UNITED STATES
NUCLEAR REGULATORY COMMISSION
ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
WASHINGTON, DC 20555 - 0001

July 14, 2011

MEMORANDUM TO: ACRS Members

FROM: Christopher L. Brown, Senior Staff Engineer **/RA/**
Reactor Safety Branch A, ACRS

SUBJECT: CERTIFICATION OF THE MINUTES OF THE ACRS MATERIALS, METALLURGY, AND REACTOR FUELS SUBCOMMITTEE MEETING, MAY 10, 2011 - ROCKVILLE, MARYLAND

The minutes of the subject meeting were certified on June 28, 2011, as the official record of the proceedings of that meeting. A copy of the certified minutes is attached.

Attachment: As stated

cc w/o Attachment: E. Hackett
C. Santos

UNITED STATES
NUCLEAR REGULATORY COMMISSION
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WASHINGTON, DC 20555 - 0001

MEMORANDUM TO: Christopher L. Brown, Senior Staff Engineer
Reactor Safety Branch A, ACRS

FROM: Sam Armijo, Chairman
Materials, Metallurgy, and Reactor Fuels Subcommittee

SUBJECT: CERTIFICATION OF THE MINUTES OF THE ACRS MATERIALS, METALLURGY, AND REACTOR FUELS SUBCOMMITTEE MEETING, MAY 10, 2011 - ROCKVILLE, MARYLAND

I hereby certify, to the best of my knowledge and belief, that the minutes of the subject meeting on May 10, 2011, are an accurate record of the proceedings for that meeting.

RA 6/ 28 /2011
Sam Armijo, Chairman, Date
Materials, Metallurgy, and Reactor Fuels
Subcommittee

Certified on: June 28, 2011
CERTIFIED by S. Armijo

ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
MINUTES OF ACRS MATERIALS, METALLURGY, AND REACTOR FUELS SUBCOMMITTEE MEETING
MAY 10, 2011
ROCKVILLE, MARYLAND

The ACRS Materials, Metallurgy, and Reactor Fuels Subcommittee held a meeting on May 10, 2011, in Room T-2B3, 11545 Rockville Pike, Rockville, MD. The purpose of this meeting was to review issues related to 10 CFR 50.46(b) rulemaking activities. Christopher Brown was the designated Federal Official for this meeting. The Subcommittee received no written statements or requests for time to make oral statements from the public. The Subcommittee Chairman convened the meeting on May 10, 2011 at 8:30 a.m. and adjourned at 3.14 p.m.

ATTENDEES:

ACRS Members
J. Armijo, Chairman
M. Corradini
S. Abdel-Khalik
J. Sieber
C. Brown
W. Shack
J. Rempe
D. Bley

ACRS Staff
C. L. Brown, Designated Federal Official

NRC Staff
Sher Bahadur, NRR
Paul Clifford, NRR
Michelle Flanagan, RES
John Voglewde, RES
Ralph Landry, NRO
Harold Scott, RES

Also Present
Mike Billone, ANL (via phone)
Gordon Clefton, NEI
Bert Dunn, AREVA
Mitch Nissley
Tom Eichenberg
Ralph Meyer (via phone)
Maureen Conley, Platts (via phone)
Ken Yueh, EPRI
Ying-Pi Lin

Other members of the public attended this meeting. A complete list of attendees is available upon request. The presentation slides and handouts used during the meeting are attached to the office copy of these minutes.

Opening Remarks and Objectives:

Dr. Sam Armijo, Chairman of the ACRS Materials, Metallurgy, and Reactor Fuels Subcommittee, convened the meeting at 8:30 a.m. The purpose of this meeting was to discuss the status of activities associated with a revision to 10 CFR 50.46(b) and the proposed rule 10

CFR 50.46c, and to gather information, analyze relevant issues and facts, and formulate proposed positions and actions, as appropriate, for deliberation by the full Committee. The presenters included representatives from the NRC's Office of Nuclear Reactor Regulation (NRR), Office of Nuclear Regulatory Research (RES), and EPRI. The rules for participation in the meeting were announced as part of the notice of the meeting previously published in the *Federal Register*. The Committee did not receive written statements or requests for time to make oral statements from members of the public.

Overview of 50.46c Rulemaking

The primary objective of proposed rule 10CFR 50.46c is to ensure core coolability during and following a design basis loss-of-coolant accident (LOCA) by assuring adequate fuel cladding ductility and fracture resistance.

Essentially, the rulemaking will replace the 17% oxidation limit in the regulations with a variable oxidation limit based on the cladding's pre-transient hydrogen content. The rulemaking will also introduce a new performance requirement to ensure cladding ductility during extended LOCA scenarios at lower temperatures by addressing breakaway oxidation. Breakaway oxidation is caused by changes in the crystal structure of the normally protective cladding oxide at temperatures above 1,200 °F, but considerably below the 2,200 °F regulatory limit. These changes can result in rapid hydrogen pickup and cladding embrittlement. Acceptance criteria would be based on experimentally determined "measured breakaway times" for specific materials In addition periodic follow-up testing would be required to confirm that changes in manufacturing processes had not inadvertently degraded breakaway oxidation resistance. . The staff is also proposing an optional test program that would allow fuel vendors or licensees to demonstrate compliance with post-quench ductility for LOCA transients in which peak temperatures are less than 2200 ºF.

Dr. Sher Bahadur, NRR gave a general introduction and introduced the staff.

Mr. Paul Clifford, NRR provided a brief historical overview and background information on the rulemaking activities for the embrittlement criteria for LOCA. He reminded the Subcommittee that the ACRS was briefed on technical basis and rulemaking strategy in December 4, 2008 in which he explained that the existing regulatory criteria (2200 ºF, 17% ECR) needed to be revised based on key research findings on cladding embrittlement. He also said that the prescriptive criteria would be replaced with performance-based requirements. At the May 10, 2011 briefing, Mr. Clifford introduced three new items to the rulemaking activities. He said that the staff has developed a draft Generic Letter to confirm interim plant safety, expanded the technical basis for treatment of fuel rod burst region, and is considering potential expansion of the rulemaking scope to include fuel fragmentation and dispersion.

Michelle Flanagan presented background, context, and details of the three regulatory guides which support ECCS rulemaking. These are: DG-1261: Test procedure for measuring breakaway oxidation behavior and periodically confirming consistent behavior, DG-1262: Testing procedure for measuring post quench ductility using ring compression tests, and DG-1263: Developing analytical limits from measured data. DGs-1261,-1262, and-1263 will be used by the staff to provide appropriate guidance to ensure adequate cladding ductility following a LOCA.

Ms. Flanagan stated that fuel-cladding research on the behavior of high-exposure fuel cladding under accident conditions had identified new cladding embrittlement mechanisms, and improved

knowledge of previously identified mechanisms. These mechanisms include, hydrogen enhanced embrittlement, breakaway oxidation, and oxidation on inner cladding surfaces due to fuel to clad bonding. She further mentioned that the proposed regulations 10 CFR 50.46c will call for material-specific analytical limits which account for material-specific burnup effects, and ECCS performance consistent with avoidance of breakaway oxidation. These regulatory guides will make it possible to revise 10 CFR 50.46c in a performance-based manner. This will be done by providing guidance for 1) consistent, comparable generation of data to establish regulatory limits for PCT and oxidation, 2) consistent and comparable data generation to establish, and periodically confirm regulatory limits related to breakaway oxidation, and 3) consistent means of using experimental data to establish regulatory limits.

Industry LOCA Oxidation Test Plans

Ken Yueh of EPRI stated that the industry has conducted a series of complementary LOCA oxidation tests to fill information and data gaps, and plans to perform additional tests. He presented preliminary results of embrittlement tests on pre-hydrided cladding samples that had been oxidized over a range of temperatures. The goal of these tests is to generate sufficient data to justify different post quench ductility acceptance criteria for LOCAs in which peak temperatures are lower than 2200°F.

Mr. Yeuh also addressed the issue of two sided oxidation away from the balloon region. It is the staff's contention that fuel to clad bonding will produce the same depth of embrittlement on the inner surface of the cladding as that produced on the outer surface, and significantly increase the severity of cladding embrittlement during the LOCA. He presented EPRI's interpretations of various experiments, and argued that inner surface embrittlement is limited to the thickness of the pre-transient inner surface oxide, and not by the presence of fuel to clad bonding. During the staff presentation, there was considerable discussion among Ms. Flanagan, Mr. Clifford and Chairman Armijo on the subject of inner surface oxidation and embrittlement, with the staff holding the view that double-sided oxidation and embrittlement due to fuel to clad bonding must be assumed for burnup levels ≥ 30 gigawatt days per ton. However, if licensees can demonstrate that this is not the case for their fuel, then the regulatory guide provides a means of accepting a different limit.

Mr. Yeuh also presented the status of the EPRI's LOCA round-robin program. He stated that the LOCA round-robin project goals were to identify and evaluate sources of variation in measured post LOCA ductility among laboratories using the test procedures developed by ANL, and to generate sufficient test data to support an ASTM test procedure. Six laboratories are participating in the round-robin. Each laboratory will conduct PQD and breakaway oxidation tests on a common set of agreed test parameters and use a common lot of material. All sample preparation will be performed by individual laboratories. Hydrogen pre-charged samples will be supplied to two laboratories. Yeuh mentioned that test data generated from each laboratory will be shared and a combined test report will be provided to each participant. Yeuh said that testing will likely be completed by late summer 2011. Chairman Armijo asked whether ANL was participating in the round robin test program. Yueh stated that ANL had been invited to participate, but had declined.

Individual Member Comments:

Member Shack asked Mr. Clifford to explain the "c" in 50.46c. In response, Mr. Clifford explained that 50.46c will be implemented over a period of time. During this time there will be

two rules (50.46(b) and 50.46c). Plants will be in compliance with one or the other until all are transitioned to 50.46c.

The staff has developed a draft generic letter to obtain plant-specific information to confirm plant safety in the interim recognizing that the implementation of the final rule would take several years. In response to the draft generic letter, the industry has proposed an alternative whereby the same information will be provided voluntarily in PWR and BWR Owner's Group reports. Last week, staff received the first of two reports. These reports are intended to document safety margins for all the PWRs. Staff expects the BWR equivalent in a few weeks. Chairman Armijo commented that this is a new regulatory action, and if the staff finds the voluntary industry reports acceptable, a generic letter will not be needed. In response, Mr. Clifford said correct.

In relation to core coolability, Chairman Armijo noted that if you demonstrate coolability in a beyond design basis event such as Fukushima, then you probably have demonstrated coolability in a design basis event, which is milder. He said Fukushima should make us rethink what we're doing. In response, Mr. Clifford said whether it's design basis or beyond design basis the issue is that this rule is focusing on LOCA and the sequence of events that occur during a LOCA, which involves a massive depressurization and a loss of coolant. Furthermore, Mr. Clifford said that the staff does not have all the facts as to what happened in Japan, and that it was his understanding that a station blackout scenario is significantly different. The sequence of events is significantly different than what would happen during a large break LOCA and could not be compared directly. Member Shack made similar comments.

