compared to the irradiated, particularly at the lower ECR where you have a sample, irradiated sample at zero ECR essentially depart greatly from the as-fabricated material.

You know, the international bodies, the research they do are geared towards a more -- I guess a generic requirement of coolability. So, not necessarily -- you know, this type of research not necessarily tied to ductility.

The next few slides I will go over some of the published data primarily from the original ANL study to support the two points that we want to make in the last slide.

MEMBER SHACK: Are you going to explain that second bullet?

CHAIRMAN ARMIJO: The second statement?

DR. YUEH: The minor -- which one?

MEMBER SHACK: The mechanical strength.

PARTICIPANT: Independent of hydrogen concentration.

CHAIRMAN ARMIJO: Yes, independent of hydrogen.

DR. YUEH: When we saw the original draft and the results, even though the irradiated material had 200 ppm of hydrogen, the result is more or less consistent with as-fabricated material without the hydrogen. Now, there is some difference because I think the irradiated tests, the four-point bend tests were conducted room temperature, while the as-fabricated material were conducted 135. So, that could explain why --

MEMBER SHACK: Well, they had one test at room temperature.

DR. YUEH: No, I think all of the irradiated material was --

MEMBER SHACK: No, I mean the as-fabricated tests. I thought they had one --

DR. YUEH: Yes, they had one.

CHAIRMAN ARMIJO: What chart are you referring to that --

MEMBER CORRADINI: Unless you're going to get back to it later.

CHAIRMAN ARMIJO: Oh, I'm just trying to make sure I understand what we're talking about.

MEMBER REMPE: So, you're talking about like just slide 19?

CHAIRMAN ARMIJO: Yes, I think it's slide 19 of Michelle's slides.

DR. YUEH: But the difference, I think it's very small, if you look at the irradiated and that. So, I think it's within the data scatter.

MEMBER SHACK: Well, I think you'd have a hard time drawing a strong conclusion, but the tendency seems to be it's the bottom of the scatter. I mean, at least that's the way I'd interpret it.

CHAIRMAN ARMIJO: So, you'd say those three diamonds, because they're at 30 degrees C could be equivalent to the --

MEMBER SHACK: One-thirty-five.

CHAIRMAN ARMIJO: Yes.

DR. YUEH: Yes, the difference is very small. So, you know, based on this and some of the earlier studies done at ANL suggest to us that it is hydrogen independent. And I guess one of the slide even -- you know, I will hopefully, you know, show that.

MEMBER SHACK: But the ANL 30 degree test is --

DR. YUEH: Is the same as -- yes.

MEMBER SHACK: -- the same as the one 135?

DR. YUEH: Yes.

MEMBER SHACK: I mean, we are arguing over something with a fair amount of scatter and a relatively small number of data points.

DR. YUEH: Very small difference.

MEMBER SHACK: But the pre-hydrided material seems to be --

CHAIRMAN ARMIJO: Well, there's a clear difference there.

DR. YUEH: Yes, but, you know, I think we do not have a full understanding of what is happening. If you look at the irradiated material, you have one data point at zero ECR that performs --

CHAIRMAN ARMIJO: Yes.

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

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

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

MEMBER REMPE: Right.

DR. YUEH: But because we only have limited number of data points and our statements were prepared before we saw these data points, but primary there's lot of scatter with the irradiated material where you have an existing oxide. So, and because our own test shows that there could be an 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.

MEMBER SHACK: But again, there's no hydrogen? I mean, that's all --

DR. YUEH: There is no hydrogen except in the region above and below the burst.

MEMBER SHACK: Right. I mean, which you pick up during the --

DR. YUEH: Yes. Yes, this is just to demonstrate, you know, even the 17 percent criteria still provide a lot of margin to survive in the quench. And I think in an accident immediately after you lose the current where you have the greatest decaying heat, you know, this essentially guarantees, at least immediately after, that you would have -- maintain coolable geometry.

CHAIRMAN ARMIJO: Ken, could you explain this chart that we're looking at here? I'm not familiar with this chart.

DR. YUEH: Okay. This is where they have a LOCA integral sample. They take it through a LOCA cycle and then --

CHAIRMAN ARMIJO: So, the peak temperatures on the bottom scale?

DR. YUEH: That's right. It's inverse. It's one over.

CHAIRMAN ARMIJO: Yes.

DR. YUEH: So, the higher temperature is on the left-hand side.

CHAIRMAN ARMIJO: Yes.

DR. YUEH: So, this trend is also consistent with the results Michelle reported about the oxidation has an impact on the quench survivability and the strength.

CHAIRMAN ARMIJO: And these are un-irradiated samples?

DR. YUEH: Un-irradiated samples.

CHAIRMAN ARMIJO: Not pre-charged with hydrogen? They put through it a transient and then there's -- just quenched. And if it fractures or doesn't fracture is there any load on it, or is it just --

DR. YUEH: There's no load on it. So, this chart serves to demonstrate that, you know, beyond quench survivability there is still quite a bit of margin.

CHAIRMAN ARMIJO: Yes.

MR. CLEFTON: And that's with the existing rule.

CHAIRMAN ARMIJO: But with where we're

going with the hydrogen influence and everything else, that dotted line of the 17 percent boundary would move to the -- that would change with the new rule, or the new criteria.

DR. YUEH: Okay. You know, I'm not so sure whether it would move or not. You know, if I can go to the next slide, in the ballooned region, you know, even though the material was not pre-charged with hydrogen they have measured a lot of hydrogen above and below the burst. And in fact, almost the higher ones it's almost close to 2,000 ppm hydrogen.

And this chart serves to demonstrate samples with different amount of hydrogen in the two rings above and below the burst. And the data is showing that there is no dependence on hydrogen in terms of the energy the sample survived after the test. So, after the test they done a Sharpie impact test. This is the energy absorption shown by the different samples. And the data in color, they all survived 0.3J impact test. But the different colors are showing different hydrogen content. And everything is so intermeshed together, you know, there does not appear to be any dependence on hydrogen.

MEMBER CORRADINI: I'm unfamiliar. What is the test being used here in comparison to the test that's being used in the Argonne data? I'm sorry that I don't understand.

DR. YUEH: In this test after the integral LOCA cycle they put it on an impact test fixture.

MEMBER CORRADINI: You mean a Sharpie test?

DR. YUEH: Sharpie test. And then --

MEMBER CORRADINI: Is that as definitive as what I thought was the ring test?

DR. YUEH: It's a different metric.

MEMBER CORRADINI: Well, I'm not a mechanics and materials type of person, so I'm going to turn to --

CHAIRMAN ARMIJO: It's another way of breaking things, but --

MEMBER CORRADINI: But I thought --

CHAIRMAN ARMIJO: But, you know, typically you don't use a round tube on a Sharpie test.

MEMBER CORRADINI: Well --

DR. YUEH: It is a round, yes.

MEMBER SHACK: Sharpie is kind of wrong word. I mean, it's an energy absorption kind of --

CHAIRMAN ARMIJO: An energy absorption kind of test, but you know --

MEMBER CORRADINI: It's a hammer test. You hold the thing on a pendulum and it goes whack. Isn't that what it is?

CHAIRMAN ARMIJO: Correct.

MEMBER SHACK: Yes.

MEMBER CORRADINI: But the thing is, Ken, you know, here there's no interaction between the hydrogen and the thinning and the oxidation in that thinnest part. I mean, you're getting the hydrogen over there in the peaks, but you're really missing that whole interplay of the hydrogen and oxygen in the thinning.

DR. YUEH: I agree this does not have that element in there, but it is -- you know, it's not a pure four-point bend test. When the hammer impact presumably in the ballooned region, it will induce a bending moment as well, but you know, the load should be transmitted to the ring where a lot of hydride is. It's not exact the same geometry, but I think some of the bending moment is still there.

DR. BILLONE: But you have no hydrogen in the rupture region.

DR. YUEH: That's true. I acknowledge that.

MR. ALVIS: Mr. Chairman, can I make a comment?

CHAIRMAN ARMIJO: Sure.

MR. ALVIS: This is John Alvis from Anatech. And I'm sure Dr. Billone will be able to confirm this, but I believe these tests were actually done in situ. So, they ran the tests, they ran the rod segment through an integral cycle, a LOCA loop. And they would hit -- they had the little -- their hammer in place. And so, no, the samples would never actually balloon in the same location, but the test was conducted in such that the hammer would always hit the same location. So, I don't think you can draw a quantitative -- you know, use these values quantitatively, but qualitatively I think you can. And as Ken was mentioning, I think it shows that for -- you know, because even though some regions in the balloon would have more hydrogen content due to -- hydrided than others, the fact is that the load's still going to be transmitted to the weakest point. And you can still see that there's really no trend in the data with the hydrogen increase.

MEMBER REMPE: Someone said; I think it was the person on the phone, that there was no hydrogen in the ballooned region?

DR. YUEH: There's no hydrogen in the burst region.

DR. BILLONE: That's correct. Mike Billone.

MEMBER REMPE: Okay. Mike?

DR. YUEH: But there will be hydrogen above and below it up to almost 2,000 ppm.

MEMBER REMPE: And why was there no hydrogen? What was the phenomenon that made no hydrogen occur in the balloon? Just because it wasn't in contact?

DR. YUEH: Because it's a fresh cladding, so there was no hydrogen before the test. The hydrogen was picked up --

MEMBER REMPE: Okay.

DR. YUEH: -- above and below, picked up

during the LOCA --

MEMBER REMPE: Okay.

DR. YUEH: -- temperature exposure.

MEMBER REMPE: Okay.

CHAIRMAN ARMIJO: And that's from the hydrogen generated by the reaction during the test?

DR. YUEH: Yes.

DR. BILLONE: So, Ken, this is Mike Billone. This isn't really different than our data set where we got failure in one of two locations, either the higher hydrogen region or in the zero hydrogen region. It just basically shows a degradation of the material with oxygen.

DR. YUEH: Yes, yes. I'm not saying there's an difference, because, you know, I've stated early on that your data is consistent with, you know, other data.

DR. BILLONE: But be careful about no hydrogen dependence until you put hydrogen in the ballooned region, which is in your next couple of slides.

DR. YUEH: Well, you know, I mean, as I said, we prepare this presentation without seeing your latest two data points with the hydrogen pre-charge. We did not see that in the report that was published.

MR. CLEFTON: Last week.

DR. YUEH: Yes.

MR. CLEFTON: Go ahead.

DR. YUEH: This is the same data set, just highlight different tests. Here I think they have also done some tests where the sample was not deformed and the test is showing consistent, you know, with the samples that were deformed. When I say "deformed," you know, ballooned and maybe a burst. Okay. The trend is similar. There's very little difference.

And then the other colored data points are these test results from JAEA where they do the quench survivability test with restraint. In this plot they have one data, one sample failed. I think the restraint is up to 500 newtons. Okay. That's what they --

DR. BILLONE: Five-hundred and forty.

DR. YUEH: Yes.

MR. ALVIS: Yes, John Alvis at Anatech. Yes, it's partially restrained. And so, the maximum restraint they get on those tests was 540 newtons.

CHAIRMAN ARMIJO: Is that the Nagase papers? I've seen a couple of papers, but okay. Then they do an axial restraint?

PARTICIPANT: Yes, during the quench.

CHAIRMAN ARMIJO: During the quench. Okay.

DR. YUEH: Okay. And then there's a whole bunch of -- a series of samples that survive the quench, so certainly within the 17 percent limit.

