

Official Transcript of Proceedings
NUCLEAR REGULATORY COMMISSION

Title: Advisory Committee on Reactor Safeguards
Materials, Metallurgy and Reactor Fuels

Docket Number: (n/a)

Location: Rockville, Maryland

Date: Tuesday, May 10, 2011

Work Order No.: NRC-897

Pages 1-270

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.

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

UNITED STATES OF AMERICA

NUCLEAR REGULATORY COMMISSION

+ + + + +

ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

(ACRS)

+ + + + +

SUBCOMMITTEE ON MATERIALS, METALLURGY AND REACTOR

FUELS

+ + + + +

TUESDAY

MAY 10, 2011

+ + + + +

ROCKVILLE, MARYLAND

+ + + + +

The Subcommittee convened at the Nuclear
Regulatory Commission, Two White Flint North, Room
T2B1, 11545 Rockville Pike, at 8:30 a.m., Dr. Said
Abdel-Khalik, Chairman, presiding.

SUBCOMMITTEE MEMBERS PRESENT:

J. SAM ARMIJO, Chairman

SAID ABDEL-KHALIK

DENNIS C . BLEY

CHARLES H. BROWN, JR.

MICHAEL CORRADINI

JOY REMPE

1 SUBCOMMITTEE MEMBERS PRESENT: (Continued)

2 WILLIAM J. SHACK

3 JOHN D. SIEBER

4

5 NRC STAFF PRESENT:

6 CHRISTOPHER L. BROWN, Designated Federal

7 Official

8 SHER BAHADUR

9 PAUL CLIFFORD

10 MICHELLE FLANAGAN

11 RALPH LANDRY

12 HAROLD SCOTT

13

14 ALSO PRESENT:

15 RALPH MEYER (via telephone)

16 MIKE BILLONE (via telephone)

17 GORDON CLEFTON

18 TOM RODACK

19 KEN YUEH

20 BOB COMSTOCK

21 BERT DUNN

22 TOM EICHENBERG

23 MITCH NISSLEY

24 YING-PI LIN

25

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

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

Opening Remarks, Sam Armijo 4

Staff Introduction, Sher Bahadur 7

NRC - Overview of 50.46(b) Rulemaking, Paul Clifford
. 8

Overview of DGs

Overview of DG-1261 Breakaway Oxidation Testing,
Michelle Flanagan 25

Overview of DG-1262 Post-Quench Ductility Testing,
Michelle Flanagan 89

Overview of DG-1263 Analytical Limits (Acceptance
Criteria), Michelle Flanagan 117

Industry Presentation - Test Results & Round Robin,
Ken Yueh 185

Public Comments

Ralph Meyer 259

Subcommittee Discussion 262

Adjourn 270

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

8:30 a.m.

CHAIRPERSON ARMIJO: All right. Good morning. The meeting will now come to order.

This is a meeting of the Materials Metallurgy and Reactor Fuels Subcommittee. I am Sam Armijo, Chairman of the subcommittee.

ACRS members in attendance are Dennis Bley, Jack Sieber, Bill Shack, Joy Rempe and Said Abdel-Khalik. Charles Brown will be here a few minutes late and we're not quite sure where Mike Corradini is, but he may come in also.

MEMBER SHACK: Nobody's ever sure where Mike is.

CHAIRPERSON ARMIJO: Yes, right. Christopher Brown of the ACRS staff is the designated federal official for this meeting.

The purpose of the meeting is to receive an update on the rulemaking activities and three regulatory guides related to the revision of 10 C.F.R. 50.46(b).

We will hear presentations from representatives of the Office of Nuclear Reactor Regulation and the Nuclear Regulatory Research. In addition, presentations will be heard from the

NEAL R. GROSS

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

1 Electric Power Research Institute.

2 The subcommittee will gather information,
3 analyze relevant issues and facts and formulate
4 proposed positions and actions as appropriate for
5 deliberation by the full committee.

6 The rules for participation in today's
7 meeting were announced as part of the notice to the
8 meeting previously published in the *Federal Register*
9 on May 2, 2001.

10 We have received no written comments or
11 requests in time to make oral statements from members
12 of the public regarding today's meeting.

13 A transcript of the meeting is being kept
14 and will be made available as stated in the *Federal*
15 *Register* notice. Therefore, we request that
16 participants in this meeting use the microphones
17 located throughout the meeting room when addressing
18 the subcommittee. Participants should first identify
19 themselves and speak with sufficient clarity and
20 volume so that they can be readily heard. And we
21 request that all cell phones be silenced.

22 Additionally, I would just like to mention
23 to presenters, as you're talking, just be careful
24 about whooshing your papers over the microphone. It
25 creates quite a bit of noise and it's very difficult

NEAL R. GROSS

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

1 for the transcription.

2 In addition, we're expecting Mike Billone
3 of the Argonne National Laboratory to be on the bridge
4 line. The bridge line is open and I'd like to ask:
5 Mike, are you on the phone?

6 (No audible response.)

7 CHAIRPERSON ARMIJO: Okay. But it's still
8 open, so he's -- I trust it's on mute?

9 MR. BROWN: Yes.

10 CHAIRPERSON ARMIJO: Okay. So, maybe
11 that's his problem. Okay.

12 MR. MEYER: Could I break in? This is
13 Ralph Meyer, NRC, retired. Now I work for Mike
14 Billone for Argonne.

15 CHAIRPERSON ARMIJO: Okay.

16 MR. MEYER: Mike will be on the phone
17 presently. I will be on the phone during the day.

18 CHAIRPERSON ARMIJO: Okay. Okay.

19 Welcome, Ralph. Good to hear from you.

20 Just some comments, background comments.
21 During the 558th meeting of the ACRS in December of
22 2008 we reviewed the technical basis and rulemaking
23 strategy proposed by the staff for revising the fuel
24 cladding embrittlement criteria in 10 C.F.R. 50.46(b).
25 Our Subcommittee on Materials and Metallurgy Reactor

NEAL R. GROSS

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

1 Fuels also reviewed the matter in December of 2008.

2 In our letter we concluded that there are
3 sufficient data and there is sufficient understand of
4 the cladding embrittlement phenomena to justify and
5 proceed with rulemaking. We also stated that the
6 rules should include proposed optional testing program
7 to allow licensees to demonstrate compliance with
8 post-quench ductility criteria on an alloy-specific
9 and temperature-specific basis. And third, we
10 recommended a round robin test program. Pointed out
11 it would be beneficial in the validation of the test
12 procedure used to demonstrate compliance with post-
13 quench ductility and breakaway oxidation criteria.

14 With that introduction, I'd like to
15 proceed with the meeting and call on Dr. Sher Bahadur
16 of the Office of Nuclear Reactor Regulation to start
17 the discussion. Sher?

18 DR. BAHADUR: Thank you, Mr. Chairman.
19 Good morning. My name is Sher Bahadur and I'm acting
20 director for the Division of Safety Systems in NRR.

21 As you mentioned, in December 2008 the
22 staff briefed this committee on the LOCA Research
23 Program findings and the rulemaking strategy for
24 revising the ECCS requirement within the 10 C.F.R.
25 50.46. During that briefing the staff introduced the

NEAL R. GROSS

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

1 concept of replacing the existing prescriptive
2 criteria with performance-based requirements. As part
3 of that performance-based requirement detailed
4 guidance, including an acceptable test procedure for
5 establishing analytical limits needed to be developed.