Chairman Armijo made a comment that the Committee needed to understand how testing would be done. In particular, he noted that the loading that a fuel rod would experience during a quench is not a compressive ring-type loading. In fact, the fuel might be loaded in bending, or in axial tension or compression, but not in ring compression. Consequently the ring compression test (RCT) is being used to measure a material property, which is ductility. In response, Dr. Mike Billone of ANL said we're doing a ductility screening test, but work by CEA in France and at Argonne has shown that if the same materials are tested in a three-point bend test and in a RCT, the ductile-to-brittle transition from both tests agree quite well. Dr. Billone also said that ANL had compared test methods with French colleagues and determined that there was close correspondence between the bend test and the ring compression test. Dr. Billone indicated that he would provide the Committee with two technical papers to review on this issue.

Member Shack raised the issue of clad ballooning. He was concerned whether the language in the rule would accommodate treatment of clad ballooning or whether a revision to the rule would be required. In response, Mr. Clifford said staff is currently discussing how the rule language would need to be modified to capture ballooning and potentially fuel fragmentation which would be a topic in the upcoming June 2011 meeting.

Member Abdel-Khalik asked about the logic justifying the proposed frequency of periodic testing and reporting, for breakaway oxidation. In response, Mr. Clifford said breakaway oxidation has been shown to be sensitive not only to alloy composition but to also to the manufacturing process. A report will be required to confirm that periodic testing has confirmed acceptable breakaway oxidation resistance. Mr. Clifford added that specific questions have been raised regarding the staff’s intent is to tie the periodic testing frequency to manufacturing process changes, or to statistical sampling. The staff is still working on this issue. Member Shack added that the vendors would be interested in knowing what periodic means also. Chairman Armijo added that fuel manufacturers routinely subject cladding to a variety of mechanical property and corrosion tests to assure that required properties have not been compromised by deliberate or

inadvertent process changes. He added that the frequency of testing should be governed by the margin between the measured cladding breakaway oxidation time and the acceptance criteria. This issue will be revisited after public comment.

There was considerable discussion regarding the industry round robin test program. Chairman Armijo asked whether Argonne had tested the same lot of material that is being used in the round-robin program. In response, Mr. Yueh of EPRI said the industry is testing a different lot of material from what was used at Argonne. Chairman Armijo noted that absence of ANL participation in the round robin was a weakness. Harold Scott of the staff stated that if the ACRS wanted ANL to participate in the round robin test program then it would need to be noted in future ACRS letters.

SUBCOMMITTEE DECISIONS AND ACTIONS:

Following the industry and staff presentations and discussions, Chairman Armijo asked if anyone had any further questions or comments.

Dr. Ralph Meyer, a member of the public and an expert on the phenomena affecting cladding embrittlement, made a comment concerning the complexity of the staff's current approach. He said that there seems to be an expectation that the three RGs are needed to meet the performance-based provisions in the rule. He also said that the hydrogen dependence of the oxidation limit is inherently performance-based and has been demonstrated by testing to be independent of material composition. He did not see any benefit in "tooling up" to do tests to find alloy specific limits on oxidation. Further, he said that one RG that addressed breakaway oxidation screening, the hydrogen correlation with burnup, and two-sided oxidation would be sufficient to support rulemaking. In his opinion, the breakaway oxidation analysis goes beyond our understanding of the breakaway phenomenon and that a simple scoping test would be sufficient to tell if the cladding was not fabricated properly. Finally, Dr. Meyer pointed out that the combination of NRC and EPRI data on embrittlement at different temperatures could be used to generate a set of acceptance curves and these could be put into the rule. Chairman Armijo thanked Dr. Meyer for his comments, particularly those related to the elimination of needless complexity and the inclusion of some hard numbers into the rule. Dr. Shack reminded the Members that the ACRS had explicitly recommended that the staff not include numerical acceptance criteria in the rule. Mr. Burt Dunn of AREVA commented that simplification of the regulatory guides would be fine, but cautioned against including numerical requirements in the rule.

The Chairman Armijo thanked everyone for their presentations and comments, and then adjourned the meeting at 3:14 pm.

BACKGROUND MATERIALS PROVIDED TO THE SUBCOMMITTEE PRIOR TO THIS MEETING:

1. Memorandum to Edwin M. Hackett, Executive Director, ACRS; from Michael J. Case, Director, Division of Engineering, Office of Nuclear Regulatory Research, dated February 16, 2011, Subject: Draft Final Regulatory Guide DG-1261, "Conducting Periodic Testing for Breakaway Oxidation Behavior," DG-1262, "Testing for Postquench Ductility," and DG-1263 "Establishing Analytical Limits for Zirconium-Based Alloy Cladding" (ML111050480)

2. Memorandum to Edwin M. Hackett, Executive Director, ACRS; Shana Helton, Chief, Rulemaking Branch, Division of Policy and Rulemaking, Office of Nuclear Reactor Regulation, dated April 6, 2011, Subject: Transmittal of Draft 10 CFR 50.36(c) Proposed Rule Language, (ML110970044)

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Note: Additional details of this meeting can be obtained from a transcript of this meeting available for downloading or viewing on the Internet at http://www.nrc.gov/reading-rm/doc-collections/acrs/tr/subcommittee/2008/ or purchase from Neal R. Gross and Co., Inc., (Court Reporters and Transcribers) 1323 Rhode Island Avenue, NW, Washington, DC 20005 (202) 234-4433.

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UNITED STATES NUCLEAR REGULATORY COMMISSION

Protecting People and the Environment

Overview of the 10 CFR 50.46c Rulemaking

May 10, 2011

Paul Clifford
Division of Safety Systems
Office of Nuclear Reactor Regulation

Meeting Agenda

1. 50.46(b) Rulemaking Overview
   - ACRS Interaction – Past, Present, Future
   - What's New

2. Regulatory Guides Supporting Rulemaking
   - PQD Test Protocols
   - Breakaway Test Protocols
   - Analytical Limits

3. Industry Testing and Round-Robin

Rulemaking Objectives*

- Following Commission directive, develop a performance-based rule which enables licensees to use advanced cladding materials without needing an exemption.
  - Replace prescriptive criteria with performance-based regulatory requirements.
  - Expand applicability beyond “zircaloy or ZIRLO”.

- Capture results of High Burnup LOCA Research Program.
  - Research identified new embrittlement mechanisms which necessitate rule changes.

* Slide from December 2008 ACRS Full Committee Meeting

ACRS Interactions – Past

ACRS briefed on technical basis and rulemaking strategy (December 4, 2008):

- Existing regulatory criteria (2200ºF, 17% ECR) need to be revised based on key research findings on cladding embrittlement:
  - Hydrogen-enhanced prior-beta layer embrittlement.
  - Cladding ID oxygen ingress.
  - Breakaway oxidation.
- Prescriptive criteria would be replaced with performance-based requirements.
  - PQD and breakaway test procedures would be provided in future Regulatory Guides.
  - ANPR would be issued to solicit stakeholder input on specific topics.

ACRS Interactions – Past (cont.)

ACRS Letter (ML083460310, December 2008):

CONCLUSIONS AND RECOMMENDATIONS

- There are sufficient data and understanding of the cladding embrittlement phenomena to justify and proceed with rulemaking.

- The rule should include the proposed optional testing program to allow licensees to demonstrate compliance with post-quench-ductility (PQD) criteria on an alloy-specific and temperature-specific basis.

- A round robin test program would be beneficial in the validation of the test procedures used to demonstrate compliance with PQD and breakaway-oxidation criteria.

Recent Progress

1. ANPR issued, public comments received and resolved.

2. PQD and breakaway empirical database expanded.

3. Specific requirements (e.g.,1% plastic strain) moved from rule to RGs.

4. Supporting draft RGs developed

New Items

1. Developed draft Generic Letter and alternate industry initiation to confirm interim plant safety.

2. Expanded technical basis for treatment of fuel rod burst region.

3. Considering expansion of rulemaking scope to include fuel fragmentation and dispersion.

Each item will be addressed in a future ACRS briefing

ACRS Interactions – Future

<u>ACRS Subcommittee:</u>

Draft RGs	- May 2011
Expanded Technical Basis & Rule Scope	- June 2011
Proposed Rule Package	- Dec. 2011
Final RGs	- TBD
Final Rule Package	- TBD

ACRS Interactions – Present

<u>Expected Outcome of Today's Briefing:</u>

1. Obtain concurrence to issue draft RGs for public comment.

2. Provide industry opportunity to brief ACRS on results of recent PQD testing and round-robin.

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Questions?

Paul Clifford, Senior Technical Advisor
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Tara Inverso, Project Manager
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UNITED STATES NUCLEAR REGULATORY COMMISSION

Protecting People and the Environment

Overview of Regulatory Guidance to support ECCS rulemaking

May 10, 2011

Michelle Flanagan
Division of Systems Analysis
Office of Nuclear Regulatory Research

Meeting Objective

To present the background, context and details of three regulatory guides which support ECCS rulemaking revisions.

Background

- Fuel-cladding research program investigated the behavior of high-exposure fuel cladding under accident conditions.

- New cladding embrittlement mechanisms identified and knowledge of previously identified mechanisms expanded
  - Hydrogen enhanced embrittlement
  - Breakaway oxidation
  - Oxidation on inner cladding diameter due to fuel cladding bond

Background

- Rulemaking initiated to revise ECCS acceptance criteria to reflect the research findings
- The revisions are also intended to develop performance-based features of 10 CFR 50.46.

- Therefore, 10 CFR 50.46c calls for:
  - Material-specific analytical limits which account for material-specific burnup effects
  - ECCS performance consistent with avoiding measured breakaway behavior
  - Periodic testing for breakaway behavior

Background

These regulatory guides make it possible to revise 10 CFR 50.46c in a performance-based manner by providing:

- a means of consistent, comparable generation of data to establish regulatory limits for PCT and oxidation
- a means of consistent, comparable data generation to establish, and periodically confirm regulatory limits related to breakaway oxidation
- a consistent means of using experimental data to establish regulatory limits

Regulatory Guides

- DG-1261: Test procedure for measuring breakaway oxidation behavior and periodically confirming consistent behavior
- DG-1262: Testing procedure for measuring post quench ductility using ring compression tests
- DG-1263: Developing analytical limits from measured data

Context

Relationship to rule language

DG-1263

Specified and acceptable analytical limits on peak cladding temperature and time at elevated temperature shall be established which correspond to the measured ductile-to-brittle transition for the zirconium-alloy cladding material **based on an acceptable experimental technique**. The calculated maximum fuel element temperature and time at elevated temperature shall not exceed the established analytical limits.

If the peak cladding temperature established to preserve cladding ductility is lower than the 2200º F limit specified in (d)(1)(i), then the lower temperature shall be used in place of the 2200º F limit.

DG-1262

Context

Relationship to rule language

DG-1263

To ensure that the zirconium-alloy cladding material's susceptibility to breakaway oxidation is beyond the realm of postulated LOCA core temperature excursions, the total accumulated time that the cladding is predicted to remain above a temperature at which the zirconium alloy has been shown to be susceptible to this phenomenon shall not be greater **than a specified and acceptable limit** which corresponds to the measured onset of breakaway oxidation for the zirconium-alloy cladding material **based on an acceptable experimental technique**. The onset of breakaway oxidation shall be measured periodically on as-manufactured cladding material and any changes in the time to the onset of breakaway oxidation shall be reported at least annually as specified in § 50.4 or § 52.3 of this chapter, as applicable, and shall also be addressed in accordance with § 21.21 of this chapter.