DR. BILLONE: Ken, may I make a comment on that slide?

DR. YUEH: Okay.

DR. BILLONE: I only want to talk about the JAEA data, which are the triangles. When you impose the 540 newton maximum load, you're doing a pass/fail test.

DR. YUEH: Yes.

DR. BILLONE: So, the sample that passed may have a strength anywhere from 550 to 10 times that amount. And if you had done what we did, which would have -- I mean, we do a test to failure, not pass/fail tests. And when we do that, we see a significant hydrogen effect. And to say it another way, if we limited our bending to 1 milliliter, all of our samples that Michelle showed would have survived and you would have concluded that there's no oxygen effect because in a pass/fail test all you know is you either passed it or didn't pass the test. So, I'm not sure that you can use a pass/fail test to conclude that there's no hydrogen effect. But keep going.

DR. YUEH: Well, yes, but I'm not concluding that there's no hydrogen effect from these tests, right?

DR. BILLONE: Okay.

DR. YUEH: You know, we came to that conclusion because your original test data -- well, not yours, but Studsvik test results, you know, is sort of in line with your test results.

DR. BILLONE: Okay.

DR. YUEH: And the Studsvik data had 200 ppm of hydrogen and your data had no hydrogen. And then they seemed to have the same capability for energy absorption or, you know, bending moment.

DR. BILLONE: No, I understand.

DR. YUEH: Yes.

DR. BILLONE: Keep going.

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

DR. BILLONE: I just wanted to offer some clarification.

DR. YUEH: Okay. And also, you know, these early data, I mean, there's a lot of data there even though it's not in the ballooned region, the burst region. But you know, it's in the adjacent area, which, you know, when you impact the sample, will see a load. And that data is showing, you know, a suggestion there is no dependence on hydrogen.

Just couple of points on the final slide. You know, from our point of view, because right now the draft rule language is primary based on ductility, maintenance of ductility, and here in the ballooned region clearly there's no ductility. You know, and the justification for that to be covered in a ductility rule is, you know, the argument made is based on strength. And so, I think, you know, it's not consistent with the principles of the intent of the draft rule, the language that it is now. And because, you know, it is in the 10 C.F.R., it is a law. So, we would recommend that maybe the ductility portion of the rule be relocated to the reg guides.

MEMBER SHACK: A modest modification.

DR. YUEH: Yes, because right now we see that, you know, it's an exemption, right? It's an exception to the rule --

CHAIRMAN ARMIJO: The balloon, even though it's not ductile, it's exempted on the basis of strength?

DR. YUEH: Yes, so it's not meeting the ductility requirement. It's just by based on strength.

Okay. And the last point is that as, you know, the Chairman brought up earlier, you know, the key is coolability, and obviously the ballooned and burst region is more limiting. And if the same thing can be applied there, why can it not be applied to the rest of the rod? Now, we, you know, came up with this point because the data, initial data is just in that -- the energy absorption in the bending moment is, you know, independent of hydrogen. Okay. So, we did not see those two data points before we draft this.

And I think it's still -- the two data points, I think it's not enough to say definitively how much dependence there is on hydrogen, especially given the irradiated material with 200 ppm of hydrogen behaved almost the same as the as-received material.

MEMBER ABDEL-KHALIK: Certainly two data points is better than none.

DR. YUEH: Yes, but we still -- there are other data points out there suggesting that if there is a dependence, it's not very strong. And certainly when people do tensile tests with hydrogen-charged material, the strength does not decrease very much.

I think that's all the slides I have.

CHAIRMAN ARMIJO: Yes, well, the issue there of the inconsistency with finding the ballooned region to be okay based on a strength criteria and the -- but requiring that the non-ballooned region be accepted on a ductility criterion is not consistent. And you're saying why not do it all on strength? Is that what you're second bullet said?

DR. YUEH: Well, as an alternative.

CHAIRMAN ARMIJO: I'd like to hear from the staff on that. What are your thoughts?

MR. CLIFFORD: If I may? This is Paul Clifford, NRR. The way the draft rule has been formulated is consistent with the way the rule exists today, and that is the preservation of ductility. Now, the performance-based metric will be maintained as that of demonstrating that you have ductility.

But the area of confusion I think that's being alluded to in this bullet is that in fact there will not be a specific performance-based requirement inside the burst region. Instead, we attempted to demonstrate that by preserving ductility outside. In other words, by limiting the time and temperature that a fuel rod can undergo during a LOCA, that by limiting that time and temperature based upon the ductility, you are in fact maintaining a reasonable degree of strength inside the burst region. So, you do not need a separate independent performance-based metric.

But, there is some concern in how we write the language, because if we were to specify that you need to maintain ductility, then it could be argued that even though there is an implicit degree of strength being maintained, and we feel that's adequate, that we're not physically maintaining ductility. So, that's something that we were going to have to deal with as we move forward and formulate the actual rule language.

CHAIRMAN ARMIJO: Yes, it's tricky, because effectively it's an argument that says if we protect the non-ballooned region and demonstrate ductility there, here are a bunch of arguments that says we don't have to measure or confirm ductility in the ballooned region. But it's arguments based on strength --

MR. CLIFFORD: Right.

CHAIRMAN ARMIJO: -- these other tests. Wasn't quite clean, but --

MR. CLIFFORD: We will need to rely upon our Office of General Counsel to make sure that we get it right when we write the rule language.

CHAIRMAN ARMIJO: Yes, that everybody understands it. Yes.

MEMBER BROWN: I was just curious as to why the OGC is going to make that as opposed to making the technical argument as to how the language ought to be.

CHAIRMAN ARMIJO: Well, they'll make the technical argument. And the issue is whether that language conforms with the ductility requirement in the rule.

MR. CLIFFORD: Right, we need to make sure that we have a level of detail so that it can be enforceable and, you know, specifically calculated and applied without interpretation.

CHAIRMAN ARMIJO: Well, you bring up a good point, Ken, there is an inconsistency that's going to have to be addressed and worked out.

Okay. Do you have anything --

MEMBER SHACK: You mentioned these tensile tests. Now, are these tensile tests with hydrogen and then subjected to a LOCA cycle and oxidation --

DR. YUEH: No.

MEMBER SHACK: -- or just hydrogen and -- so you're saying if I just put hydrogen in and I don't bother to oxidize, then it doesn't make any effect on strength?

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

MEMBER SHACK: Okay. But it's a very different kind of --

CHAIRMAN ARMIJO: But that's a different thing, yes.

DR. YUEH: You know, it is. I think I don't have the data, you know, with me because we didn't have a lot of time to prepare this, because as I said, we discovered this document accidently last week. I think some other people may have done something with hydrogen pre-charge. And I think I heard, you know; I don't have the data with me, as I said, that the strength even after the LOCA cycle is not very significantly impacted by hydrogen.

CHAIRMAN ARMIJO: Even after the LOCA?

DR. YUEH: After the LOCA. It's not as strongly dependent as ductility is.

CHAIRMAN ARMIJO: Right. Well, that's really what the Argonne tests -- you know, if they could have measured ductility, they would have measured ductility. But they couldn't, so they measured strength.

Any other comments or questions from the members?

(No audible response.)

CHAIRMAN ARMIJO: Okay. We have people on the bridge line, quite a few people. So, if there's any questions or comments from people on the bridge line, now's a good --

PARTICIPANT: Make sure they're open.

CHAIRMAN ARMIJO: Chris? Where did Chris go?

MEMBER CORRADINI: He went to make sure it's open.

CHAIRMAN ARMIJO: The bridge line's open. And if you're on the line and you wish to make a comment, please identify yourself.

MR. MONTGOMERY: Mr. Chairman, this is Robert Montgomery.

CHAIRMAN ARMIJO: Hello, Robbie.

MR. MONTGOMERY: How are you?

CHAIRMAN ARMIJO: Very well, thank you.

MR. MONTGOMERY: Thank you for giving me the opportunity to speak. I'll note my new affiliation. I'm currently employed at Pacific Northwest National Labs.

I just wanted to note a point that Mike Billone made regarding the Japanese data on quench and axial force and load. Their data set is quite comprehensive and it was not developed just purely on a pass/fail basis. There is a significant amount of data that was taken prior to the development of the 540-newton limit that includes tests ran with unrestrained or unlimited load. And they developed basically a load versus hydrogen dependency for pre-hydrided samples oxidized at various level of oxidation. So, I just wanted to make that point clear. The 540-newton limit came after that data set was developed based on other structural analyses to determine a load limit on the assembly based on a load calculation and defined at the maximum foreseeable load on the fuel rods due to quenching. The axial load would be limited to about 540 newtons. It would be actually a little lower than that -- a little higher than that and they --

CHAIRMAN ARMIJO: Yes, so --

MR. MONTGOMERY: So, I want to make sure that that data is represented fairly in this presentation.

CHAIRMAN ARMIJO: Now, is that published work, Rob?

MR. MONTGOMERY: Yes, it is. Yes, it is. Nagase from JAEA has published that work and I believe I've shown those in the past, that data, at some of the previous ACRS meetings.

CHAIRMAN ARMIJO: Yes.

MR. MONTGOMERY: They show the fracture load as a function of hydrogen --

CHAIRMAN ARMIJO: And they ran a lot of those tests to failure? They didn't just stop at the 540?

MR. MONTGOMERY: That is correct.

CHAIRMAN ARMIJO: Okay. And the other thing, were all of them just a simple axial loading? Was there any kind of bend testing going on in those programs?

MR. MONTGOMERY: No, there were not.

CHAIRMAN ARMIJO: Okay.

MR. MONTGOMERY: Those programs all focused on the axial load.

CHAIRMAN ARMIJO: Okay. Well, look, I appreciate that point and maybe, Chris, we can dig up some of those papers. Members may want to take a look at them. I do.

Okay. Thank you, Rob.

Anyone else on the bridge line wishes to make a comment?

(No audible response.)

CHAIRMAN ARMIJO: Okay. Anyone within the room? Do you wish to make a comment?

(No audible response.)

CHAIRMAN ARMIJO: No? Okay.

Okay. Well, look, with that, I don't think we have any more business.

Committee members, one last chance?

(No audible response.)

CHAIRMAN ARMIJO: Okay. Well, I'd like to thank the staff and EPRI for their presentations. We have a pretty complicated set of rule. We have a pretty complicated set of reg guides and issues. And I think it's going to take a lot of communication to sort out all these things out. Things are going out for public comment now. That's a time for everyone to get their views on the record. And we will be reviewing the reg guides after the public comment period, and as well as the draft rule language before and after. So, we've got quite a bit of work ahead of us, and I hope everybody sticks with it.

With that, I'll adjourn the meeting. Thank you.

(Whereupon, the meeting was adjourned at 11:02 a.m.)