6 The staff has completed those guidance
7 documents and these staff regulatory guidance
8 documents is the subject of today's briefing. The
9 staff in today's meeting would present the three draft
10 guidance. And then following this meeting the staff
11 would publish these reg guides for public comments.

12 So with that as a brief introduction, I'd
13 like to ask Paul Clifford. Paul is a senior level
14 advisors in the Division of Safety Systems in NRR.
15 I'll ask him to start the briefing and give you an
16 introduction of the agenda. And as you know, the
17 briefing would be shared also by Michelle Flanagan
18 from the Office of Research.

19 So with that, I'll ask Paul to start.

20 MR. CLIFFORD: Thank you, Sher. Good
21 morning. I'd like to start by just quickly walking
22 through the agenda so we all understand how this
23 meeting will progress.

24 Today I will be providing a brief summary
25 of the 50.46(b) rulemaking project with respect to

NEAL R. GROSS

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

1 past, present and future ACRS interactions. My
2 presentation will be followed by Michelle Flanagan
3 from the Office of Research who will begin her
4 presentation with an overview of the three draft reg
5 guides to illustrate how the guidance supports the
6 performance-based requirements within the draft rule
7 language. This overview will be followed by detailed
8 presentations on each of the three reg guides.

9 Towards the end of the day the industry
10 will present results from their ongoing LOCA Research
11 Program and describe a round robin-type exercise
12 conducted at several sites.

13 MEMBER SHACK: Just to get myself
14 oriented, what's the point of the 50.46(c)? I mean,
15 this is not going to be an alternative, right? I
16 mean, this is going to be the embrittlement rule.

17 MR. CLIFFORD: Correct. That's a good
18 question. 50.46(c), the designation (c) is because
19 when the rule is first implemented, there will be
20 plants that are still in compliance with the existing
21 50.46. And then there will be a staged implementation
22 whereby plants will move over to 50.46, the new
23 version of 50.46 which were designated (c).

24 So for a period of time in the interim
25 there will be two rules. Neither one will be

1 optional, but plants will be in compliance with either
2 one until they are all transitioned to 50.46(c), at
3 which time 50.46(c) will then replace 50.46.

4 MEMBER SHACK: Okay. There's also
5 language in one of the guides that says, you know, an
6 alloy-specific hydrogen uptake model will be required
7 if a licensee chooses to use the hydrogen-dependent
8 embrittlement threshold provided in this regulatory
9 guide. Does he really have a choice?

10 MR. CLIFFORD: No.

11 MEMBER SHACK: Okay. That's what I
12 thought, but the language just seemed to imply that he
13 did.

14 MS. FLANAGAN: I will note that.

15 MR. CLIFFORD: What?

16 MS. FLANAGAN: I will note that.

17 MR. CLIFFORD: Okay. This slide outlining
18 the 50.46 rulemaking objectives was presented at the
19 last briefing in December of 2008. These objectives
20 have not changed. Following the commission directive,
21 the proposed rule has been developed which replaces
22 the prescriptive criteria for performance-based ECCS
23 requirements. In addition, the applicability of the
24 rule has been extended beyond just Zircaloy or ZIRLO.
25 In addition, the proposal captures the results of the

NEAL R. GROSS

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

1 High Burnup LOCA Research Program.

2 During the past ACRS briefing the findings
3 of the LOCA Research Program were presented. These
4 findings demonstrate that the existing regulatory
5 criteria which is a peak cladding temperature of 2200
6 degrees Fahrenheit and a maximum local oxidation of 17
7 percent ECR needed to be revised and expanded upon to
8 achieve the underlying objective of the rule, which is
9 to maintain fuel rod cladding ductility. The
10 research identified new embrittlement phenomena
11 including hydrogen-enhanced prior-beta layer
12 embrittlement, cladding ID, oxygen ingress and
13 breakaway oxidation.

14 During the December meeting of 2008 the
15 staff outlined the scope of the proposed rule,
16 including the development of the performance-based
17 requirements which capture the research findings. At
18 that time the staff was considering specific numerical
19 criteria within the rule along with the optional
20 testing procedure as Dr. Armijo identified at the
21 beginning of this meeting. And that future regulatory
22 guidance would develop and provide guidance on the
23 specifics for showing compliance and for performing
24 the optional testing. The staff was also considering
25 issuing an Advance Notice of Proposed Rulemaking to

NEAL R. GROSS

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

1 solicit stakeholder input on specific topics.

2 In response to this meeting the ACRS
3 issued a letter. There were three specific
4 recommendations. The first, recognizing that
5 additional testing was ongoing on post-quench
6 ductility of the timing for breakaway oxidation. The
7 ACRS recommended proceeding with rulemaking. Second,
8 the proposed rule should allow licensees to perform
9 testing and define specific post-quench ductility
10 analytical limits. And finally, concerned with the
11 reproducibility of test results and lab-to-lab
12 variability the ACRS recommended a detailed test
13 procedure be developed and validated by a round robin-
14 type test program.

15 There has been a lot of progress since the
16 last briefing, and this slide will walk through the
17 progress. First, the ANPR was issued. That was
18 August 2009. Comments were received from several
19 utilities, each of the three fuel vendors,
20 international research and regulatory agencies, and
21 members of the general public. The comments and the
22 staff's response to those comments will be documented
23 in the proposed rule package.

24 In addition, the Office of Research has
25 completed additional PQD and breakaway testing. This

NEAL R. GROSS

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

1 testing includes post-quench ductility tests on
2 irradiated cladding segments at intermediate hydrogen
3 levels; roughly 200 to 300 weight ppm range, and an
4 investigation into the transient temperature profile
5 effects on the timing of breakaway oxidation. Also
6 the rule language was updated, removing specific
7 numerical requirements which were -- that moved to the
8 associated regulatory guidance documents, which we
9 will be talking about today. And finally, three reg
10 guides were developed and Michelle Flanagan from the
11 Office of Research will be presented each today.

12 Slot 7 identifies new items related to
13 50.46(b) rulemaking, but items which have not been
14 previously described to the ACRS. The first is that
15 the staff has developed a draft generic letter to
16 obtain plant-specific information to confirm plant
17 safety in the interim recognizing that the
18 implementation of the final rule would take several
19 years. In response to the generic letter, the
20 industry has proposed an alternative whereby the same
21 information will be provided by our PWR and BWR
22 Owner's Group reports. Last week we received the
23 first of two reports. This report documented safety
24 margins for all the PWRs. We expect the BWR
25 equivalent in a few weeks.

NEAL R. GROSS

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

1 MEMBER SHACK: And you will review these
2 reports and decide whether they provide the
3 information that you thought you were going to get out
4 of the generic letter. Is that the process?

5 MR. CLIFFORD: That's correct. We will
6 audit these reports and the underlying engineering
7 calculations and then we will write a memo, or we will
8 write our own report documenting the safety of the
9 plants.

10 MEMBER BROWN: But what they recommend
11 does not necessarily go into the rule in terms of
12 requirements. Is that -- I mean, your -- I'm trying
13 to recall back to the previous meeting when you laid
14 out, you know, a new set of criteria.