DG-1261

Schedule

- Three draft guides are now in inter-office concurrence
- Draft guides will be issued for public comment at the same time as the proposed rule is issued for public comment
- Draft guides will then follow standard revision and review process

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UNITED STATES NUCLEAR REGULATORY COMMISSION

Protecting People and the Environment

DG- 1261: Conducting Periodic Testing for Breakaway Oxidation Behavior

May 10, 2011

Michelle Flanagan
Division of Systems Analysis
Office of Nuclear Regulatory Research

Context

Relationship to rule language

DG-1263

To ensure that the zirconium-alloy cladding material's susceptibility to breakaway oxidation is beyond the realm of postulated LOCA core temperature excursions, the total accumulated time that the cladding is predicted to remain above a temperature at which the zirconium alloy has been shown to be susceptible to this phenomenon shall not be greater **than a specified and acceptable limit** which corresponds to the measured onset of breakaway oxidation for the zirconium-alloy cladding material **based on an acceptable experimental technique**. The onset of breakaway oxidation shall be measured periodically on as-manufactured cladding material and any changes in the time to the onset of breakaway oxidation shall be reported at least annually as specified in § 50.4 or § 52.3 of this chapter, as applicable, and shall also be addressed in accordance with § 21.21 of this chapter.

DG-1261

Objective
DG-1261

The objective of this regulatory guide is to enable performance-based rule language in 10 CFR 50.46c by providing a means of consistent, comparable data generation to establish, and periodically confirm, regulatory limits related to breakaway oxidation for zirconium-based alloys.

Thereby:

(1) Simplifying the staff's review process
(2) Reducing regulatory uncertainty, minimizing the costs associated with the implementation of the regulatory requirements proposed for 50.46c.

Objective
DG-1261

Criteria for success:

(1) Through stakeholder interaction and public comment, it is determined that:
- the details and expectations of one acceptable method for measuring a zirconium-based alloy's breakaway oxidation behavior are communicated effectively and completely
- using the test procedures produces repeatable measurements within a laboratory
- using the test procedures produces consistent measurements between laboratories

(2) Therefore: Differences in measured values of time to breakaway behavior are a reflection of allowable differences in material behavior, and not the result of differences in experimental protocol.

Background
DG-1261

- Captures the experimental technique used in NRC's LOCA research program
- Includes flexibility, where possible, to allow variation of equipment and procedures in use at other laboratories
- Draft of the procedure published for comment in conjunction with the "Advance Notice of Proposed Rulemaking (ANPR)" in August 2009
- The experimental procedure provided has been revised in consideration of the comments received in response to the ANPR.

Guidance
DG-1261

Establish the onset of breakaway oxidation

- Use experimental procedure in Appendix A
  - Test matrix defined which includes temperatures of interest and degree of replicate testing to characterize variability
- Provide experimental results as part of the documentation supporting the staff's review and approval of the new fuel design

Guidance
DG-1261

Periodic Testing

- Use experimental procedure in Appendix A
  - A reduced test matrix focuses on the temperature at which the minimum time to breakaway oxidation was measured and states that 5 repeat tests are sufficient if breakaway is not observed
- Demonstration that breakaway was not experienced can be linked to time of established analytical limit

Guidance
DG-1261

- Reporting results
  - Objective of periodic testing is to confirm that a cladding's susceptibility to breakaway oxidation has not been altered.
  - Therefore, it is acceptable to report only changes in the time to the onset of breakaway oxidation.
  - Results of periodic testing shall be provided within the annual reports "specified in § 50.4 or § 52.3 of this chapter, as applicable, and shall also be addressed in accordance with § 21.21 of this chapter"

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UNITED STATES NUCLEAR REGULATORY COMMISSION

Protecting People and the Environment

DG- 1262: Testing for Postquench Ductility

May 10, 2011

Michelle Flanagan
Division of Systems Analysis
Office of Nuclear Regulatory Research

Context

Relationship to rule language

DG-1263

Specified and acceptable analytical limits on peak cladding temperature and time at elevated temperature shall be established which correspond to the measured ductile-to-brittle transition for the zirconium-alloy cladding material **based on an acceptable experimental technique**. The calculated maximum fuel element temperature and time at elevated temperature shall not exceed the established analytical limits.

If the peak cladding temperature established to preserve cladding ductility is lower than the 2200º F limit specified in (d)(1)(i), then the lower temperature shall be used in place of the 2200º F limit.

DG-1262

Objective
DG-1262

To enable performance-based rule language in 10 CFR 50.46c by providing a means of consistent, comparable data generation to establish regulatory limits on peak cladding temperature and time at elevated temperature that corresponds to the measured ductile-to-brittle transition for a specific zirconium-alloy cladding material.

Thereby:

(1) Simplifying the staff's review process
(2) Reducing regulatory uncertainty, minimizing the costs associated with the implementation of the regulatory requirements proposed for 50.46c.

Objective
DG-1262

Criteria for success:

(1) Through stakeholder interaction and public comment, it is determined that:
- the details and expectations of one acceptable method for measuring a zirconium-based alloy's post quench ductility behavior are communicated effectively and completely
- using the test procedures produces repeatable measurements within a laboratory
- using the test procedures produces consistent measurements between laboratories

(2) Therefore: Differences in measured values are a reflection of differences in material behavior, and not a result of differences in experimental protocol.

Background
DG-1262

- Captures the experimental technique used in NRC's LOCA research program
- Includes flexibility, where possible, to allow variation of equipment and procedures in use at other laboratories
- Draft of the procedure published for comment in conjunction with the "Advance Notice of Proposed Rulemaking (ANPR)" in August 2009
- The experimental procedure provided has been revised in consideration of the comments received in response to the ANPR.

Guidance
DG-1262

- Use experimental technique to measure the ductile-to-brittle transition for a Zr-based cladding alloy
  - Can be used for generating data for any zirconium-alloy cladding material
  - Can be used for generating data at peak oxidation temperatures less than 1200° C
  - Includes discussion of using the procedure for testing irradiated material

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UNITED STATES NUCLEAR REGULATORY COMMISSION

Protecting People and the Environment

DG- 1263: Establishing Analytical Limits for Zirconium-Based Alloy Cladding

May 10, 2011

Michelle Flanagan
Division of Systems Analysis
Office of Nuclear Regulatory Research

Objective
DG-1263

To enable performance-based rule language in 10 CFR 50.46c by providing a consistent means of using experimental data to establish regulatory limits related to cladding embrittlement and the breakaway behavior of zirconium-based alloys during LOCA conditions.

Thereby:

(1) Simplifying of the staff's review process
(2) Reducing regulatory uncertainty, minimizing the costs associated with the implementation of the regulatory requirements proposed for 50.46c.

Objective
DG-1263

(1) Establish an acceptable analytical limit for time at elevated temperature for the materials tested in NRC's LOCA research program

(2) Provide Guidance on requirements for:

- New cladding alloys to demonstrate comparable performance with the established database and use the analytical limit provided in the guide
- New or existing cladding alloys to establish a zirconium-alloy-specific limit other than the limit provided in the guide
- Establishing analytical limits at peak oxidation temperatures less than 1,204 ° C (2,200 ° F).

(3) Provide guidance on establishing an acceptable analytical limit to demonstrate that ECCS performance precludes the occurrence of breakaway oxidation

Objective
DG-1263

Criteria for success:

(1) Through stakeholder interaction and public comment, it is determined that the expectations for establishing analytical limits on peak cladding temperature and time at elevated temperature under LOCA conditions are determined to be communicated effectively and completely

Guidance

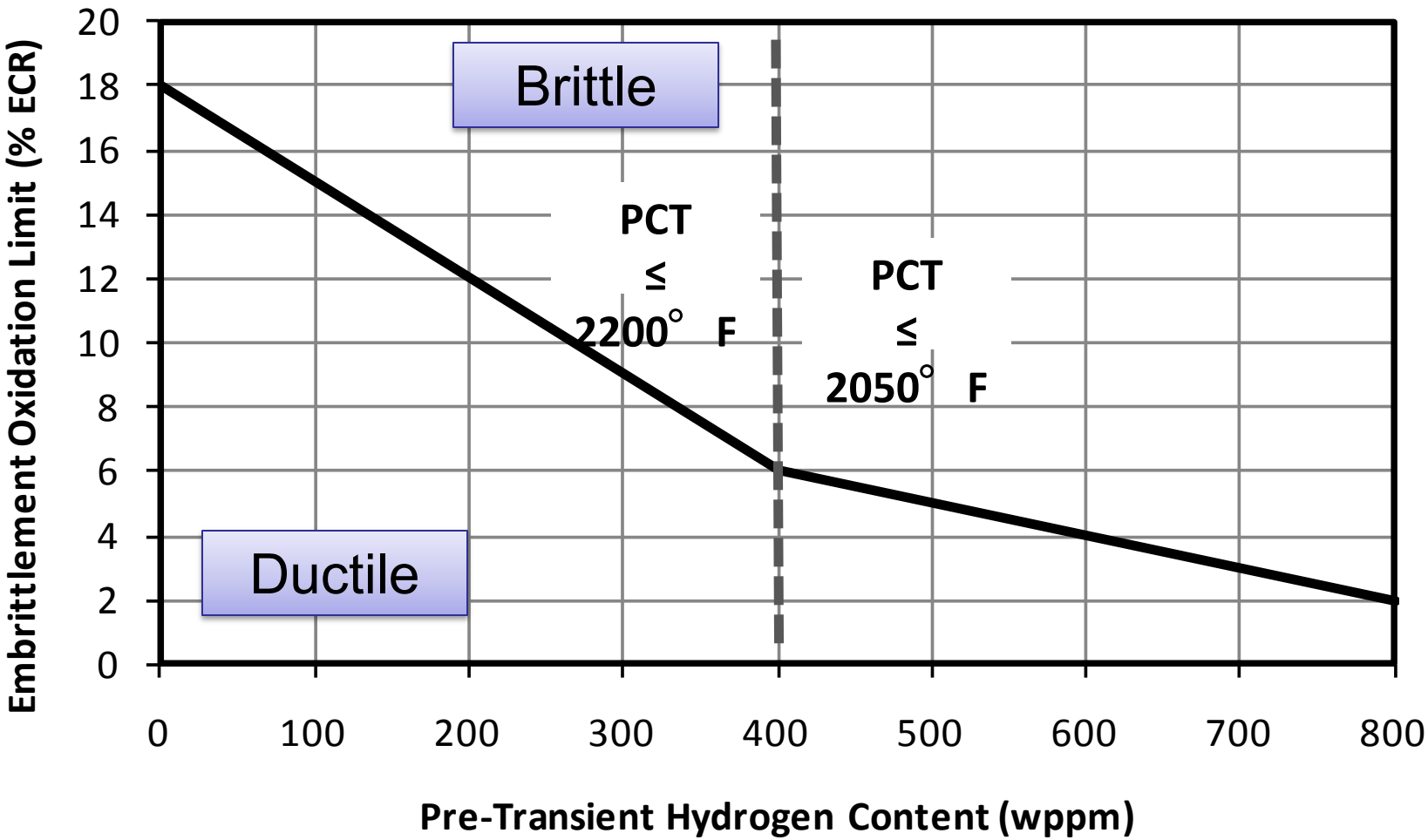
DG-1263

An acceptable analytical limit for time at elevated temperature for the materials tested in NRC's LOCA research program:

(1) Based on the data from NRC's LOCA research program
(2) Applicable to Zry-2, Zry-4, ZIRLO™, and M5
(3) PCT is related to limitations of experimental data
(4) Demonstrating that ECCS performance is such that local oxidation and peak cladding temperature are calculated below the analytical limits is acceptable to demonstrate compliance with 10 CFR 50.46c.