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

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

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

301-415-1024; tara.inverso@nrc.gov

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

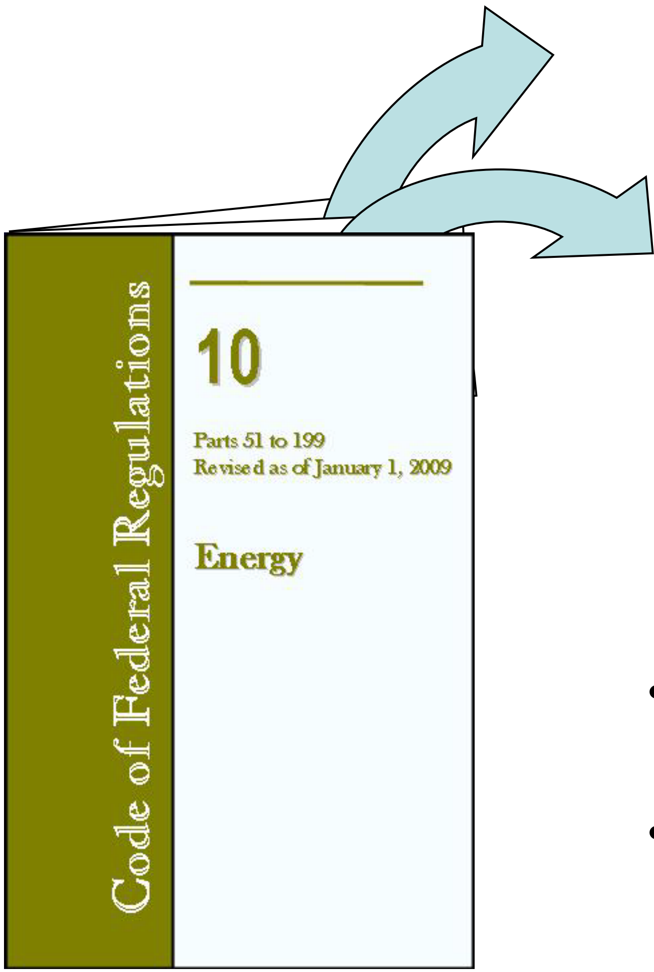
Michelle Flanagan
Michelle.Flanagan@nrc.gov
Division of Systems Analysis
Office of Nuclear Regulatory Research

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.

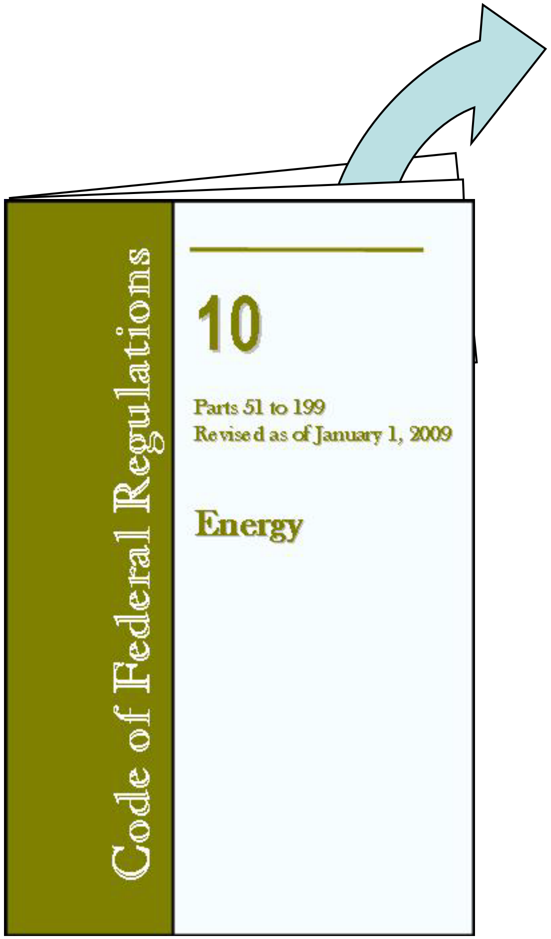
Appendix A of 10CFR Part 50, General Design Criteria 35 Emergency Core Cooling

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**)

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

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:

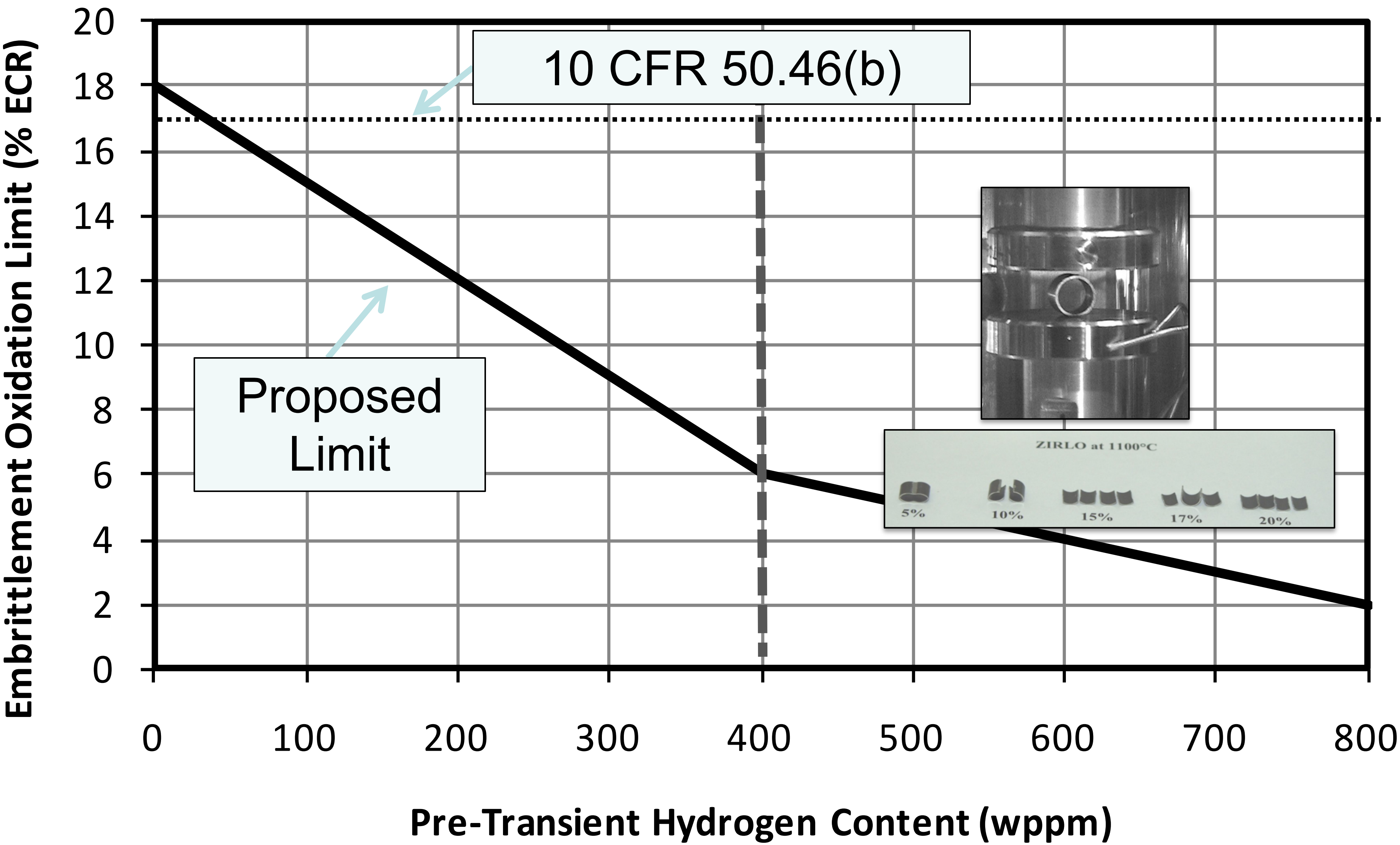
- The calculated maximum fuel element cladding temperature **shall not exceed 2200º F**.
- The calculated **total oxidation** of the cladding **shall nowhere exceed 0.17** times the total cladding thickness before oxidation.

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

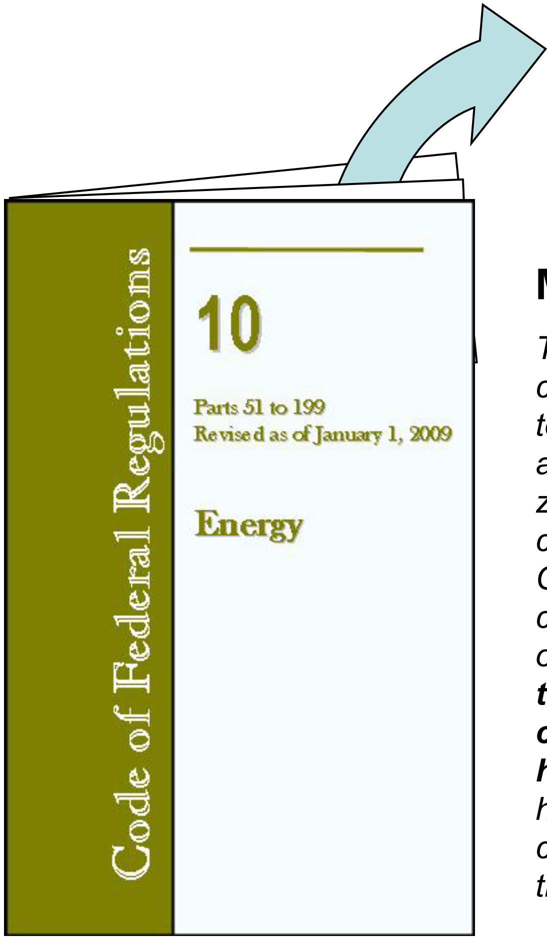
Finding: Completed embrittlement program indicated the oxidation criterion is not sufficient for high burnup cladding

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Research Findings



Existing treatment of the Balloon



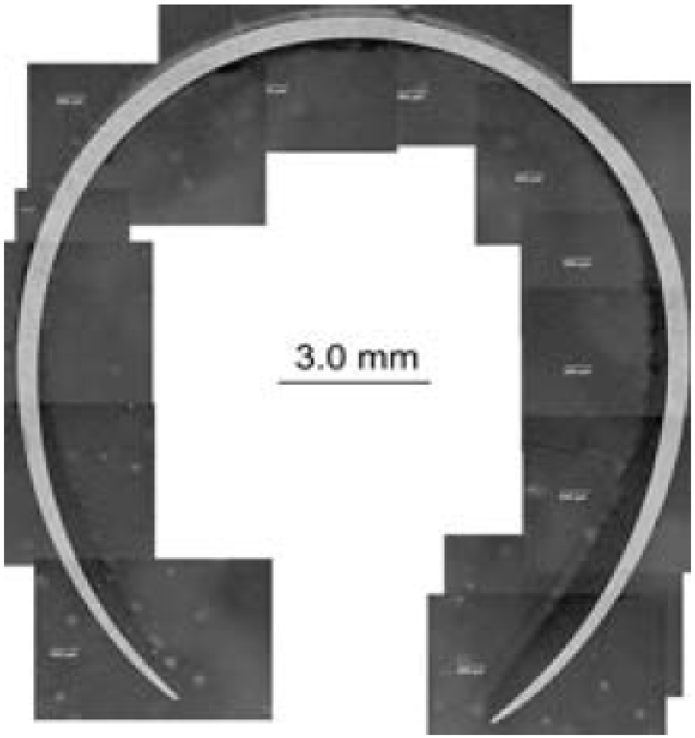
§ 50.46, "Acceptance criteria for emergency core cooling systems for light-water nuclear power reactors"