15 MR. CLIFFORD: Right.

16 MEMBER BROWN: And I guess my
17 understanding from looking at this was that you all
18 were doing -- you said we're doing research and we're
19 going to develop this and have these tests and all
20 this. Now the Owner's Group wants to bring in another
21 set of reports where they're doing their own research.
22 Is that the story on that part of it?

23 MR. CLIFFORD: Yes, later today the
24 industry will present tests that they've done
25 independent of the research tests on post-quench

NEAL R. GROSS

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

1 ductility.

2 MEMBER BROWN: That you're all sponsoring?

3 MR. CLIFFORD: Correct. And their test
4 results don't supersede ours. They in a sense would
5 complement ours. They will have the ability with the
6 new rule to run their own tests and many of these
7 tests have already been written, already been
8 executed, and they'll be able to develop their own
9 analytical criteria if they feel that the -- I
10 shouldn't say -- but the analytical criteria that
11 would be documented in our reg guide is overly
12 restrictive.

13 MEMBER BROWN: Okay. Thank you.

14 CHAIRPERSON ARMIJO: But in this category,
15 these are entirely new issues for the ACRS. I mean,
16 we have not reviewed these things.

17 MR. CLIFFORD: These three --

18 CHAIRPERSON ARMIJO: So these are new
19 administrative actions or regulatory actions. A
20 generic letter is pending receipt of acceptable
21 reports from the industry?

22 MR. CLIFFORD: Correct.

23 CHAIRPERSON ARMIJO: And if you find them
24 acceptable, that generic letter would not be
25 necessary, is that correct?

NEAL R. GROSS

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

1 MR. CLIFFORD: That is correct.

2 CHAIRPERSON ARMIJO: Okay. And then as
3 far as the expanded technical basis for the burst
4 region and fuel fragmentation, those are new technical
5 matters that you're going to be bringing to us in the
6 future?

7 MR. CLIFFORD: Correct.

8 CHAIRPERSON ARMIJO: Okay.

9 MR. CLIFFORD: Yes, I'll go through the
10 schedule later.

11 Just to finish, the Office of Research has
12 completed these integral LOCA testing on non-
13 irradiated and irradiated fuel rod cladding segments
14 to investigate the mechanical properties of the fuel
15 rod burst region. Remember that during a LOCA many
16 fuel rods are predicted to experience fuel rod
17 ballooning and burst due to the elevated cladding
18 temperatures in combination with the increasing delta-
19 P across the cladding wall. The performance of the
20 small burst region of the fuel rod was largely outside
21 the scope of the original Argonne LOCA Research
22 Program.

23 The Office of Research is also
24 investigating fuel pellet fragmentation and dispersal
25 under LOCA conditions. All available integral LOCA

NEAL R. GROSS

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

1 test data from various domestic and international
2 research programs is being compiled and the staff will
3 decide whether or not to expand the scope of this
4 rulemaking to include new regulatory requirements
5 related to these phenomenon. Each of these items will
6 be addressed in a future ACRS briefing.

7 That brings us to this slide. Today we'll
8 be talking about the draft reg guides. It is
9 important to point out that the ACRS will have another
10 opportunity to address these three reg guides
11 following the public comment period before these
12 documents are finalized. Next month we'll be
13 presenting the expanded technical basis and any
14 related changes to the scope of the rule. In December
15 we will be presenting the entire proposed rule
16 package.

17 A few internal milestones which are not
18 listed on this ACRS schedule. August 2011 is the
19 completion date for the proposed rule package and the
20 start of internal concurrence. November 2011 is the
21 office-level concurrence on the proposed rule package,
22 and that's needed to support the 30-day submittal to
23 the ACRS for the December meeting. And finally,
24 February 2012 is the date that the proposed rule
25 package goes to the EDO. After the proposed package

NEAL R. GROSS

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

1 goes up to the Commission and out for public comment,
2 the staff would then address each of the comments
3 received and complete the final rule package. And
4 it's expected that the ACRS would then review the
5 final reg guides in combination with the final rule
6 package sometime in 2013.

7 On the final slide, just reiterate what
8 the expectations of today's meetings are, obtain
9 agreement or concurrence on issuing the draft reg
10 guides for public comment and provide the industry
11 with an opportunity to brief the ACRS on their recent
12 PQD testing and their round robin test program.

13 CHAIRPERSON ARMIJO: Okay. I have a
14 question on this introduction. I just want to step
15 back and note that today's meeting focuses on various
16 phenomenon that affect the ductility if the cladding,
17 cladding embrittlement and then the consequences if
18 the cladding is brittle what happens then? But in an
19 earlier letter; I forget what year that was in, the
20 ACRS reviewed this and we -- our comments were related
21 to make it more -- make the rule address core
22 coolability. Really core coolability was -- is the
23 bottom line. And the implication is that if we do a
24 better job on cladding ductility, we would prevent any
25 phenomena that would impede core coolability from

NEAL R. GROSS

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

1 occurring, or at least reduce the chances that core
2 coolability would be impeded.

3 And just reflecting on Fukushima, the
4 events at Fukushima, for the very long times when the
5 core had no cooling, the three different reactors'
6 temperatures; who knows what they may have reached or
7 how long, but very long times, I have really two
8 questions or comments. One is, with everything we're
9 doing here and proposing to do to improve the
10 ductility of the cladding or assure the cladding has
11 greater than one percent plastic strain capability,
12 would that have made any difference as far as core
13 coolability in the Fukushima events?

14 And then the second question is, the staff
15 should sit back and think about is, whether we have
16 already demonstrated core coolability in a very severe
17 set of three events, three reactors, which are somehow
18 being cooled. You know, the progression of the
19 accident to melting through the vessel, melt -- you
20 know, breaching containment hasn't happened and
21 without the benefit of a lot of work that we think
22 would help, more ductile cladding. So, I'm just
23 wondering if we're down in the details of cladding
24 embrittlement whether it really makes much difference
25 as far as core coolability. And I'd just leave that

NEAL R. GROSS

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

1 as a thought.

2 I don't necessarily want to debate it, but
3 maybe for the full committee meeting the staff should
4 have some thoughts on that to reflect on whether we're
5 really doing some good as far as safety or whether
6 we're just making a, granted, somewhat better cladding
7 or assuring somewhat better mechanical properties to
8 the cladding but not really affecting the primary goal
9 of assuring core coolability.

10 MR. CLIFFORD: Right. Well, I'd just like
11 to quickly respond that 50.46 defines a set of
12 acceptance criteria which is based upon the
13 performance of the field during a LOCA, but ultimately
14 it's used to judge the performance of the ECCS
15 systems; your pumps, your valves, your accumulators,
16 and whether or not -- well, you have to have some
17 figure of merit which to judge whether this \$1 billion
18 system is performing its function.

19 What happened in Japan is -- I mean, all
20 the facts aren't know, but it's my understanding that
21 was -- a station blackout scenario is significantly
22 different. The sequence of events is significantly
23 different than what would happen during say a large-
24 break LOCA. And even during a station blackout with
25 the increase in pressure and such, if you can't really

NEAL R. GROSS

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

1 get your ECCS system to initiate, to turn on to
2 perform its function because of the high pressure, you
3 really can't compare the two directly.