Guidance
DG-1263

Acceptable analytical limit for time at elevated temperature for the materials tested in NRC's LOCA research program



Guidance
DG-1263

Demonstrating comparable performance for new cladding alloys:

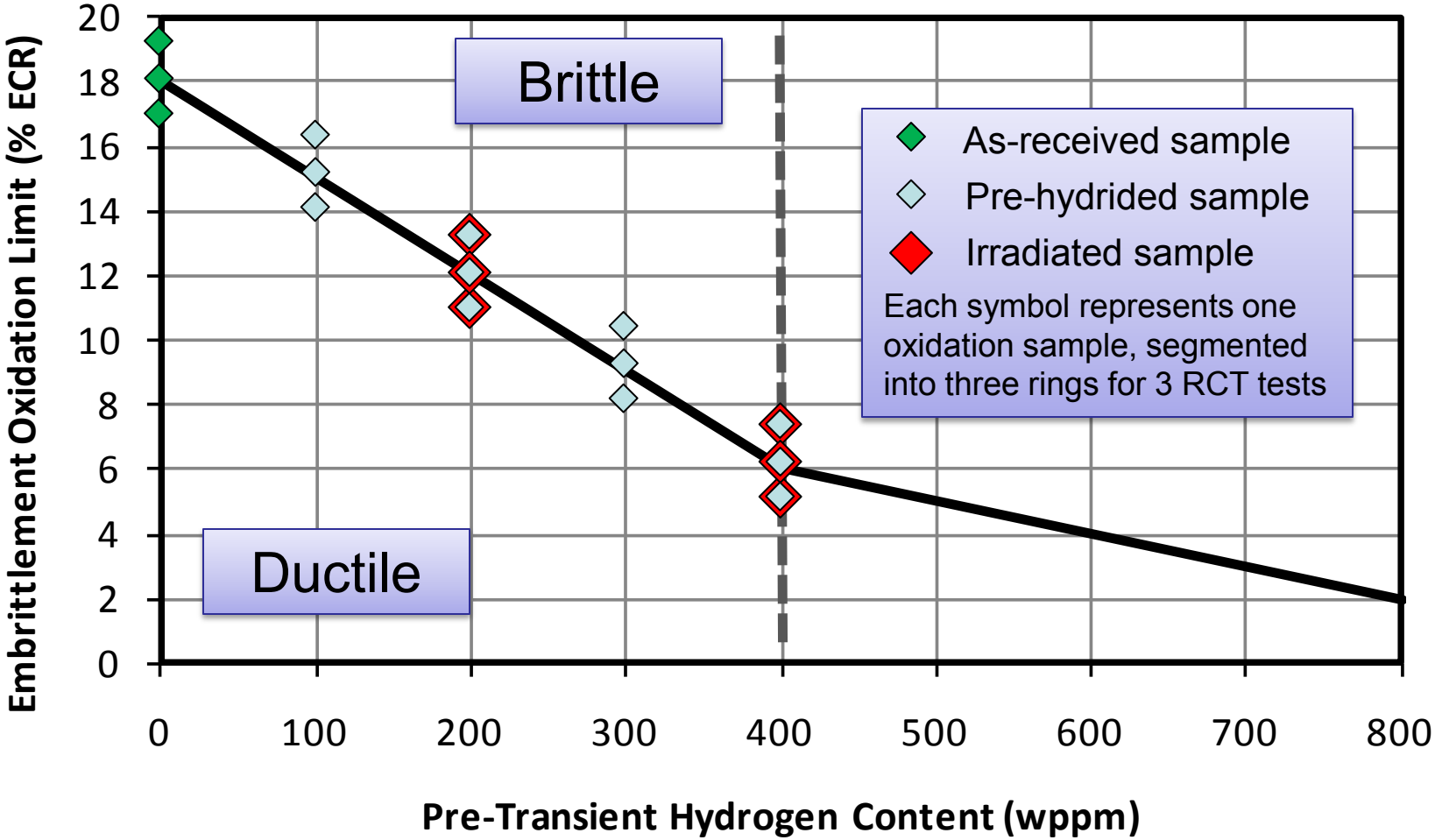
(1) Focus on confirm that the transition to brittle behavior does not take place at a lower equivalent cladding reacted (ECR) than the provided limit
(2) Methodology includes testing of as-received, prehydrided, and irradiated material
(3) Methodology uses the experimental procedure in DG-1262 to generate RCT data
(4) Experimental results submitted as part of the documentation supporting the NRC staff's review and approval of the new fuel design
(5) Demonstrating that ECCS performance is such that local oxidation and peak cladding temperature are calculated below the analytical limit is acceptable to demonstrate compliance with 10 CFR 50.46c.

Guidance

DG-1263

Demonstrating comparable performance for new cladding alloys

an acceptable test matrix for a cladding material that is anticipated to have a maximum hydrogen content of 400-wppm hydrogen at end of life



Guidance
DG-1263

Establishing Alloy-Specific Limits or Limits at a PCT Lower than 2,200° F:

(1) Methodology is designed to characterize a cladding alloy's embrittlement behavior through the entire spectrum of conditions expected during operation
(2) Methodology includes testing of as-received, prehydrided, and irradiated material
(3) Methodology uses the experimental procedure in DG-1262 to generate RCT data
(4) Experimental results submitted as part of the documentation supporting the NRC staff's review and approval of the new fuel design
(5) Demonstrating that ECCS performance is such that local oxidation and peak cladding temperature are calculated below the analytical limit is acceptable to demonstrate compliance with 10 CFR 50.46c.

Guidance
DG-1263

Establishing Analytical Limits for Breakaway Oxidation:

(1) Provide experimental results for testing for breakaway oxidation behavior
(2) Methodology uses the experimental procedure in DG-1261 to generate data
(3) Establish time limit for the total accumulated time that the cladding may remain above 650 ° C as part of the documentation supporting the NRC staff's review and approval of the new or existing fuel design
(4) Applicants may elect to establish the analytical limit for breakaway oxidation with conservatism relative to the measured minimum time (i.e., reduce the time) to the onset of breakaway oxidation
(5) Demonstrating that ECCS performance is such that the total accumulated time that the cladding is predicted to remain above a temperature at which the zirconium alloy has been shown to be susceptible to this phenomenon is not greater than the proposed limit is acceptable to demonstrate compliance with 10 CFR 50.46c.

Guidance
DG-1263

Other topics covered:

(1) Qualification of Hydrogen Pickup Models
- Submit PIE data and a hydrogen update model as part of the documentation supporting the NRC staff's review and approval of the new or existing fuel design

(2) Accounting for Uncertainty and Variability in Hydrogen Content
- Uncertainty should be quantified
- Allowable CP-ECR based on predicted peak circumferential average hydrogen content for the individual rod

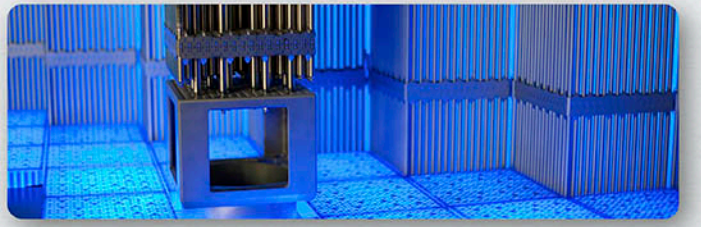
(3) Application in the Rupture Region
- define the cladding thickness as the cladding cross-sectional area divided by the cladding circumference, taken at a horizontal plane at the elevation of the rupture
- calculate two-sided oxidation using the CP correlation

Guidance
DG-1263

Other topics covered:

(4) Accounting for Double-Sided Oxidation Due to the Fuel-Cladding Bond Layer
- One acceptable approach would be to calculate two-sided local oxidation for fuel rods with a local (nodal) exposure beyond 30 GWd/MTU
- A different threshold may be proposed by a licensee and provided as part of the documentation supporting the NRC staff's review and approval of the new or existing fuel design
- A different threshold could be supported by metallographic images of bonding layers as a function of burnup

(5) Breakaway Oxidation Analytical Limits
- identify the limiting combination of break size, break location, and initial conditions and assumptions that maximize the total accumulated time
- Operator actions can be credited



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Industry LOCA Test Plans and Results

Ken Yueh
Senior Project Manager

ACRS Subcommittee Meeting
May 10th, 2011

Motivations for Industry LOCA Research Efforts

- Research data used as the basis for the LOCA rule were generated or applied in a conservative condition/manner
  - Many plants do not operate near the limiting conditions
  - Some phenomena have not been fully evaluated
- EPRI has sponsored several complementary test programs to fill some of the gaps
  - To better understand fuel performance under more realistic conditions

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Presentation Outline

- Preliminary high temperature oxidation test results
- Inner diameter oxygen pickup (two-sided oxidation)
  - Fuel pellet interaction
  - Impact of limited ID oxygen source on PQD
- LOCA round robin test plans

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High Temperature Oxidation Preliminary Results

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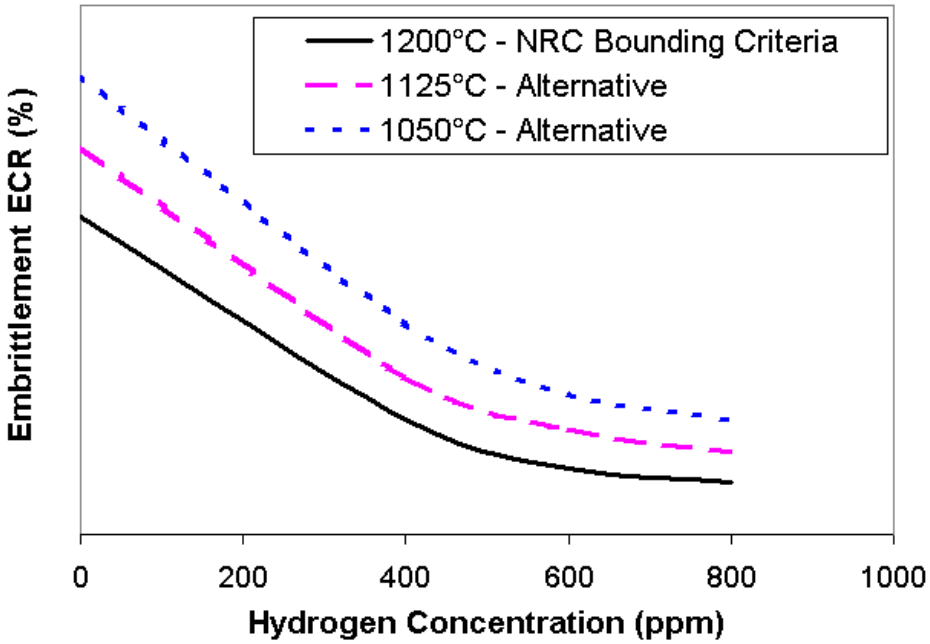
High Temperature Oxidation