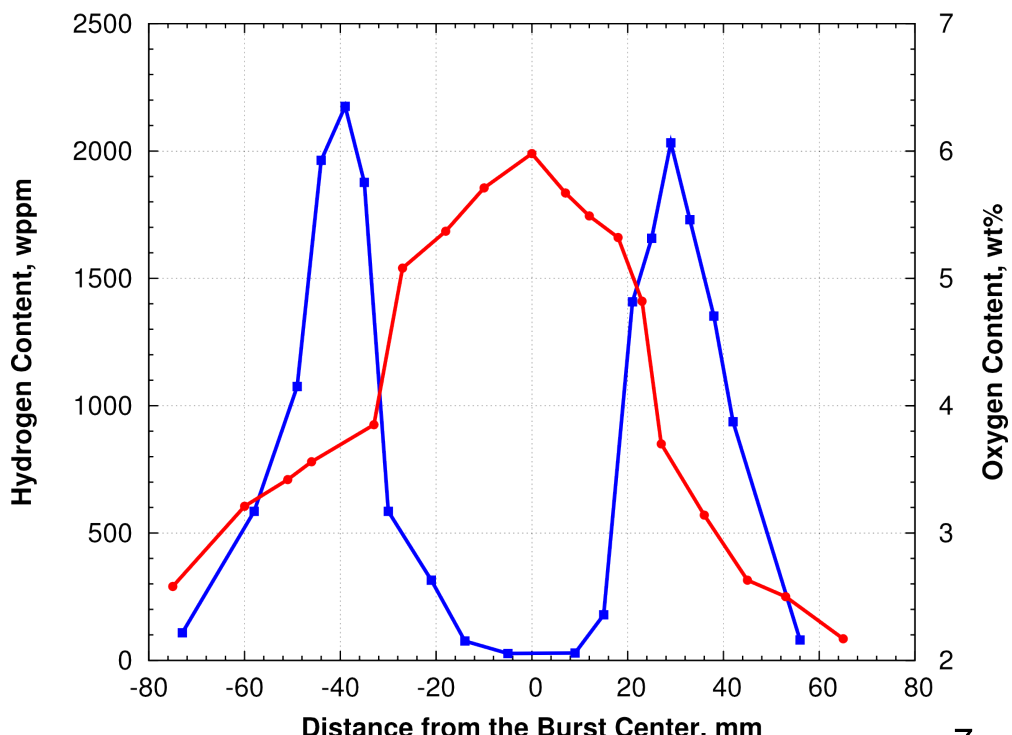
Maximum cladding oxidation is defined within the regulations:

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



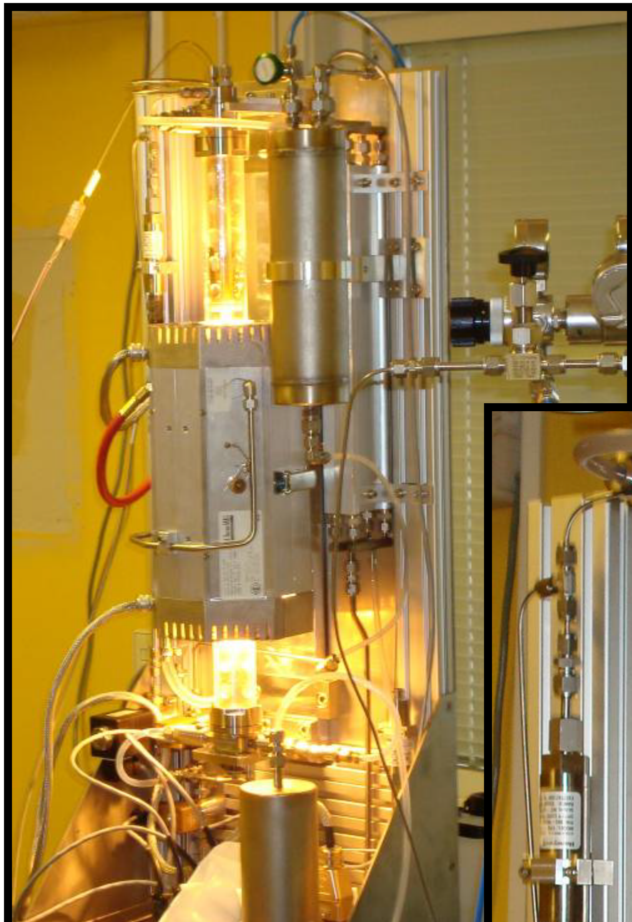


Proposed Treatment of the Balloon Region in RIL-0801

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."

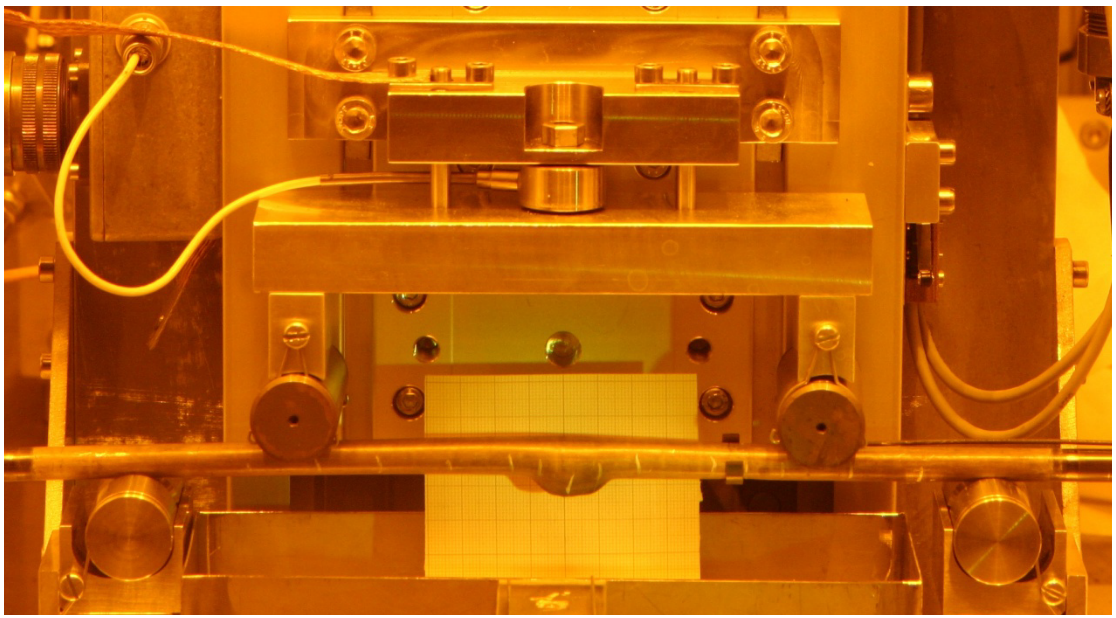
Investigation on Balloon Mechanical Behavior



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

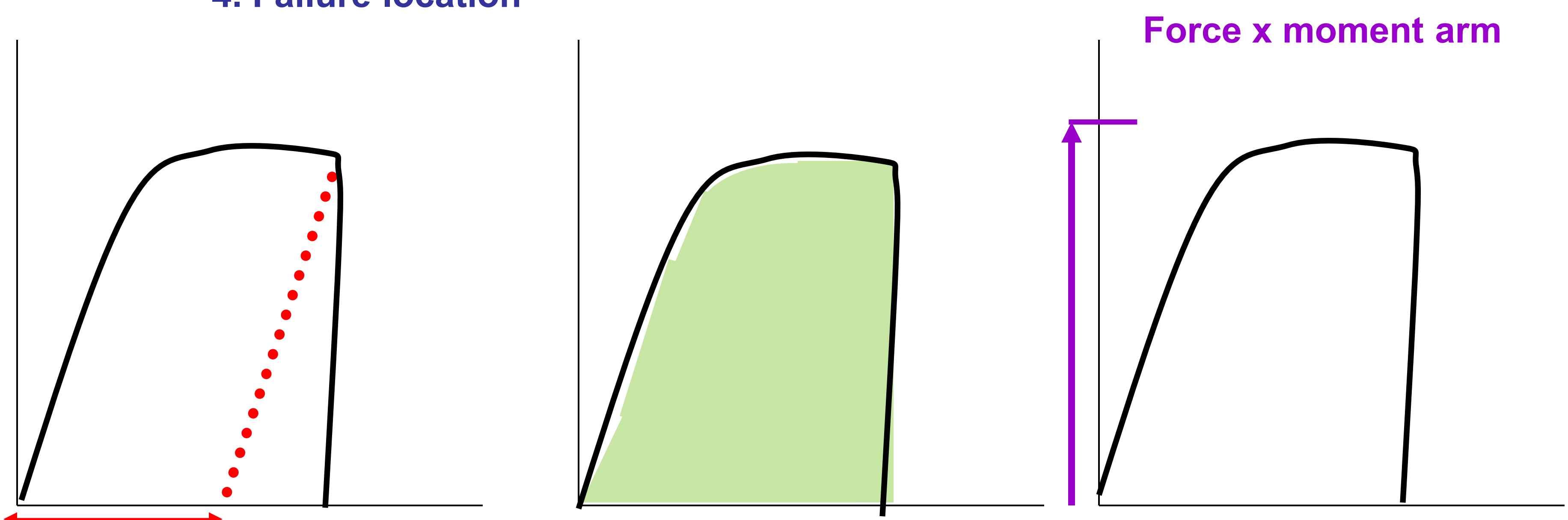


Bend tests were used to evaluate the balloon mechanical behavior ***in a mechanical test that applies a uniform bending moment to the ballooned region***. The axial location and nature of fracture was recorded. The observations of bend tests on irradiated material were compared to bend test results on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

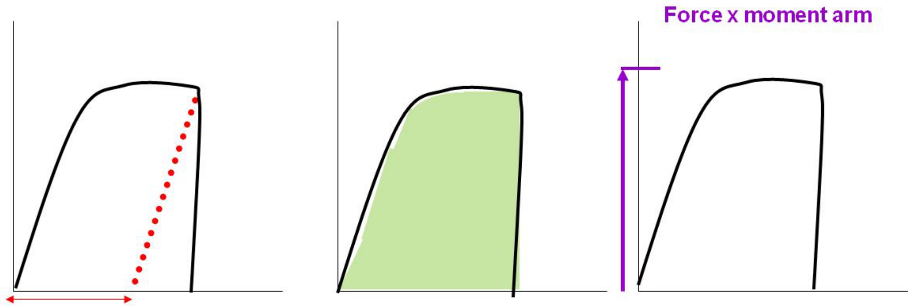
Investigation on Balloon Mechanical Behavior

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



ANL

Studsvik

Investigate influence of:

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

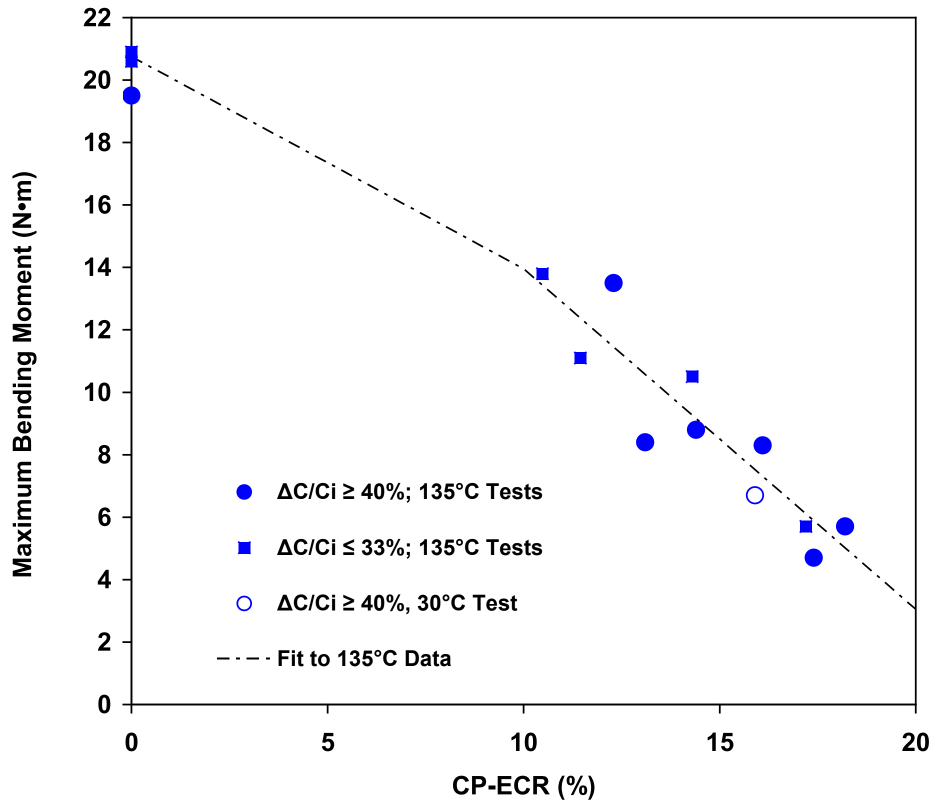
Results – As-Fabricated

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

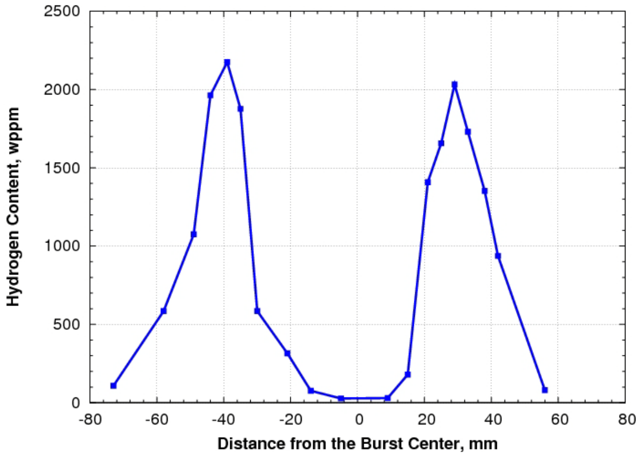


Maximum bending moment as a function of maximum oxidation level (CP-ECR) for post-LOCA samples subjected to 4-PBTs with the rupture region in tension for all tests but one. Bend tests were performed at 135°C and 2 or 1 mm/s to 14-mm maximum displacement. One bend test was performed at 30°C and 1 mm/s.

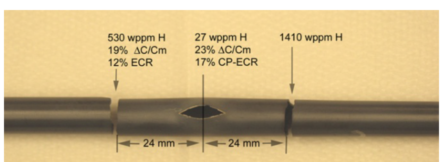
For ECR > 10%; M_{max} = 13.96 – 1.090 (CP-ECR – 10%), N•m

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

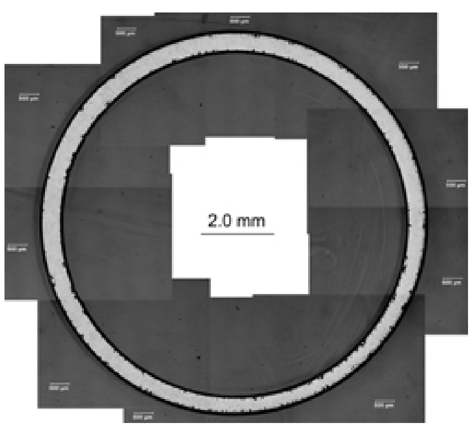
Results – As-Fabricated
Failure Location



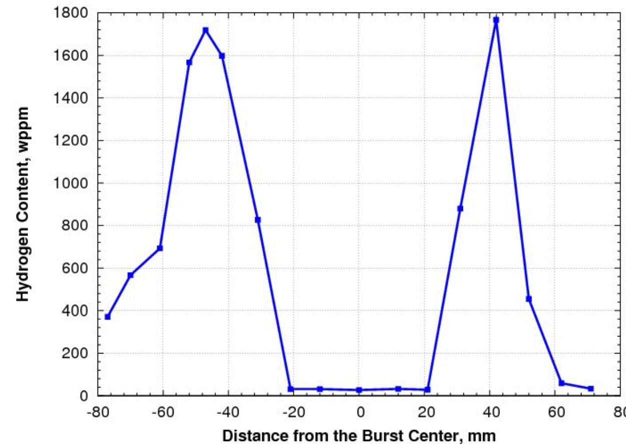
(a) Hydrogen-content profile



b) Measured values at failure locations

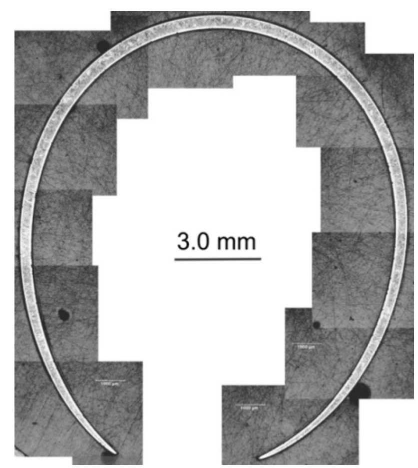


(c) Low-magnification image of severed cross section at -24 mm



(a) Hydrogen-content profile


(b) Failure location



(c) Low-magnification image of severed cross section

Results – As-Fabricated

Failure Energy

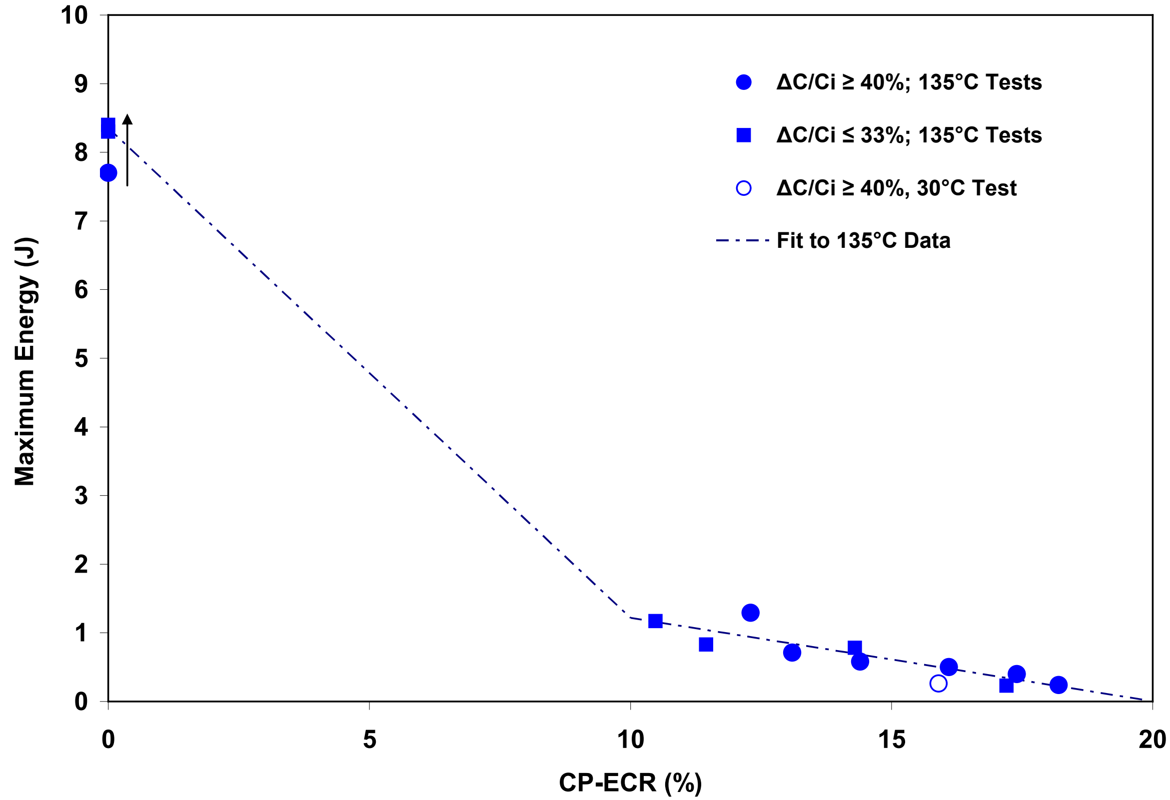
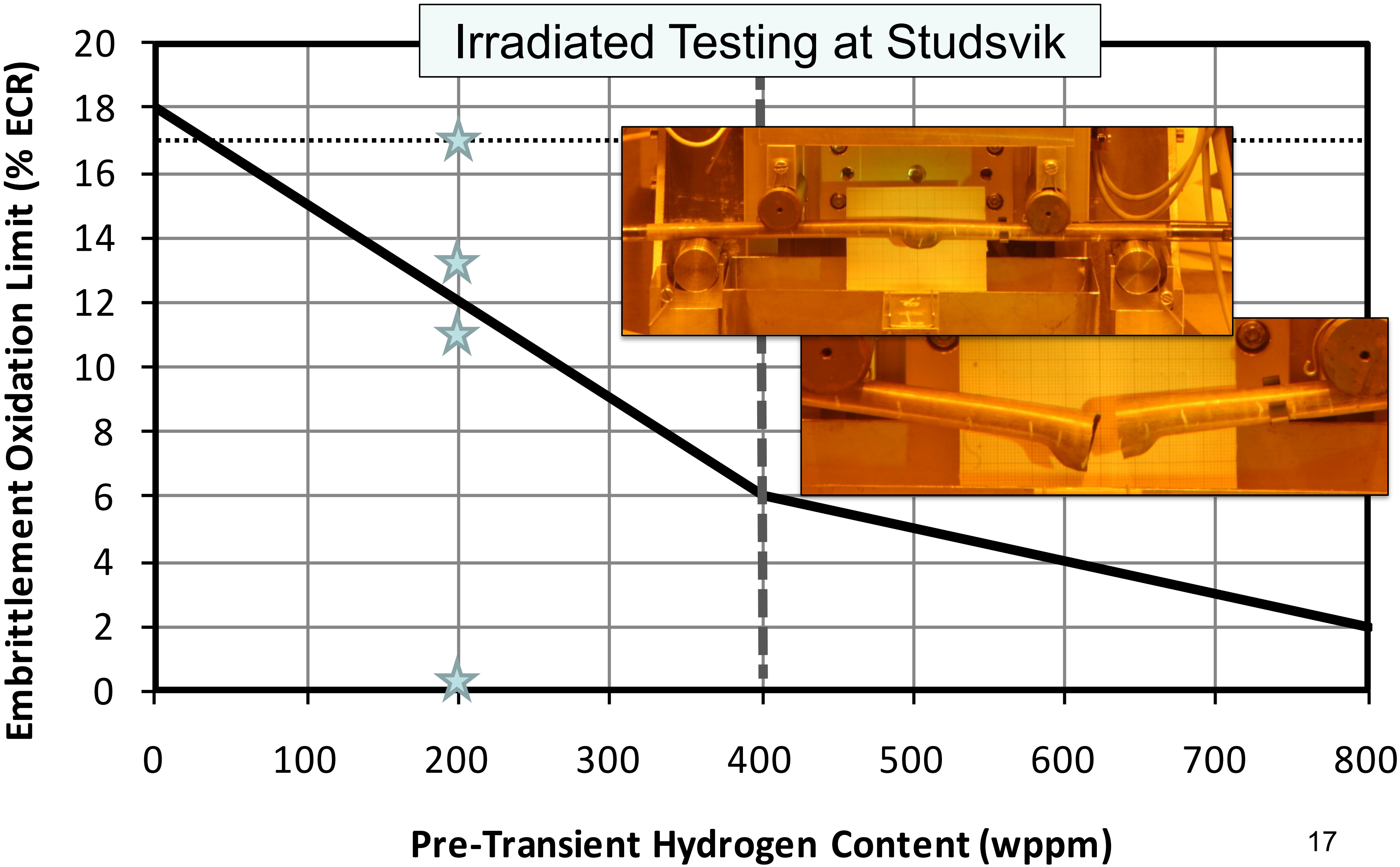