4 CHAIRPERSON ARMIJO: Yes, I'm just saying
5 all that's true, you know, but if you sit back and
6 say, you know, everything -- just about everything
7 that could go wrong went wrong, but at the end of the
8 day whatever's inside those vessels is being cooled;
9 maybe not very well, but certainly the progression of
10 the accident was impeded and whether cladding
11 embrittlement made any difference or not is hard to
12 justify, at least that's my thinking right now.

13 And I'd appreciate if the staff would, you
14 know, kind of be prepared because, you know, this
15 cladding embrittlement rule is really there to assure
16 core coolability. And if it doesn't make a difference
17 in a severe accident, why would it make a difference
18 in a milder accident as far as core coolability?
19 That's poorly worded, but that's kind of the thoughts
20 I'd like the staff to consider.

21 MR. BAHADUR: I think the issues that you
22 have raised, Mr. Chairman, are very germane to the
23 entire effort that NRC is doing towards the Japan
24 event and how it affects our regulatory framework.

25 CHAIRPERSON ARMIJO: Yes.

1 MR. BAHADUR: We are aware that the
2 Commission has made a task force. The task force of
3 three senior managers is looking exactly into the
4 effectiveness of our current regulations and also to
5 see where we need to make changes. So --

6 CHAIRPERSON ARMIJO: Yes. Well, you know,
7 clearly our job is to create rules that can make an
8 impact on safety. And if we have experience, new
9 experience that says, hey, you know, this rule
10 wouldn't have helped us a bit at Fukushima, or in the
11 absence of cladding that was tested to meet the
12 requirements of this rule of core coolability to some
13 extent has been demonstrated already. So, that's
14 where I'm struggling trying to figure out are we
15 really doing the right thing in pursuing the cladding
16 embrittlement. Will it really make a significant
17 difference as far as safety?

18 MEMBER SIEBER: Yes, could I add something
19 to that? I think the rule is designed to deal with
20 design basis events. Fukushima is obviously well
21 beyond the design basis and it's not clear to me that
22 you can design fuel that will withstand no cooling
23 whatsoever for long periods of time. So, I think in
24 my view the rule is necessary because we are in design
25 basis space and there has to -- and that's where the

NEAL R. GROSS

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

1 risk is. You know, there's more risk of a design
2 basis accident than beyond design basis. And
3 therefore, we need to assure that the fuel will
4 maintain sufficient integrity so that it is coolable
5 throughout the entire design basis event. And that's
6 my understanding of what it is you're doing here. Is
7 that correct?

8 MR. CLIFFORD: Yes, the rule is --

9 MEMBER SIEBER: So it's two different
10 issues; design basis and beyond the --

11 CHAIRPERSON ARMIJO: My question really
12 boils down real simple. If you demonstrated
13 coolability in a beyond design basis event such as at
14 Fukushima. If you've demonstrated core coolability,
15 then certainly you've got coolability in a design
16 basis event, which is milder. So, you know, that's
17 really the kind of question I'd like the staff to
18 think about because there's an awful lot of work
19 that's gone into this thing with a presumption that it
20 would make, you know, a bigger difference as far as
21 our assurance of core coolability and whether we
22 really still -- you know, that unfortunate experience
23 at Fukushima should make us rethink what we're doing.

24 MR. CLIFFORD: Right. I think it's really
25 two issues. It's whether it's design basis or beyond

NEAL R. GROSS

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

1 design basis. And then there's the issue of really
2 this rule focusing on LOCA and the sequence of events
3 that occur during a LOCA, which really involves a
4 massive depressurization and a loss of coolant. And
5 whether or not GDC-35 core coolability requirements
6 for a LOCA design basis should be judged the same way
7 as core coolability for a station blackout scenario.
8 And what are the phenomena? What are you trying to
9 protect during a station blackout and what systems are
10 required? Certainly it wouldn't be the same systems
11 that are responding to a station blackout as you would
12 expect during a LOCA. So, you need to judge the
13 performance of those systems based upon what you're
14 trying to protect to ensure core coolability during
15 that station blackout.

16 CHAIRPERSON ARMIJO: Okay. Any other
17 questions?

18 MEMBER SHACK: Well, just that's my
19 comment, is I mean you have to have coolability in
20 every scenario.

21 CHAIRPERSON ARMIJO: Right.

22 MEMBER SHACK: A station blackout
23 scenario, a LOCA scenario. And the requirements to do
24 that are different in the two. I mean, and, you know,
25 we're dealing today particularly with the LOCA

NEAL R. GROSS

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

1 scenario, but that doesn't mean that, you know, that
2 that's not -- it's the necessary but not sufficient
3 condition to assure coolability. If you've done it
4 for just one scenario. There's other scenarios to
5 worry about, but you know, we're focusing today on the
6 LOCA scenarios.

7 MR. CLIFFORD: Right.

8 CHAIRPERSON ARMIJO: Okay. Why don't we
9 just move on?

10 MS. FLANAGAN: Okay. I am going to begin
11 my presentation today with an overview of the three
12 regulatory guides that have been developed to support
13 the rulemaking and how they interact with the proposed
14 rule language. So, the objective would be to present
15 the background, the context and the details of these
16 three regulatory guides and their relationship to the
17 rulemaking revisions.

18 So, Paul actually covered most of this
19 background, so I'm going to go through this quickly.
20 But these regulatory guides were developed in the
21 context of the Fuel Cladding Research Program and
22 based on the phenomena that were identified to be
23 important in that research program.

24 The rulemaking was initiated to revise the
25 ECCS acceptance criteria to reflect the research

NEAL R. GROSS

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

1 findings and at the same time the revisions were
2 intended to develop performance-based features in the
3 10 C.F.R. 50.46. And so therefore, the proposed rule
4 language is structured to call for material-specific
5 analytical limits which account for material-specific
6 burnup effects. It calls for ECCS performance to be
7 consistent with avoiding measured breakaway behavior
8 and it also calls for periodic testing for our
9 breakaway oxidation behavior.

10 So, in order to support the performance-
11 based rule language, three regulatory guides were
12 developed which provide a means of consistent,
13 comparable data generation to establish limits for
14 peak cladding -- sorry, yes, peak cladding temperature
15 and oxidation, a means of consistent comparable data
16 generation to establish and periodically confirm
17 regulatory limits related to breakaway oxidation and
18 then a consistent means of using experimental data to
19 establish regulatory limits.

20 So, the three regulatory guides are:
21 Draft Guide 1261; and that's really a test procedure
22 for measuring breakaway oxidation behavior and
23 periodically confirming consistent behavior. So, it's
24 a data generation regulatory guide. Draft Guide 1262
25 is a test procedure for measuring post-quench

NEAL R. GROSS

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

1 ductility using ring compression tests. So again,
2 it's a data generation regulatory guide. And then
3 Draft Guide 1263 is a methodology for using that data
4 that's generated to actually develop analytical
5 limits. So that is the draft regulatory guide which
6 explains the extent of testing, how that testing will
7 be used to assess variability and actually derive
8 analytical limits that are supported by the data.

9 So along with the regulatory guides that
10 were provided to the public in support of this
11 meeting, we also made available our draft proposed
12 rule language. And one of the reasons for that is
13 really to present the context in which these
14 regulatory guides exist.