- Motivation
  - ANL data indicates ECR accumulated at lower temperatures is not as detrimental to ductility for Zircaloy-4
- Test goals
  - Generate sufficient test data to propose alternative PQD criteria not tied to 1200°C
  - Attempt to demonstrate ECR is not reduced to zero at hydrogen > 600 ppm
  - Determine feasibility of developing an embrittlement model



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High Temperature Oxidation Test Details

- Expand ANL database on cladding ductility
- Peak cladding temperatures (1050°C – 1200°C)
- Hydrogen contents (As-built – 1000 ppm)
- Testing procedures mostly consistent with ANL guidelines
  - Indirect resistance heating furnace
- Embrittlement model development
  - Establish oxygen profile prior to cooling and quenching
  - Evaluate oxygen segregation and microstructure changes during cooling and their impact on ductility
  - Establish metallurgical conditions at critical ductile-to-brittle transitions

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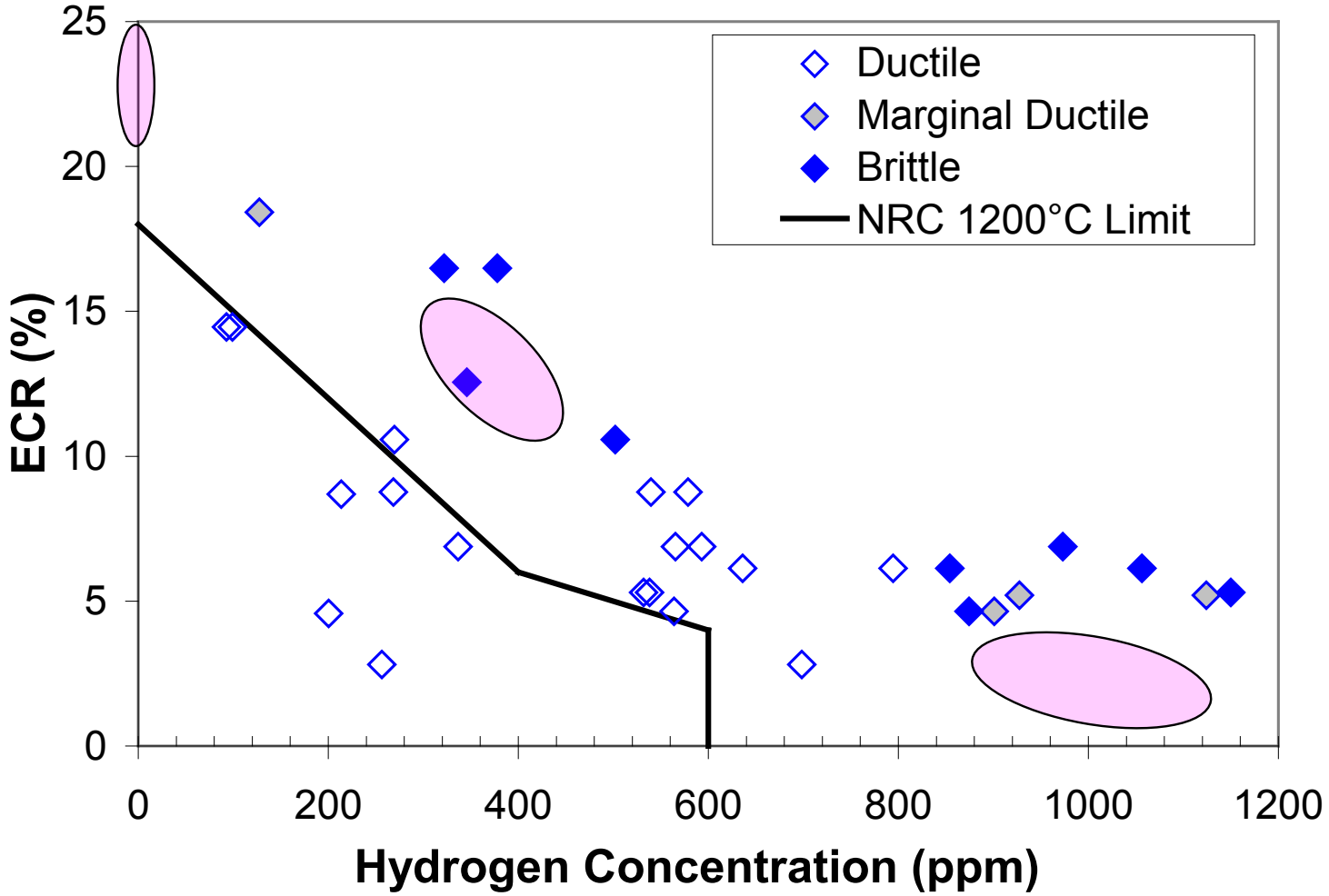
High Temperature Oxidation Preliminary 1050°C Test results

- A few additional tests planned to fill gaps (Summer 2011)



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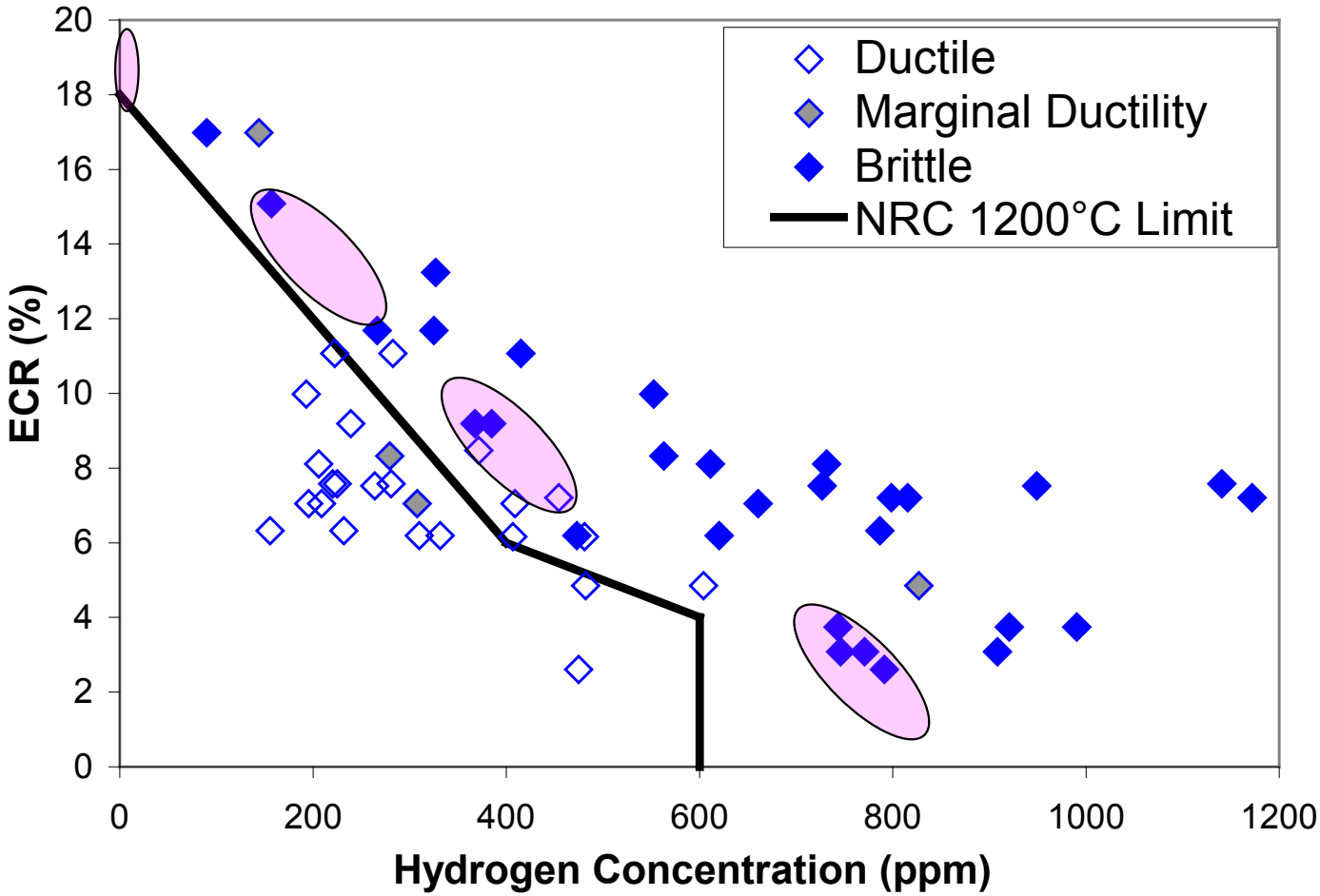
High Temperature Oxidation Preliminary 1125°C Test results

- More data to be generated (Summer 2011)



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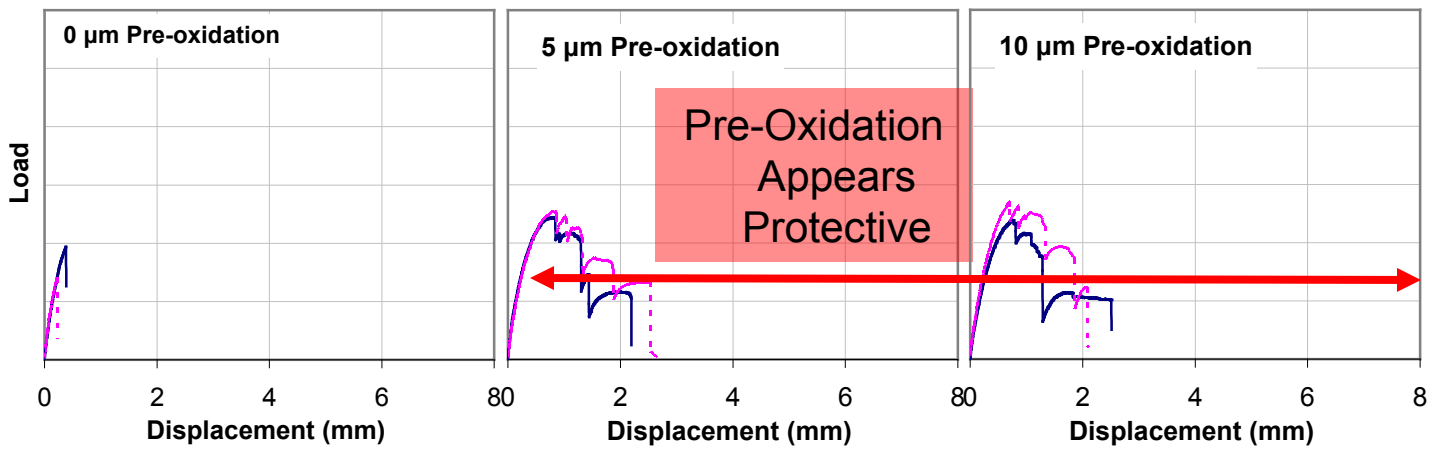
High Temperature Oxidation
Test results 1200°C

- Insufficient test data to establish trend at this time
  - Industry testing appears to yield results more restrictive than published irradiated ANL test results
  - Difference could be influenced by pre-existing oxide

- two-sided oxidation
- 475s
- ~22 % ECR



  - Impact of pre-existing oxide to be evaluated
- More testing in progress

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High Temperature Oxidation Test Summary

- Higher embrittlement ECR at lower oxidation temperatures is clearly demonstrated
  - The PCT of many plants and fuel will not reach 1200°C
- RCT based acceptance criteria is conservative
  - Clad at PCT only a short time