Figure 4. Maximum (for 0% CP-ECR) and failure (for ≥10% CP-ECR) energy as a function of oxidation level (CP-ECR) for post-LOCA samples subjected to four-point bending with the rupture region in tension for all tests but one. Bend tests were performed at 135°C and 2 or 1 mm/s to 14-mm maximum displacement.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

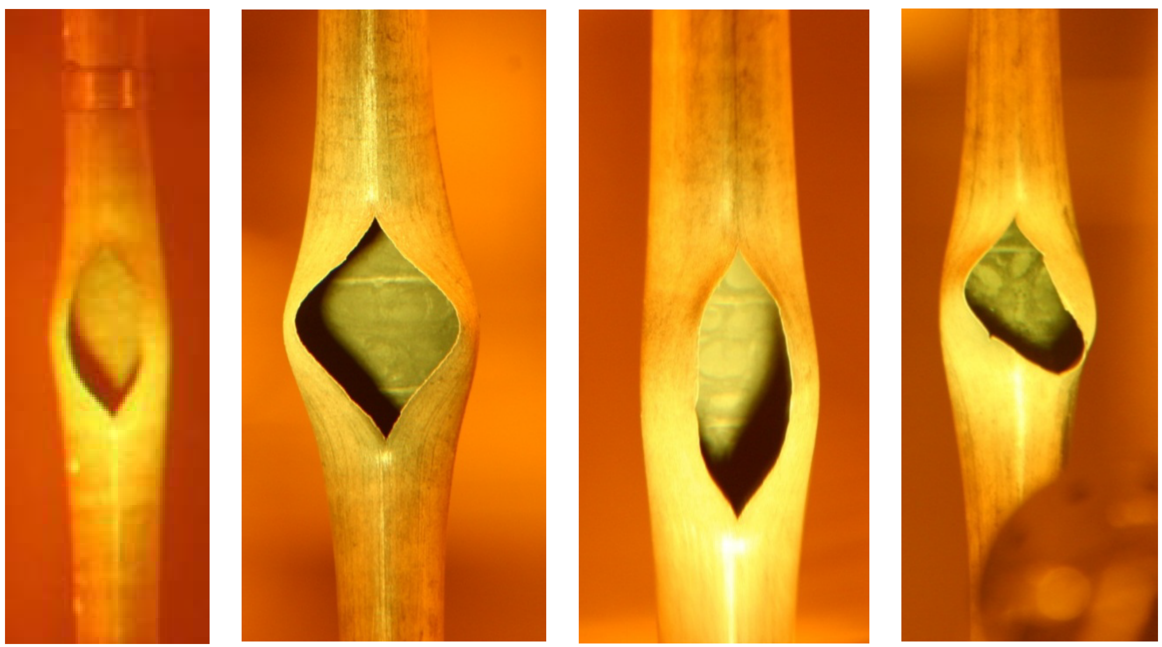
For ECR > 10%; E_{max} = 1.22 – 0.121 (CP-ECR – 10%), J

Investigation on Balloon Mechanical Behavior



Results – Irradiated Tests

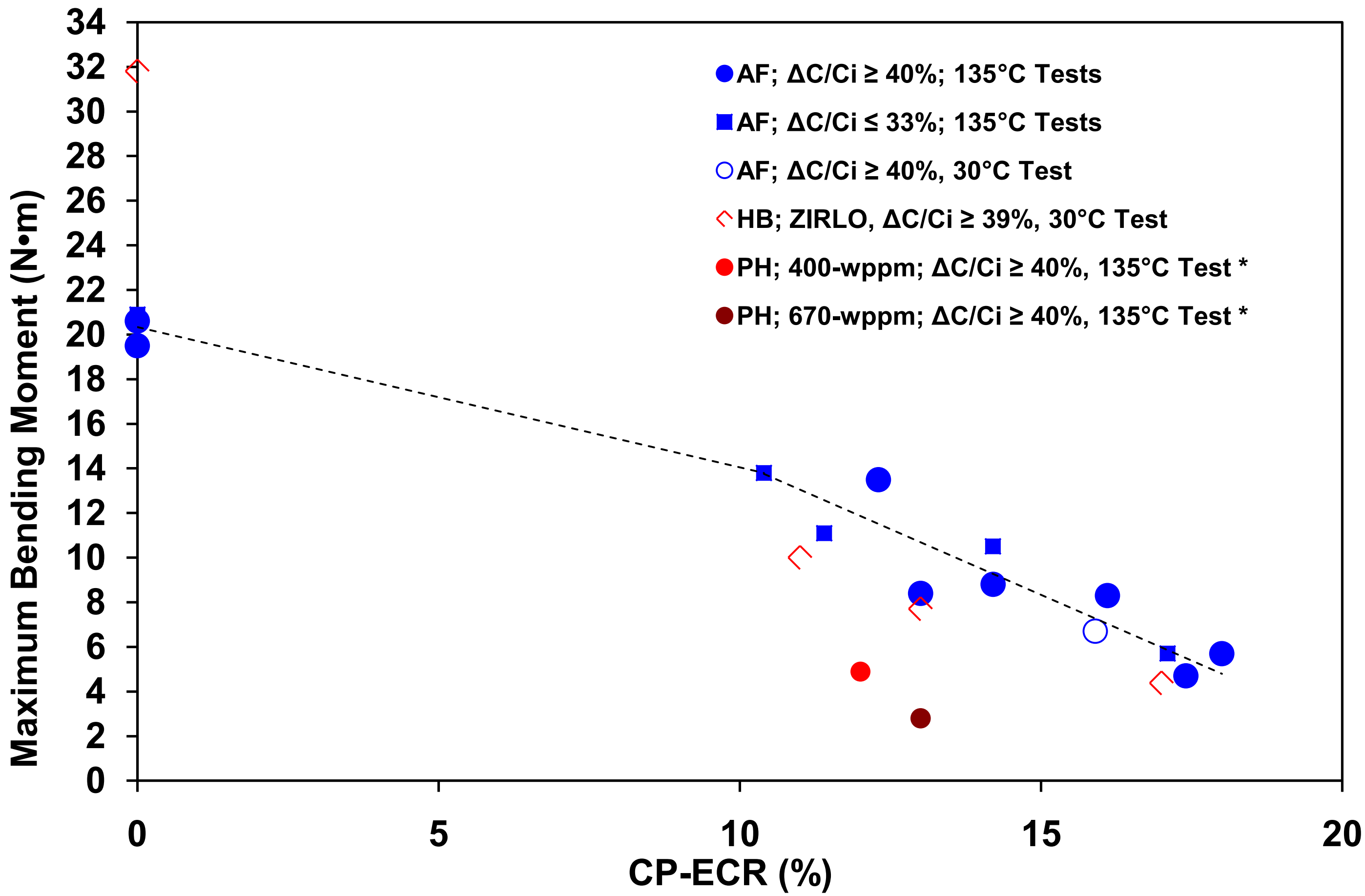
	189	191	192	193
Comments	Ramp to rutpure test	Ramp to PCT, held for 25s at PCT	Ramp to PCT, held for 5s at PCT	Ramp to PCT, held for 85s at PCT
Burnup	≈ 72 GWD/MTU	≈ 71 GWD/MTU	≈ 72 GWD/MTU	≈ 72 GWD/MTU
PCT	950 ± 20°C	1185 ± 20°C	1185 ± 20°C	1185 ± 20°C
Measured Strain	48%	50%	56%	50%
Calculated ECR	≈ 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

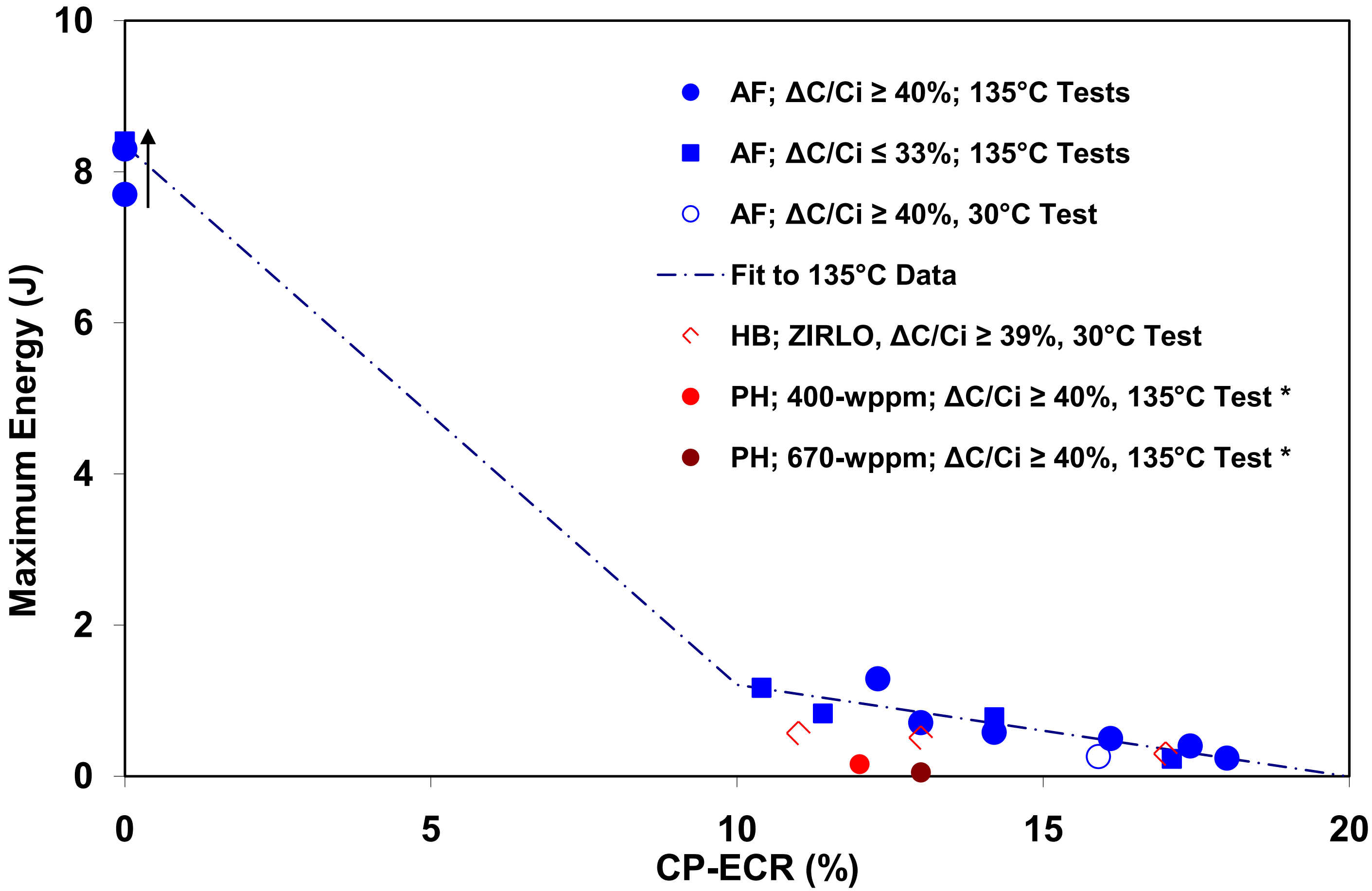
Results – Comparing AF, PH & Irradiated data