15 The draft rule language as it's written
16 right now states, "Specified and acceptable analytical
17 limits on peak cladding temperature and time at
18 elevated temperature shall be established which
19 correspond to the measured ductile-to-brittle
20 transition for the zirconium cladding alloy material
21 based on an acceptable experimental technique." And
22 so in this case an acceptable experimental technique
23 is defined in Draft Guide 1262. And the methodology
24 to use that data to develop specified and acceptable
25 limits is outlined in Draft Guide 1263.

NEAL R. GROSS

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

1 So in parallel we have the rule language
2 proposed to address breakaway oxidation behavior. And
3 again, the language says "a specified and acceptable
4 limit based on acceptable experimental technique."
5 And so in this case we have an acceptable experimental
6 technique defined with Reg Guide 1261 and a
7 methodology for using that data to develop an
8 analytical limit outlined and discussed in Draft Guide
9 1263.

10 MEMBER BROWN: Can I ask a -- this is a
11 simple -- I'm not a materials scientist, so this is a
12 simpleminded question.

13 MS. FLANAGAN: Yes?

14 MEMBER BROWN: You're going to develop an
15 analytical technique that says based on experimental
16 -- why -- if you have a whole range of experimental
17 data that provides a set of limits that you've
18 generated from these tests, why doesn't that set the
19 boundary as opposed to -- are you going to be
20 extrapolating outside this bound with your analytical
21 techniques? So you're not going to be running the
22 tests to --

23 MS. FLANAGAN: I think that --

24 MEMBER BROWN: -- you know, plant
25 conditions that are consistent? And so you're going

NEAL R. GROSS

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

1 to be depending on extrapolations?

2 MS. FLANAGAN: No, I think I understand
3 your question and I can see why it's not clear yet.
4 It will be something that's discussed in the later
5 presentations. Because for the materials that were
6 tested in the program, you're exactly right. There is
7 already a limit that's available that could be used
8 readily. And then the test procedures really
9 establish how additional cladding alloys would be
10 tested to confirm that they are performing similar to
11 that established database or under different
12 conditions. And so some -- there is opportunities for
13 other conditions to be tested and then analytical
14 limits to correspond to -- I guess what I'll say is
15 that we developed sort of bounding criteria. And then
16 there's room in the test procedures to develop more
17 plant-specific or alloy-specific limits.

18 MEMBER BROWN: Okay.

19 MS. FLANAGAN: And I'm not sure I answered
20 your question.

21 MEMBER BROWN: Not totally.

22 MS. FLANAGAN: Okay.

23 MEMBER BROWN: My concern is; and I guess
24 it's a fallout of the program that I left, was most of
25 our materials; at least based on my limited

NEAL R. GROSS

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

1 understanding, were set based on the tests that we
2 ran.

3 MS. FLANAGAN: Right.

4 MEMBER BROWN: And we didn't exceed those
5 boundaries based on -- I mean, you will develop
6 obviously analytical tools that allow you to evaluate
7 the data within the range --

8 MS. FLANAGAN: Yes.

9 MEMBER BROWN: -- of where you did your
10 test, but not to go outside unless you've demonstrated
11 that you could go outside based on another set of
12 tests that --

13 MS. FLANAGAN: Okay.

14 MEMBER BROWN: -- laid out another set of
15 limits for you. So, I guess that's why I was confused
16 when I looked at this -- you know, at the high-level
17 part of this stuff. I don't pretend to understand all
18 the nitty-gritty details.

19 MS. FLANAGAN: No, but I think I might
20 have used a word that might have -- I said "analytical
21 limits," but it's not -- we haven't developed an
22 analytical tool to extrapolate from this experimental
23 set to other conditions. It's more like an analytical
24 limit meaning we've set a speed limit through test
25 data and then a LOCA-analysis tool would use that

NEAL R. GROSS

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

1 speed limit to say whether they're above and below it.

2 So, I think I understand where the
3 confusion is and I hope that the coming slides will
4 clear that up.

5 MEMBER BROWN: Okay. Now, let me segue
6 back to my earlier question.

7 MS. FLANAGAN: Yes.

8 MEMBER BROWN: Relative to the industry,
9 you've gone out and developed this stuff. You've come
10 up with a set of whatever your analytical limits are,
11 which I'll assume you answer the question later.

12 MS. FLANAGAN: Yes.

13 MEMBER BROWN: These are guidance --

14 MS. FLANAGAN: Yes.

15 MEMBER BROWN: -- and therefore you've
16 given industry -- and based on a lot of work and now
17 somebody's got to come in and tell you -- but you're
18 giving them license to come and tell you, hey, we'd
19 like to do this a different way. We don't want to run
20 the tests the way you show in this thing. We don't
21 want to use the ring compression tests for whatever
22 that tests for, etcetera, etcetera. And that's a --
23 I mean, that's just like opening up the box to a whole
24 new range, and that just seems to be a little bit
25 difficult. If you've got a set of criteria that you

NEAL R. GROSS

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

1 know you can live -- you think you can live with based
2 on all the research you did --

3 MR. CLIFFORD: I think a lot of thought
4 went into how we developed this rule. First of all,
5 it is a performance-based rule, so we're trying -- and
6 we were directed to develop a performance-based rule.
7 So we first define what we're trying to protect; and
8 that is, a measure of ductility. For this specific
9 requirement here, post-quench ductility you need to
10 demonstrate that you maintain a measured amount of
11 ductility. Now how you achieve that, you're right,
12 you could achieve that by doing five different types
13 of tests. We chose to use ring compression tests
14 based on historical reasons. It's an accurate,
15 reproducible test.

16 MEMBER BROWN: That sounds like a good set
17 of reasons.

18 MR. CLIFFORD: But there's always a degree
19 of testing that's going to be required in the future.
20 For instance, we tested Zirc 2, Zirc 4, ZIRLO and M5.
21 If someone comes in with a new alloy chemical
22 composition, we're going to question, well, geez, is
23 that really applicable? We don't want to extrapolate
24 this to a new material, so we're going to say, well,
25 you need to run the test. Well, how should they run

NEAL R. GROSS

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

1 that test? That's why we needed to develop a specific
2 test criteria we found acceptable. They're free to go
3 off and develop a different test procedure, but of
4 course all of the benefits that we've established and
5 documented in the reg guide are out the window and now
6 all the emphasis is on them to show that their test
7 procedure is a good measure of ductility, it's
8 reproducible, it address uncertainties.

9 MR. BROWN: Okay.

10 MR. CLIFFORD: And, you know, experimental
11 procedures are going to improve over time. So, it's
12 kind of nice to have the flexibility to say, well, if
13 you find a better way of doing this that you can
14 evolve as opposed to just setting in stone thou shalt
15 use this test on this material and justify it in the
16 future.

17 MR. BROWN: Okay. Go ahead. I like
18 stones.

19 MS. FLANAGAN: Well, the other thing I'll
20 say is that with the material that would be provided
21 to support analytical limits in this case, if the
22 draft procedure that we're issuing is followed, then
23 there would not need to be any discussion about what
24 test procedure was used to generate that data.

25 MR. BROWN: If they used the guides, is

NEAL R. GROSS

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

1 what you're saying, yes.