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Recommendations

- Test data indicates alternative acceptance criteria can be justified
  - Family of embrittlement curves at different PCTs
  - Interpolation of acceptance criteria between PCTs and application of pin specific PCT
  - Use of model predictions should the phenomenon be successfully modeled

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ID Oxygen Pickup

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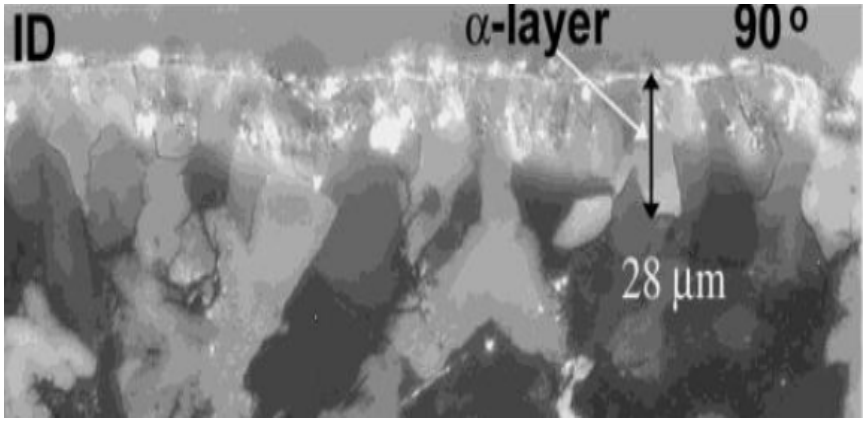
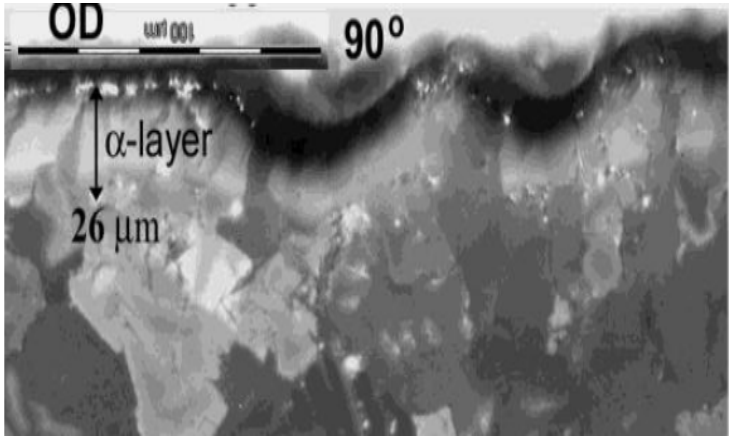
Background

- NRC announced the inclusion of two-sided oxidation away from the ballooned and burst region into rule
  - NRC cited similar ID and OD alpha phase thickness in the IFA650.5 test, PCT 1050°C, to justify two-sided oxidation





- A 3μm oxide has sufficient oxygen to generate such an oxygen stabilized alpha layer, Halden report claimed oxygen source from bonded fuel

Oxygen for the alpha layer could have come from pre-transient oxide layer rather than bonded fuel

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Alternative Hypothesis

- The ID surface oxygen pickup does not occur at the same rate or to the same extent as OD surface since ID oxygen source may be limited
  - Bonded fuel was suggested as a source of oxygen, but Limerick and Halden integral test results suggest it is limited
    - Literature test data indicate pellet-clad contact is needed for oxygen transfer from pellet to clad
  - Internal oxygen source may be limited to the pre-transient oxide

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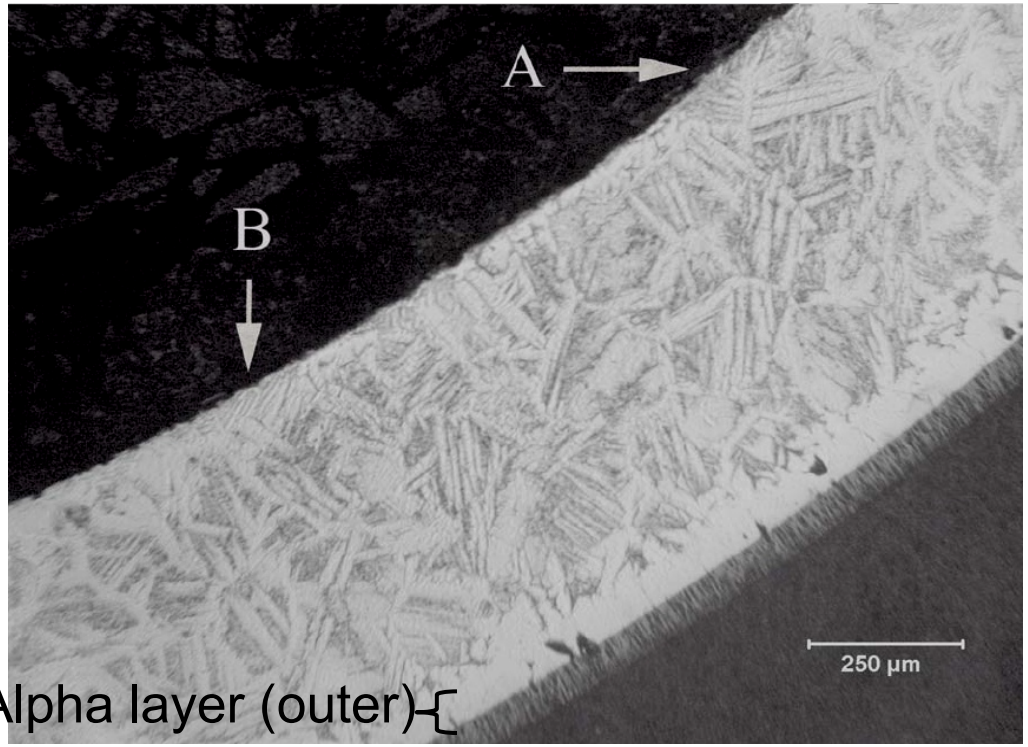
Experimental Evidence – Limerick Fuel

- No evidence of more alpha layer near bonded fuel



Alpha layer (outer)

Limerick fuel at 57-60 GWd/MTu

NUREG/CR6967Interpretation

(A): This inner-surface region does not have an alpha layer even though in close proximity to fuel material. More typical of what is observed for most of the inner surface at this axial location.

(B): Evidence of some local inner surface oxygen-stabilized alpha

ID surface oxide clearly absorbed by the clad, no significant evidence of bonded fuel reaction

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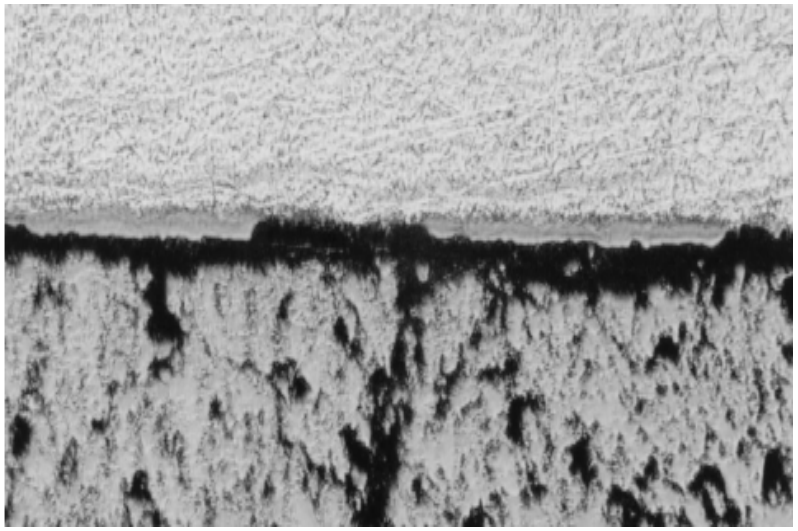
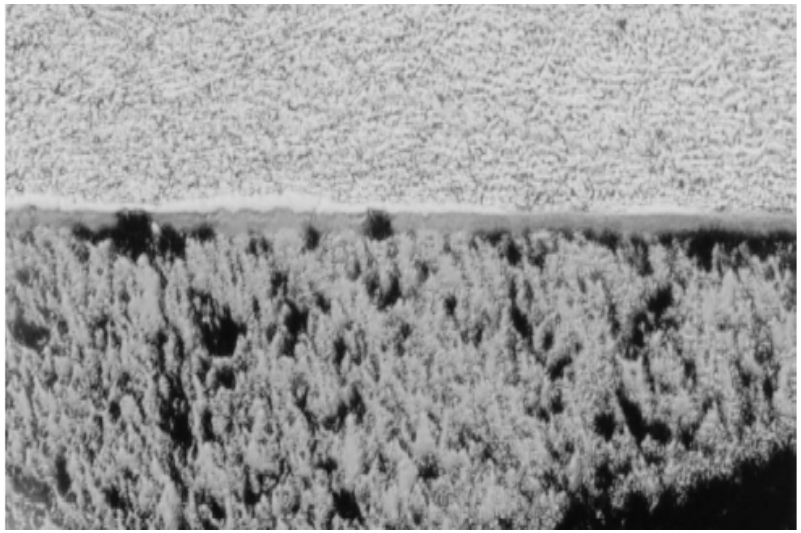
Experimental Evidence

- Typical structure of bonded fuel





  – In every case where fuel bonding takes place there is an oxide layer between the fuel clad and bonded fuel

Absence of significant observed fuel-clad reaction in both Halden and ANL tests suggests oxygen transfer from bonded fuel is limited, and may be limited to the pre-transient oxide

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Fuel-Clad Interaction Test

- Goals
  - Verify Hoffman's observations
  - Evaluate the extent of reaction with contact pressure and pre-oxidation
- Fuel-clad reaction test conditions
  - Short rodlets, approximately 6.5" in length, sealed with and without non-irradiated natural uranium pellets in He
  - Fresh and pre-oxidized cladding
  - With or without contact pressure
    - Oversized pellets and positive external pressure to create contact conditions
  - 1000 and 1100°C test temperatures
  - 1 to 30 minutes of exposure at temperature
  - Samples tested in both horizontal and vertical orientations

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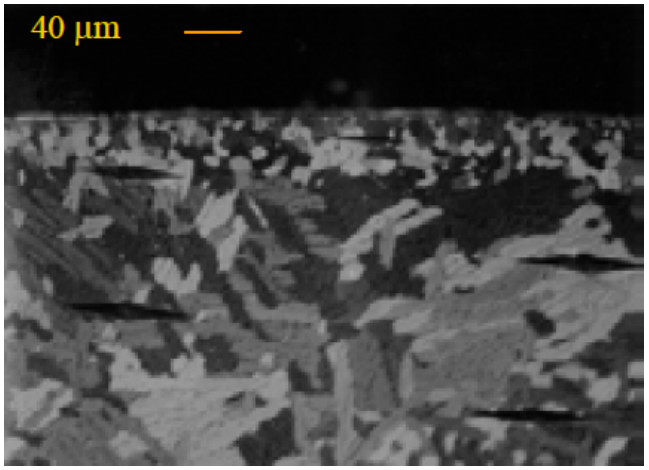
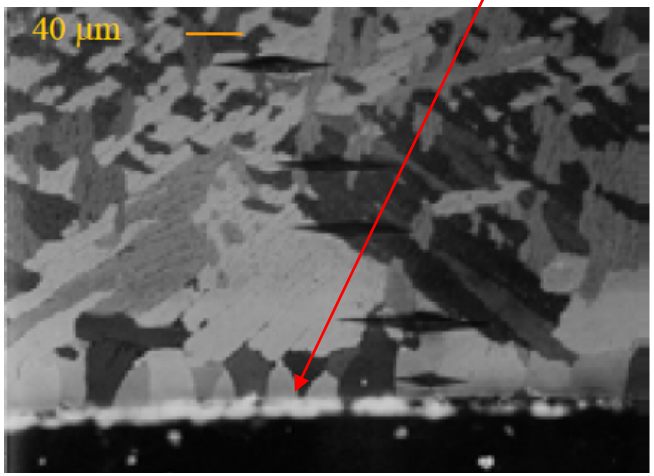
Fuel-Clad Interaction Test