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. <u>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.</u>

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

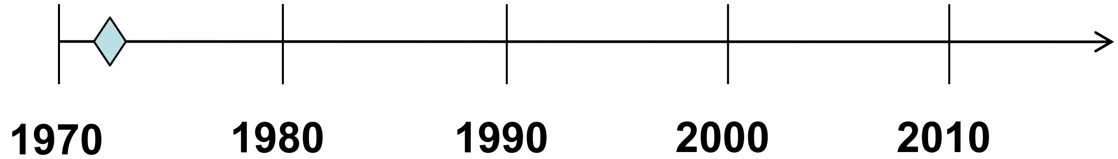
- RECALL: Original approach to embrittlement criteria falls out of the belief that specific prediction and quantification of LOCA loads is not possible
- A more extensive program could have been conducted and/or mechanical testing of ballooned and ruptured cladding could be required in order to license 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

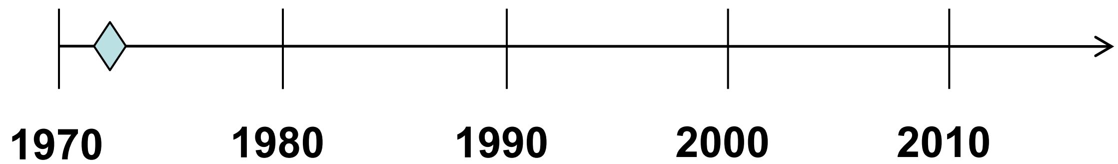
- RECALL: Original approach to embrittlement criteria falls out of the belief that specific prediction and quantification of LOCA loads is not possible
- A more extensive program could have been conducted to generate an acceptance criteria which is more mechanistic.
- Additional data still may not be 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).

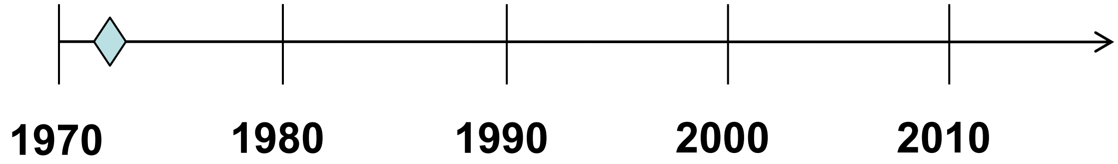
Regulatory History of the Balloon



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.

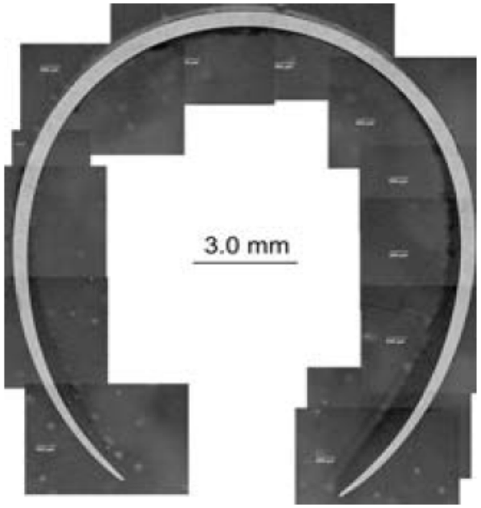
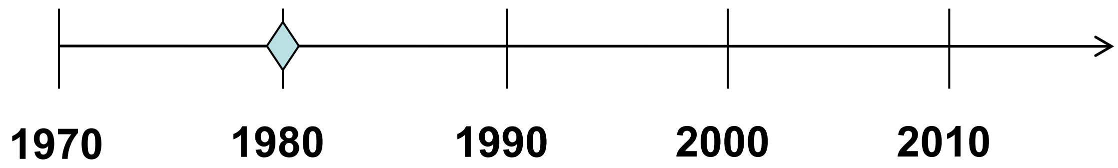


Fig. 1. Ballooned and ruptured ZIRLO cladding (ANL)

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

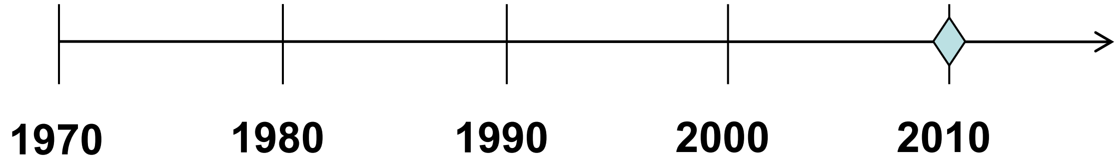
Regulatory History of the Balloon

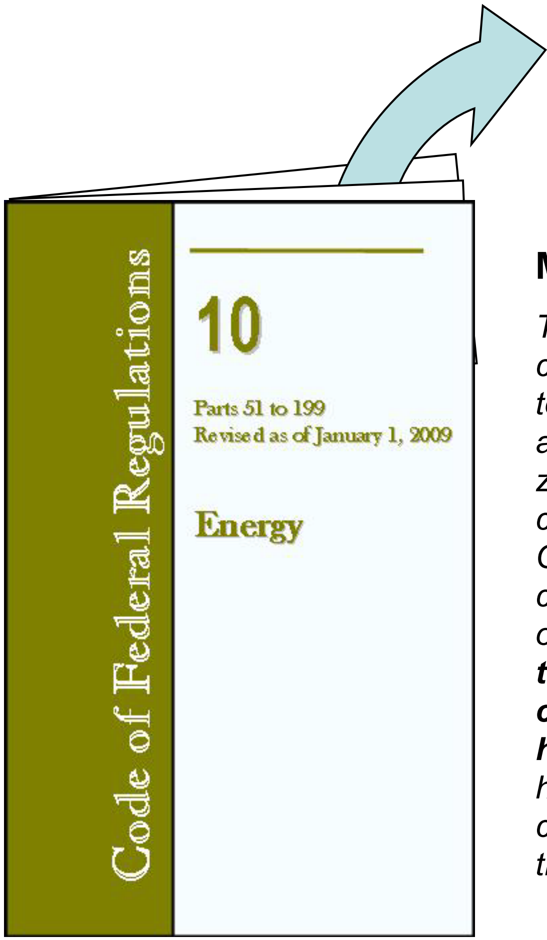


A second complication was discovered after the rulemaking was completed. Research reported in the early 1980’s in both the U.S. (NRC) and Japan (JAERI) found regions of high hydrogen concentration just above and below the rupture location. This was a consequence of oxidation of the inside cladding surface 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





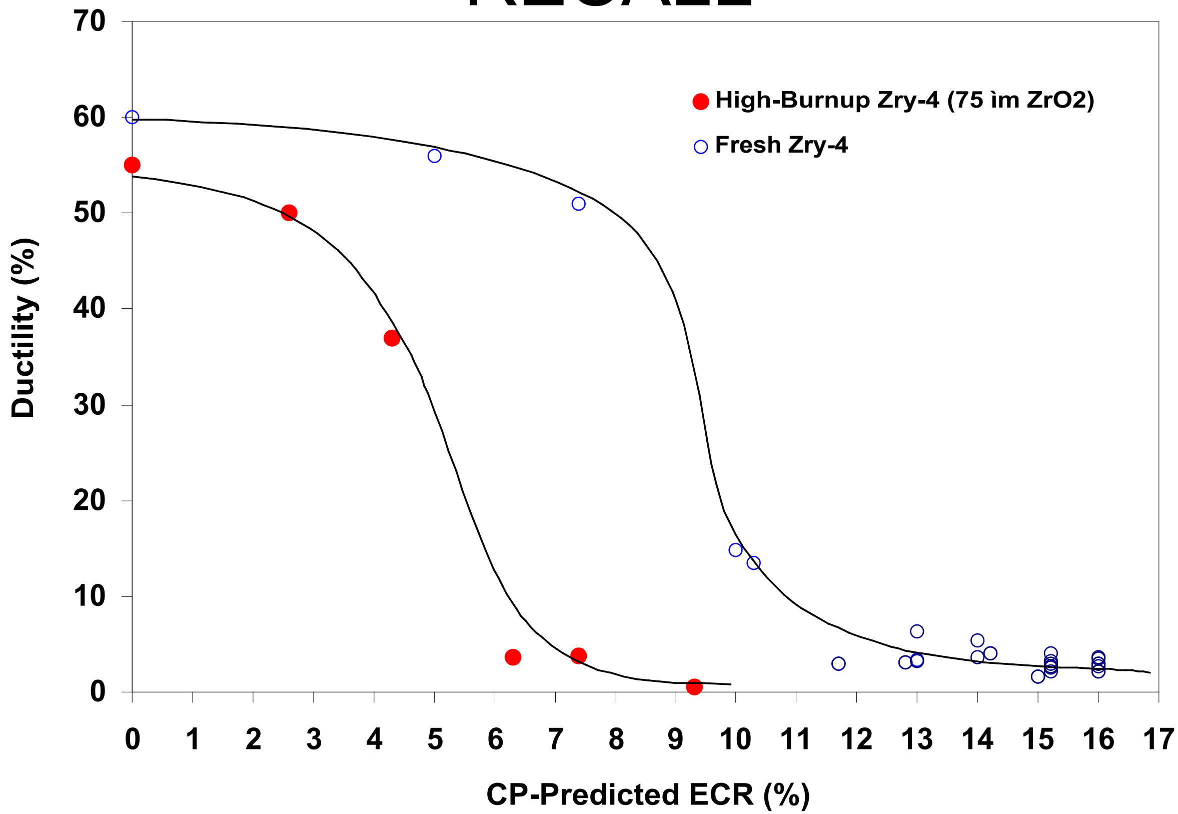
50.46 Acceptance criteria for emergency core cooling systems for light-water nuclear power reactors.