2 MS. FLANAGAN: Right, if they used the
3 guides. And that is the test procedure. And that has
4 already been determined to be acceptable to the staff.
5 And then any other test method would require a lot
6 more interaction and engagement. And so, it's not
7 like it would be as easy as it might be sounding to
8 actually go through and --

9 MR. BROWN: Okay. I won't mouse milk this
10 anymore. Just say thank you.

11 MS. FLANAGAN: Okay. So, the last item
12 I'm going to present in the context of this overview
13 is a schedule for the regulatory guides. So, at this
14 time the regulatory guides are in inter-office
15 concurrence. And then once that process is complete,
16 the draft guides will be issued for public comment.
17 And that public comment period will be at the same
18 time as the proposed rule is issued for public
19 comment. And so the intention there is that as the
20 regulatory guides interact with the rule, the complete
21 picture would be available. And then the comments
22 could not only be on the proposed rule or the
23 regulatory guides, but actually in their relationship
24 to each other and it would be clear how the rule would
25 be implemented. And then after that the draft guides

NEAL R. GROSS

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

1 will follow the standard revision and review process.

2 So, that is an overview of the three
3 regulatory guides and their relationship to the rule.
4 And I'm about to get into some details of the content
5 of each regulatory guide.

6 Before I do that, are there any questions
7 on the overview slides other than what we've tried to
8 discuss?

9 MEMBER SHACK: Suppose you needed to do
10 some more work on ballooning in that. Do you think
11 that the language in the rule accommodates that, that
12 that's really a reg guide kind of issue, or will you
13 need a revision of the rule if you decide to address
14 that?

15 MR. CLIFFORD: We're currently discussing
16 how the rule language would need to be modified to
17 capture ballooning and potentially fuel fragmentation,
18 and that will be the topic of the June meeting.

19 MEMBER SHACK: Okay.

20 MR. CLIFFORD: So --

21 MEMBER SIEBER: You do expect ballooning
22 though even in the design basis space, right?

23 MR. CLIFFORD: Absolutely.

24 MEMBER SIEBER: Because you want to assure
25 that that's limited so that you still get --

NEAL R. GROSS

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

1 MR. CLIFFORD: Correct.

2 MEMBER SIEBER: Okay. And so that's where
3 the temperature limit comes in. Okay.

4 MS. FLANAGAN: Okay. So, the next
5 presentation is going to get into the content of Draft
6 Guide 1261. And this draft guide is titled,
7 "Conducting Periodic Testing for Breakaway Oxidation
8 Behavior." So again, just the context for this is
9 established within the proposal language that an
10 acceptable experimental technique is defined in this
11 regulatory guide.

12 The objective of this regulatory guide is
13 really to support the performance-based rule language
14 by providing a means of consistent comparable data
15 generation to establish and periodically confirm
16 regulatory limits related to breakaway oxidation, and
17 in doing so, simplify the staff's review process and
18 also reduce regulatory uncertainty and the costs
19 associated with implementation of a performance-based
20 rule.

21 And so I've outlined the criteria for
22 success. When do we know that this draft guide has
23 done everything that we intend that it does? And so,
24 to say our criteria for success, I'll say that through
25 stakeholder interaction and public comment, the

NEAL R. GROSS

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

1 objective is that the details and expectations of one
2 acceptable method for measuring zirconium-based
3 alloys' breakaway oxidation behavior has determined to
4 be communicated effectively and completely. Also,
5 that using the test procedure is determined to produce
6 repeatable measurements within a laboratory and that
7 using the test procedure produces consistent
8 measurements between laboratories. And in doing so we
9 would be clear that the differences that are in
10 measured values using the test procedure are actually
11 a reflection of differences in material behavior
12 rather than any -- a result of any differences in
13 experimental protocol.

14 MEMBER BROWN: How do you establish a
15 laboratory-to-laboratory testing criteria, I mean, if
16 one guys runs the test and he gets a set of data and
17 another lab runs the test with their equipment, which
18 may be different slightly than the other guy's --

19 MS. FLANAGAN: Yes.

20 MEMBER BROWN: -- and you get different
21 data? I mean, did you all put a -- is there a
22 percentage variation? Is there a statistical analysis
23 that you require specifically that some, I don't
24 know --

25 MS. FLANAGAN: The draft regulatory guides

NEAL R. GROSS

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

1 have discussion of different equipment, like different
2 types of furnaces and different types of capabilities
3 that would exist at different labs. And actually,
4 I'll get into this in a later slide. But one of the
5 objectives was to provide flexibility where there is
6 different equipment available, but then to establish
7 within that range a test procedure that despite
8 differences in -- or in equipment that you'd still
9 come out with the same measurement, so to define the
10 boundaries for which the test must be conducted so
11 that you're within a repeatable --

12 MEMBER BROWN: The reason I ask the
13 question is because I just finished -- in one of my
14 other jobs they're reviewing a set of test results for
15 a particular performance of a material, an insulation
16 material. And to go back and look at when this
17 particular company ran the test first for one design,
18 which had the same -- actually the same product, same
19 exact product in terms of how they manufactured it.
20 They did it in-house with their own guy who knew how
21 to do it run the test and everything. They came up
22 with a set of results. Looked very good. That guy
23 retired. They went to an outside lab to do it.
24 Reviewed the second set of results. The results were
25 a factor of 10 difference. An order of -- now, they

NEAL R. GROSS

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

1 both met the limit --

2 MS. FLANAGAN: Yes.

3 MR. BROWN: -- but they were a factor of
4 10 difference, which calls into some question.

5 MS. FLANAGAN: I think that if we had that
6 measurement, we would say that this criteria for
7 success has not yet been met.

8 MEMBER BROWN: And I was just looking how
9 you put that out there though --

10 MS. FLANAGAN: Yes.

11 MEMBER BROWN: -- so that industry knows
12 that --

13 MS. FLANAGAN: Right.

14 MEMBER BROWN: -- when they're running
15 those tests.

16 MS. FLANAGAN: Yes, and so that is why the
17 criteria for success are really dependent on
18 stakeholder interaction and the public comment period.
19 That is why that relationship is so critical because
20 it does actually require some demonstration.

21 MR. CLIFFORD: I think the industry later
22 on today will present how they plan on doing a round
23 robin at several different laboratories. So, the test
24 procedures will be exercised at different labs and I
25 think it's important -- well, the tricky part of

NEAL R. GROSS

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

1 course is to provide flexibility, but to also
2 understand whether or not that flexibility will create
3 this uncertainty. So, you need to know what the
4 results are sensitive to. I mean, do you want to give
5 them the flexibility of calibrating the equipment a
6 certain way or placing the thermocouples in a certain
7 location? But if that directly impacts the results,
8 then that flexibility can't be provided in the reg
9 guide. So, the trick is to exercise these procedures
10 at different labs and see what the results are.

11 MEMBER BROWN: Okay. Well, thank you.

12 MEMBER ABDEL-KHALIK: What's the logic for
13 the annual frequency of reporting, periodic testing on
14 slide 11?

15 MR. CLIFFORD: Breakaway oxidation has
16 been shown to be sensitive to not just chemical
17 composition but to also portions of the manufacturing
18 process.