- Halden IFA-650.5 test temperature profile approximately simulated
  - Pre-oxidized clad to ~7 μm at 650°C, no fuel pellet
  - Oxygen stabilized alpha similar to Halden test observed



Outer Diameter



Inner Diameter

Result confirms a pre-transient ID oxide can supply oxygen to form an oxygen stabilized alpha layer as seen in IFA 650.5

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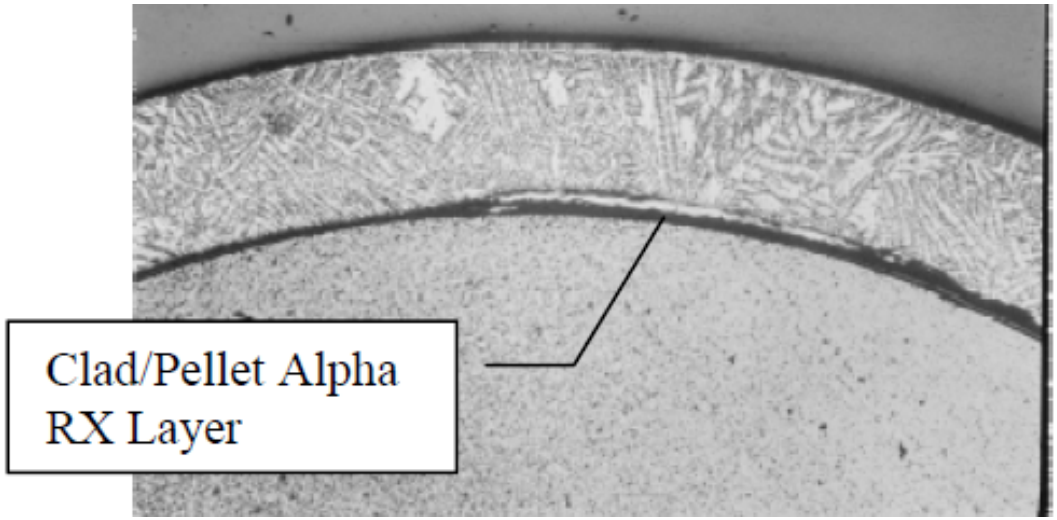
Fuel-Clad Interaction Test

- Half of the test samples, independent of test contact pressure conditions, showed no pellet-clad reaction
- Minor localized pellet-clad reaction observed on some of the samples



Reaction layer is minor and not directly observed in irradiated LOCA integral tests and therefore limited oxygen transfer from the fuel

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Impact of Limited ID Oxygen Source on PQD

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Impact of Limited Oxygen Source on PQD Test Plan

- Evaluate the impact of a pre-transient oxide on the PQD
  - Zircaloy-2 and a few Zircaloy-4
  - Unrestricted double sided oxidation
  - Unrestricted OD/restricted ID oxidation
    - Pre-oxidized sealed capsules
  - Test parameters
    - 0, 5 and 10 μm pre-oxidation at 800°C
    - 1100 and 1200°C oxidation temperatures
    - 2 ECRs
  - Post quench ductility testing

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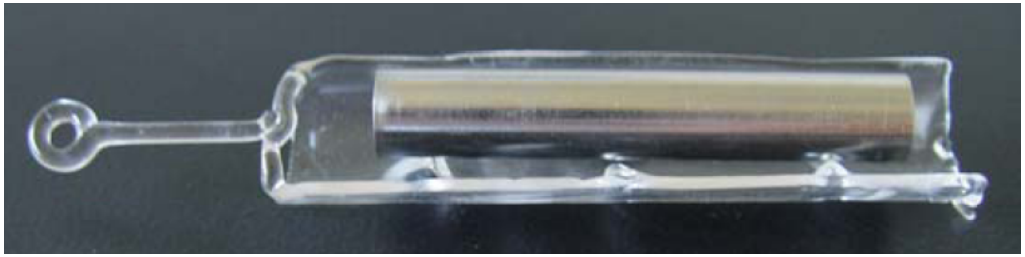
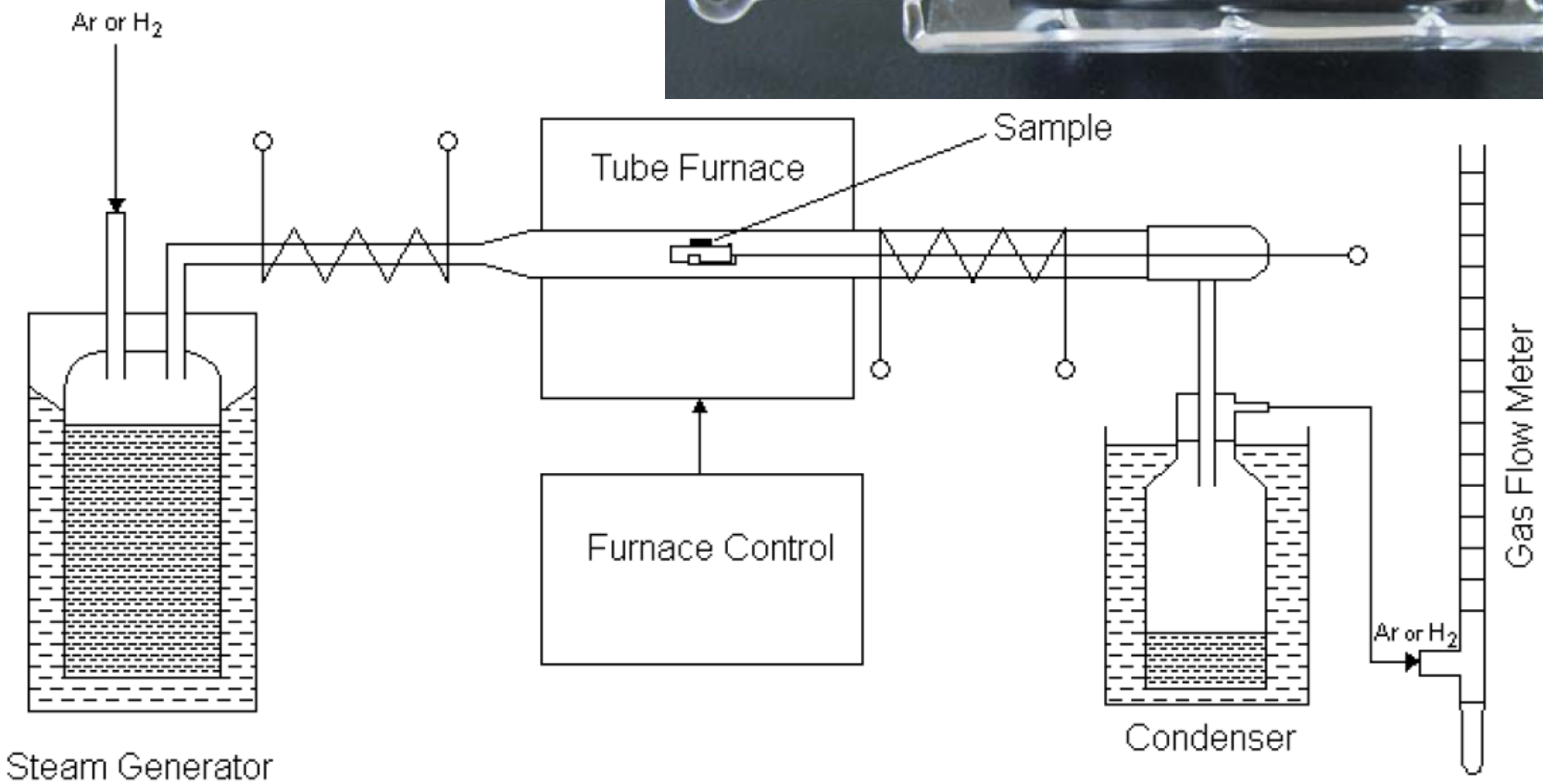
Impact of Limited Oxygen Source on PQD Test Setup

- Three zone horizontal furnace





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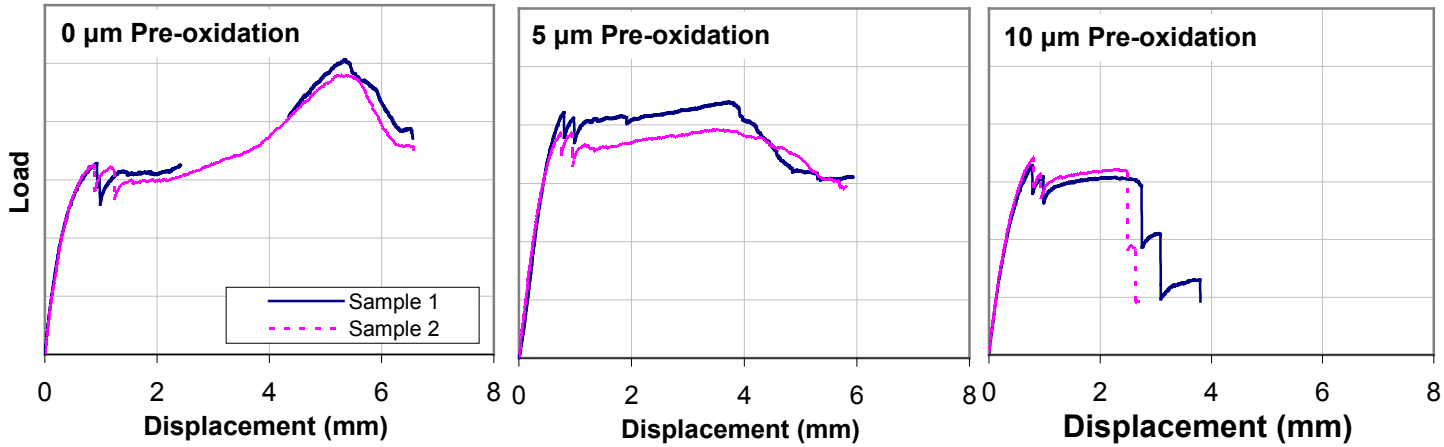
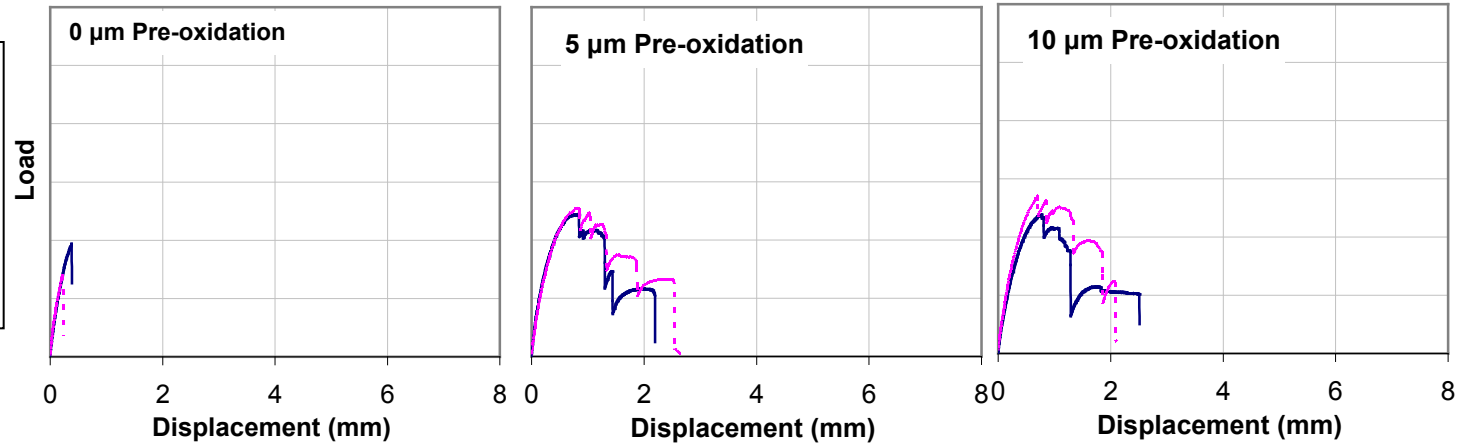
Impact of Limited Oxygen Source on PQD Results – 1200°C