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

RECALL



ELECTRIC POWER RESEARCH INSTITUTE

Comments on Mechanical Behavior of Ballooned and Ruptured Cladding

Ken Yueh
Senior Project Manager

ACRS Subcommittee on Materials, Metallurgy & Reactor Fuels

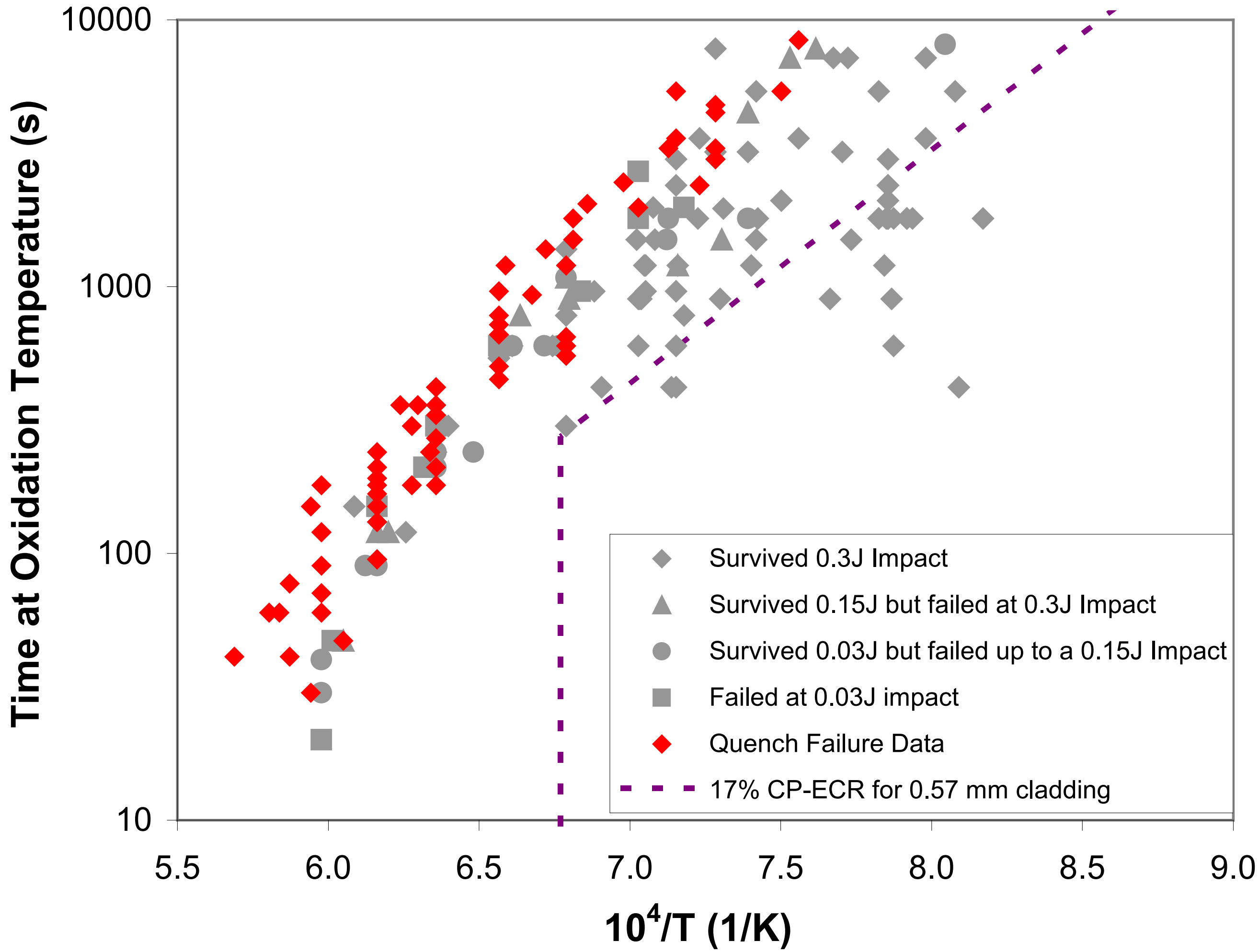
June 23, 2011

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

Published Test Results Review

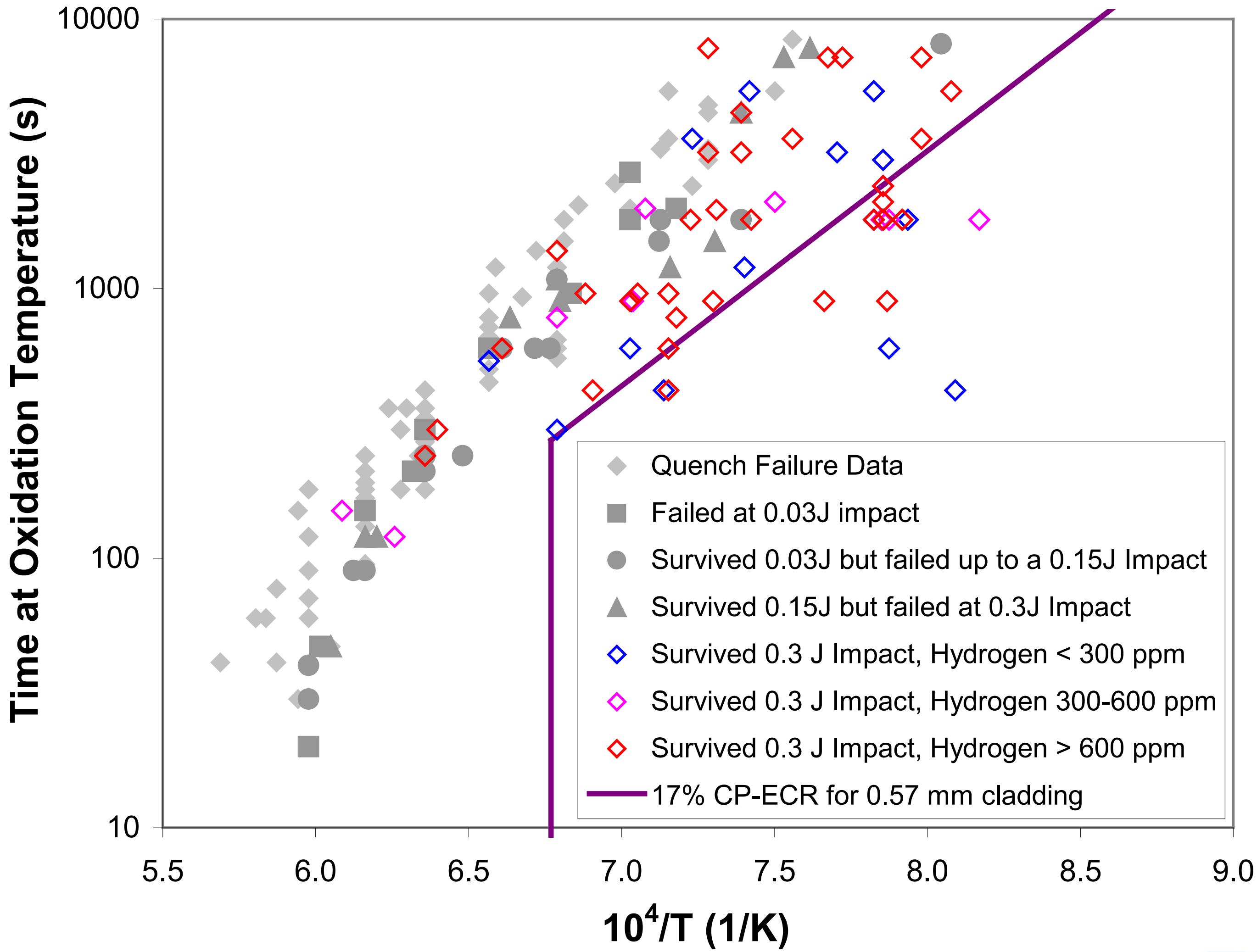
- 17% limit has a lot of margin to quench failure



* Chung and Kassner, NUREG/CR-1344

Published Test Results Review

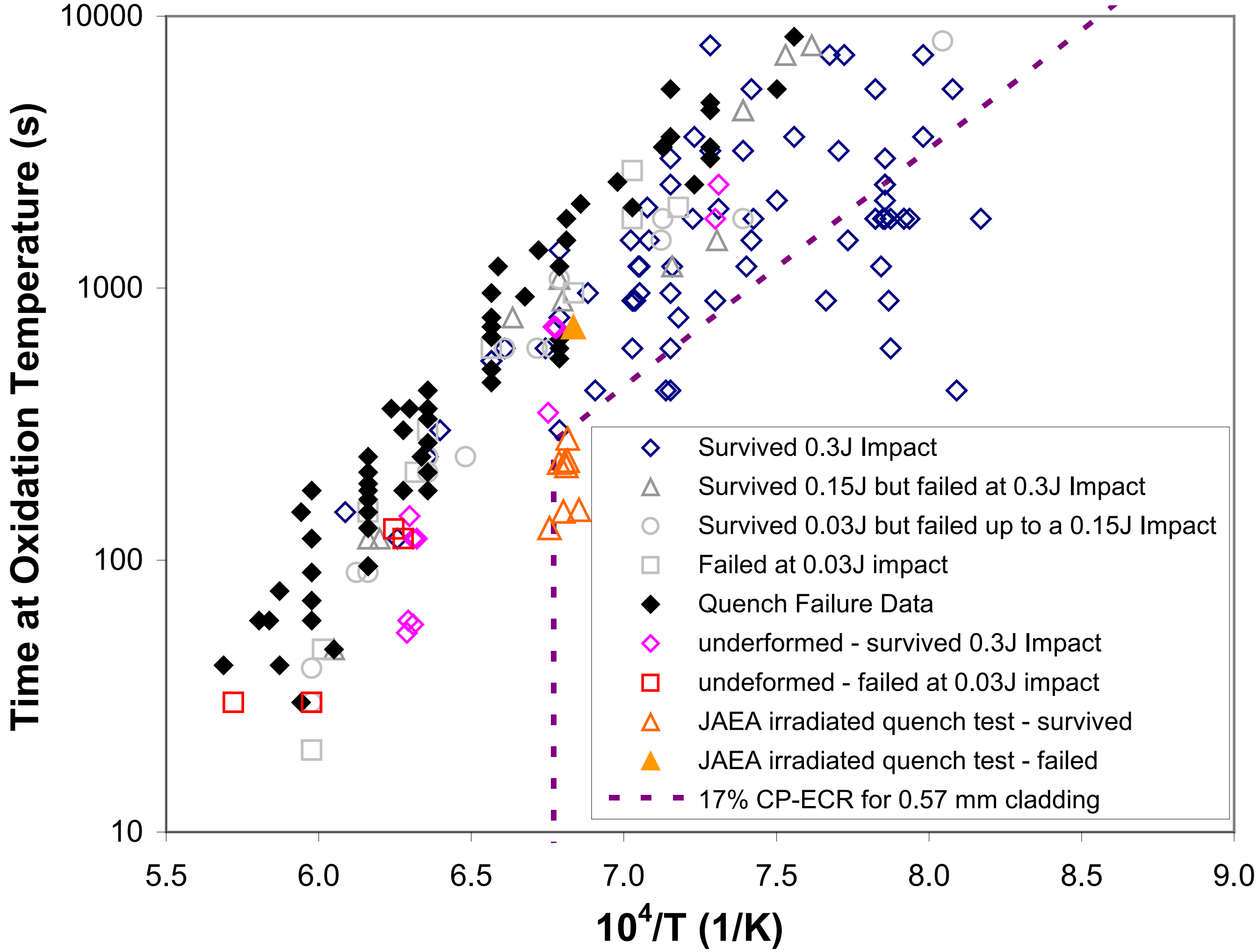
• No hydrogen dependence



* Chung and Kassner, NUREG/CR-1344

Published Test Results Review

- Similar behavior with irradiated and non-deformed regions



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

ELECTRIC POWER RESEARCH INSTITUTE

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

ELECTRIC POWER RESEARCH INSTITUTE

Together…Shaping the Future of Electricity

ELECTRIC POWER RESEARCH INSTITUTE