19 MEMBER ABDEL-KHALIK: Right, that's why
20 I'm asking how is the decision made that annual
21 testing is adequate?

22 MR. CLIFFORD: It's not annual testing.
23 It's annual reporting, right?

24 MS. FLANAGAN: Right. So, we expect an
25 annual -- or in this outline of what is structured

NEAL R. GROSS

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

1 here, there would be a report that is submitted
2 annually to confirm that the periodic testing has not
3 revealed a difference in performance over the last
4 year. And it's really a balance between --

5 MEMBER ABDEL-KHALIK: So, what does the
6 word "periodic" mean?

7 MS. FLANAGAN: Periodic in this sense, as
8 far as we receive information, is annual. And then
9 there could be more frequent testing that's conducted
10 if that's appropriate.

11 MEMBER ABDEL-KHALIK: No, I mean, what's
12 the meaning of the word "periodic" measurement or
13 "periodic" testing? What is the meaning of the
14 "periodic" there? On a every-heat basis? Every-core
15 basis?

16 MR. CLIFFORD: That's what we're still
17 working out, whether or not -- and this will be
18 addressed during the public comment period. We have
19 specific questions to this subject, whether or not we
20 want to define periodic as being something that's tied
21 directly with changes to the manufacturing process, or
22 whether it's tied to a statistical sampling of every
23 10,000 tubes. So, we're still working out that
24 detail, but the annual reporting would just be the
25 reporting. There could be multiple tests during the

NEAL R. GROSS

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

1 period of that year.

2 MEMBER ABDEL-KHALIK: Right, I understand
3 that. But my focus is this periodic testing. What
4 does it mean? And I would appreciate it if you
5 address that as we go along.

6 MS. FLANAGAN: Yes, I'd say that it's a
7 question that we are -- as Paul explained, that we're
8 still working with. But the objective is to identify
9 things that can be taking place within the
10 manufacturing process which could potentially have an
11 impact on breakaway behavior. And so, that's the
12 objective of measuring periodically. And then the
13 appropriateness of time increments versus lot
14 increments.

15 MEMBER ABDEL-KHALIK: The logic is -- I
16 mean, if you know there are so many things in the
17 manufacturing process that impact the results, then
18 it's a crap shoot. So how do you define this
19 periodicity of testing?

20 MS. FLANAGAN: No, I mean, I really do
21 appreciate the question. I think that that's
22 something that we have been looking at. Are there
23 thresholds or phenomena that we could hone in on that
24 would really define what's appropriate there? And
25 that's something that we have to explore and define so

NEAL R. GROSS

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

1 that it's clear to everybody. I mean, we have some
2 sense of it, but I think it is --

3 CHAIRPERSON ARMIJO: Well, when you do a
4 manufacturing process qualification on fuel cladding
5 for example, there's a whole raft of tests that are
6 performed to assure that it will meet its performance
7 requirements, both for regulatory purposes and also
8 for just performance, true performance. So routinely
9 when manufacturers change their processes, they will
10 check and do a whole series of checks to make sure
11 that that process change doesn't change the
12 performance. And so, I think manufacturers know how
13 to do that and wouldn't have a big problem in doing
14 it.

15 In the case of the embrittlement testing,
16 whether it's breakaway oxidation or other phenomena,
17 if they've demonstrated with their basic material and
18 their fabrication process that they've got lots of
19 margin to the criteria, whether it's 5,000 seconds or
20 3,000 seconds; whatever it is, if they've demonstrated
21 a lot of margin, then I would expect they'd have a
22 pretty good justification for not testing every time
23 there's a trivial change in the manufacturing process
24 and they -- but it's up to them to make sure that it
25 would not affect the cladding performance. If they're

NEAL R. GROSS

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

1 right on the edge, I would think they'd be very
2 cautious and test just about every change that could
3 possibly affect the surface of that cladding.

4 So, I think you're going to have to really
5 look at the requirements to address those changes
6 which are beyond the qualification program and the
7 cladding manufacturing process. And every cladding
8 manufacturing process, they don't just qualify the
9 exact parameters used in manufacturing. They qualify
10 a broader range of variables to make sure there's some
11 -- you know, that if something's a little bit off, the
12 whole thing doesn't fall apart.

13 So, I think it's really up to the
14 manufacturers to identify what could -- based on their
15 experience and their knowledge, what could affect the
16 embrittlement of the cladding. And if they think
17 there's a reasonable chance that that could happen,
18 they should test. And that's going to take some give
19 and take to find out what is rational, but if there's
20 a requirement that any manufacturing process change
21 shall require retesting, I think that's incredible
22 overkill and wouldn't be helpful to anybody because
23 there's lots and lots of changes in the manufacturing
24 of fuel that go on all the time.

25 MEMBER SHACK: But to follow Said's

NEAL R. GROSS

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

1 question, that assumes that you're controlling all the
2 variables that are important and you're --

3 CHAIRPERSON ARMIJO: Right, that's the
4 point.

5 MEMBER SHACK: Well, you know, but how do
6 you provide that assurance to yourself?

7 CHAIRPERSON ARMIJO: Well, these guys have
8 been doing this for a living for a long, long time.
9 There are a lot of variables beyond cladding
10 embrittlement that they have to control. Just plain
11 corrosion. Just plain mechanical properties. There's
12 a lot of things that they have to control. This is
13 just one more thing. And so, I think it's -- I took
14 a quick look at the draft guide and I was glad to see
15 that it wasn't focused on -- it didn't say all
16 manufacturing changes shall require retesting. That's
17 a simplistic -- one-size-fits-all-kind of requirement
18 and it's not in there. So, I think you're doing the
19 right thing to get the comment, public comments to
20 come back and saying, hey, focus on the things that
21 will make a change in the performance of the cladding
22 with respect to embrittlement. And it's really
23 surface preparation. It's a huge, huge thing.
24 And so knowing that, that's where the focus should be,
25 particularly since you've demonstrate that cladding

NEAL R. GROSS

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

1 composition doesn't make that much difference.

2 So, really that's the debate. You know,
3 you could easily say all manufacturing changes shall
4 require retesting. If that's the case, that would not
5 make sense, to me anyway.

6 MEMBER ABDEL-KHALIK: I guess the question
7 still remains in my own mind at least --

8 MS. FLANAGAN: No, I understand.

9 MEMBER ABDEL-KHALIK: -- you know, what is
10 the threshold?

11 MS. FLANAGAN: Yes. No, I understand
12 that.

13 MEMBER SHACK: And I'm sure the vendors
14 will be very interested in that question, too.

15 MEMBER ABDEL-KHALIK: Right.

16 MEMBER SHACK: Yes.

17 MS. FLANAGAN: I agree.

18 MEMBER ABDEL-KHALIK: It triggers a
19 requirement for testing.

20 MS. FLANAGAN: Yes. No, I understand.

21 MEMBER SIEBER: Let me ask sort of a
22 simplistic question. In my experience -- I worked in
23 specialty metals for a little bit and there is -- as
24 you produce this material there is a variability of
25 the composition of the material that affects its

NEAL R. GROSS

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

1 tensile strength, its melting point, its oxidation
2 levels and so forth. Is the testing frequent enough
3 in this periodic testing to be able to pick up alloys
4 that are sort of the fringes of the specifications as
5 opposed to the so-called perfect mix that the alloy
6 specifies? In other words, to me the alloy
7 composition is one of the bigger variables in the
8 manufacturing process. Sam, maybe you could correct
9 me if I'm --

10 CHAIRPERSON ARMIJO: Well, it's
11 composition, it's heat treatment, it's surface
12 preparation, all of those things.

13 MEMBER SIEBER: A lot of things, yes.

14 CHAIRPERSON ARMIJO: And they all do
15 periodic testing whether they've made a process change
16 or not. Just every so many thousand tubes something
17 gets tested for hydrogen, for corrosion, for
18 mechanical properties. So, that goes on all the time.
19 And this test was straightforward enough, it could be
20 one additional test. Okay.