- Sealed, one-sided
- 460s exposure



- Open, two-sided
- 475s exposure
- ~22 % ECR



Reduced impact on PQD from limited ID oxygen source Demonstrated

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Quantification of Limited Impact on PQD Test Plan

- Quantify the impact of a pre-transient oxide on PQD (Zircaloy-4)
  - Unrestricted double sided oxidation
  - Unrestricted OD/restricted ID oxidation
    - Pre-oxidized sealed capsules
  - Test parameters
    - 10 and 20 μm pre-oxidation at 800°C
    - 1200°C oxidation temperature with limited number at 1100°C
    - 3 ECRs determined by AEKI to bracket transition

Pre-oxidation (μm)	Target ECR	
	Open	Closed
0	15,18,21	15,18,21
10	15,18,21	12,15,18
20	15,18,21	12,15,18

  - Post quench ductility testing

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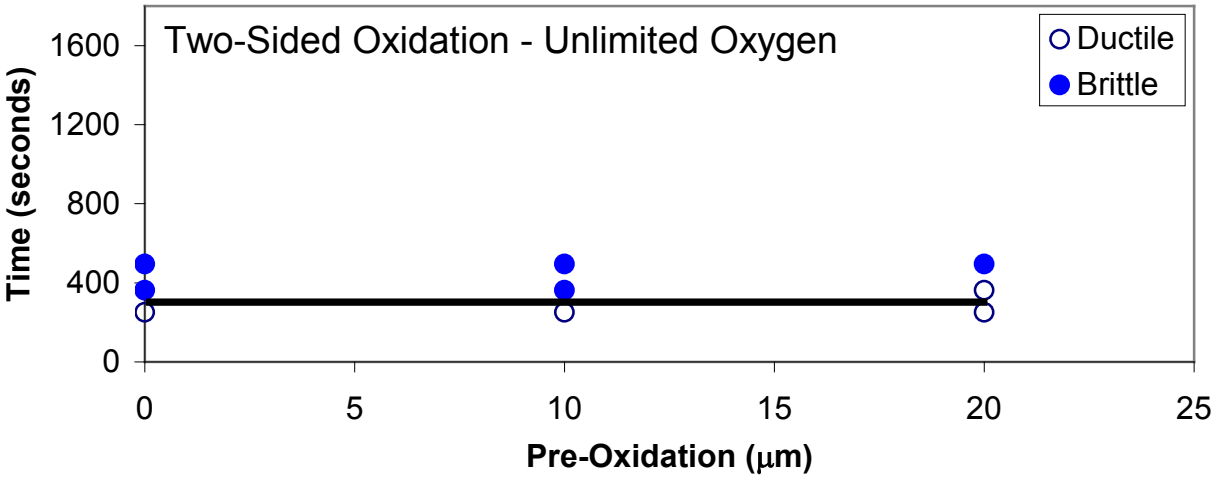
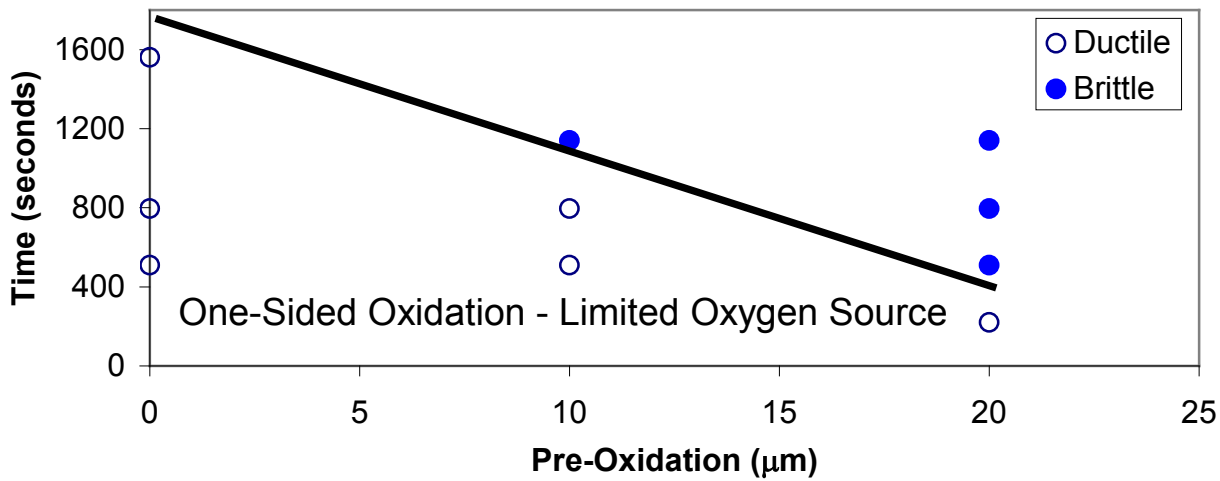
Impact of Limited Oxygen Source on PQD Quantification of Impact on PQD – 1200°C





- Results within expectation
  - Time to ductility loss for one-sided oxidation samples increased significantly with no pre-oxidation, 362 to ~1800 seconds
  - Difference decreases with increasing pre-oxidation, ~400 vs. 362 seconds at 20 μm pre-oxidation

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ID Oxygen Pickup Summary

- Oxygen stabilized alpha phase cited in IFA-650.5 could be generated from a pre-transient oxide rather than from fuel
- Limited potential for pellet-clad reaction
  - Reaction is generally localized and impact should be minor
- Impact of limited ID oxygen source on PQD was quantified
  - Impact of limited ID oxygen source on PQD is less than un-restricted two-sided oxidation
    - Reduction in ductility lose is significantly less compared to un-restricted two-sided oxidation up to 20 μm of pre-oxidation
- Pre-oxidation slightly improves clad PQD performance

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Recommendations

- Test demonstrated clad embrittlement is much reduced with limited ID oxygen source
  - Regulatory guidance should recognize this and allow for reduced impact under some conditions
    - e.g., 50% if pre-transient oxide is less than 10 μm

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LOCA Round Robin

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LOCA Round Robin
Project Goals

- Identify and evaluate sources of variation
  - Between laboratories (different procedures and methods)
  - Other experimental
- Generate sufficient test data to support ASTM test procedures

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LOCA Round Robin Program Framework

- Project goals require participation of multiple laboratories (5 minimum)
  - Each laboratories to conduct PQD and breakaway oxidation test on a common set of agreed test parameters
    - Use a common lot of material
  - All sample preparation will be performed by individual laboratories
    - Hydrogen pre-charged samples will be supplied to two laboratories
- Test data generated from each laboratory will be shared and a combined test report will be provided to each participants

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LOCA Round Robin
Test Plans 1/3

- A common set of PQD and breakaway tests conducted by all laboratories
  - Major parameters are consistent with ANL recommendations
  - A few minor exceptions

Post Quench Ductility

  - ANL-like temperature profile at 1200°C set point
  - Recommended ECR targets

Hydrogen Content (ppm)	Target CP ECR (%)		
As-Built	16	18	20
200	10	12	14
400	4	6	8
600	3	5	7

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LOCA Round Robin
Test Plans 2/3

- Oxidation sample data collection and evaluation
  - As charged hydrogen concentration
  - Weight gain per ASTM G2 procedure and check consistency
  - Photograph abnormal oxide appearance
  - Metallography to verify oxidation and temperature uniformity (1 or 2 samples)
- Ring compression test
  - 135°C+/-2°C
  - 0.033+/-.005 mm/second loading rate
- RCT data collection and evaluation
  - Load displacement versus time/Permanent strain if available
  - Photograph each sample, some local hydrogen analysis
  - 1% plastic strain criteria

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LOCA Round Robin
Test Plans 3/3

Breakaway Oxidation

- ANL recommended temperature profile
- Determine breakaway oxidation at 800 and 1000°C to within 500 seconds
- Breakaway oxidation data collection and evaluation
  - Weight gain per QA procedure/ASTM G2 and check for consistency
  - Photograph abnormal oxide appearance
  - Metallography to verify oxidation and temperature uniformity (1 or 2 samples)
  - Post test hydrogen measurements if needed

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LOCA Round Robin
Labs and Test Equipment

- Seven laboratories joined the Round Robin

Laboratory	H Charging Capability	Furnace Type	RCT Platform	Breakaway Online Instr.
AEKI	No	Resistance	Flat	Yes (hydrogen)
AREVA (via CEA)	Yes	Direct resistance		
GNF	Yes	Resistance		None
KAERI	Yes	Radiant	Flat	Yes (weight)
Oakridge	Yes	Resistance		
Studsvik*	No	Radiant		None
Westinghouse	Yes	Resistance	Flat	None

* May drop out of round robin because equipment moved into hot-cell

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LOCA Round Robin Status

- Test material acquired in December 2010 and as-received condition sent too all participating laboratories
  - Hydrogen pre-charged samples shipped to one laboratory in April
- Studsvik will likely reduce their scope or drop out due to equipment relocated into hot-cell
- Variations in hydrogen pre-charge values will complicate data evaluation
  - ASTM B10.02 subcommittee consulted, adopted a wait and see position
- Testing will likely be completed summer 2011

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LOCA Round Robin
Milestones and Schedule

Step	Details	Schedule
1	Identify laboratories and solicit participation	Complete
2	Setup framework	Complete
3	Secure test material	Complete
4	Start test	Complete
5	Complete test	Summer 2011
6	Distribute data to participants and ASTM	TBD
7	Review data with the NRC and ASTM	TBD
8	Draft ASTM procedure	TBD
9	ASTM and NRC review procedure	TBD
10	Implement ASTM procedure	TBD

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