21 MEMBER SIEBER: Well --

22 CHAIRPERSON ARMIJO: But there's also the
23 issue -- when you've made a process change, you may
24 need to re-qualify your process; and that's a much
25 bigger deal. You know, if you made a significant

NEAL R. GROSS

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

1 process change, you would say, hey, that's out of the
2 manufacturing qualification program that we ran, so we
3 have to re-qualify; and that's a big deal.

4 MS. FLANAGAN: Yes.

5 MEMBER SIEBER: Well, your statement
6 though is that this testing goes on all the time. The
7 regulatory guide doesn't require testing to go on all
8 the time. It requires it to go on periodically.

9 CHAIRPERSON ARMIJO: Yes.

10 MEMBER SIEBER: And periodically hasn't
11 been defined yet, and so my question is when you end
12 up defining periodically is it sufficiently frequent
13 to be able to catch these variations in the
14 manufacturing cycle that's due to natural variations
15 and alloy composition, heat treatment and so forth, as
16 opposed to the rigor of the actual fuel manufacture
17 itself? Because that's pretty rigorous, in my
18 experience, that alloys and so forth have more
19 variability in my experience associated with them.

20 You know, and so I guess as we go along I
21 will pay attention to how you determine what's
22 frequent enough, what kinds of bands or controls do
23 you set on that so that if a given manufacturer sees
24 a wider variation in the quality of the product, does
25 that mean more testing is required or more refinement

NEAL R. GROSS

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

1 of the manufacturing process is required?

2 MS. FLANAGAN: Yes, I certainly appreciate
3 -- this is a conversation that has a lot of interest.
4 You know, there's a lot of -- we'll be looking to the
5 public comment period as well as future ACRS
6 interactions to really define this and really get
7 feedback on what -- on the topic.

8 And I'll also say that later in the
9 presentation when I'm talking about the analytical
10 limits that are established, I'll talk a little bit
11 about potential places to put in conservatism and
12 margin, and that might end up addressing some of the
13 questions here. But I do appreciate that's a topic
14 that there's a lot of interest in and that certainly
15 the public comment period will be very valuable to
16 really look at some of that.

17 So, I have a slide here that discusses the
18 background of this regulatory guide and how -- or this
19 draft guide and how it was developed. The draft guide
20 captures the experimental technique that was used in
21 NRC's LOCA Research Program. And as I said before, it
22 includes flexibility where possible to really allow
23 variation of equipment and procedures that is in use
24 at other laboratories.

25 And the test procedure itself; not the

NEAL R. GROSS

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

1 regulatory guidance and the regulatory positions, but
2 the test procedure itself was issued for public
3 comment in conjunction with the ANPR that was issued
4 in August 2009. And we did receive comments. And the
5 experimental procedure that's in this draft guide has
6 considered these comments and in some cases there have
7 been changes to directly address those comments that
8 have already been received. That's a little bit of
9 background about how we developed them.

10 MEMBER BROWN: How detailed do you capture
11 the experimental technique?

12 MS. FLANAGAN: Quite detailed. I mean, it
13 gets into water quality, furnace thermocouple
14 calibration. I mean, there's quite a lot of detail
15 about what makes a difference in this kind of test and
16 what to be careful of. And also in some cases what
17 things to be cautioned of that you may develop non --
18 I want to be careful how I say this. You might have
19 the material look worse than it really is. Like what
20 qualities could you do? For example, surface finish
21 in preparing your sample. That might not be in the
22 manufacturing process, but as you're preparing your
23 test you might do something that could inadvertently
24 make those conditions worse. So, there's really a lot
25 of detail.

NEAL R. GROSS

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

1 MR. BROWN: Does the reg guide actually
2 require -- I'm using that -- don't get upset with the
3 word, okay, please.

4 CHAIRPERSON ARMIJO: Find acceptable.

5 MEMBER BROWN: Pardon?

6 CHAIRPERSON ARMIJO: Find acceptable.

7 MEMBER BROWN: Yes. My point -- let me
8 refresh my brain here. The actual setup -- I raise
9 this setup of the test equipment. The reason I ask
10 the question is experience is a marvelous teacher of
11 things that go wrong. We had a specific technique
12 which said when you set up the measure and make this
13 particular measurement, you can't use leads any more
14 than; I'm an electrical guy, okay, 1½ feet long that
15 have to be separated by, you know, 12 inches. They
16 have to have such-and-such. You have to have, in
17 other words, the entire layout because it was a very
18 low, very small quantity of resistance we were trying
19 to measure.

20 MS. FLANAGAN: Yes.

21 MEMBER BROWN: Very low resistance. And
22 any types of EMI and anything else can affect you.
23 The shielding you had, the way it was grounded, the
24 way it was -- there was a whole -- the technique was
25 confirmed. It was in the IEEE standard. When we got

NEAL R. GROSS

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

1 the results back, the vendor -- you know, they did not
2 document that they actually set it up that way. We
3 asked for the documentation. They said, well, they
4 didn't do that because the guy who was running the
5 test knew how to do it.

6 MS. FLANAGAN: Yes.

7 MEMBER BROWN: And so, you know, that
8 raised a whole other question about, well, did he
9 really establish it the right way? And for these,
10 that would seem to me that this data you're taking is
11 not -- you know, you're not measuring stuff in
12 megavolts or whatever. You're making very small
13 measurements.

14 MS. FLANAGAN: No, but the parallel is
15 there. I mean, the same type of --

16 MEMBER BROWN: But my point being is does
17 the reg guide tell -- require capturing -- required to
18 specify that you got to document not only the results,
19 the data results and how they -- but that you complied
20 with the actual test setup, have it recorded that,
21 yes, here's the measurements of this, this, this,
22 whatever. The thermocouples for instance --

23 MS. FLANAGAN: Yes.

24 MEMBER BROWN: -- you get the calibration
25 via some metrology setup and there's a sheet that

NEAL R. GROSS

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

1 says, yes, here's when we did it, here's the guy that
2 did it, here's the machine that did it, all the way
3 down the line. Does it specify that you have to
4 document that as part of the test report?

5 MS. FLANAGAN: Well, if you -- that is
6 defined in the test procedure. And then if you say
7 that I complied with this procedure, then you would
8 have complied with this procedure.

9 MEMBER BROWN: That -- you didn't --
10 you're not --

11 MS. FLANAGAN: You're asking if --

12 MEMBER BROWN: Is it written down during
13 the performance of the procedure --

14 MS. FLANAGAN: Right.

15 MEMBER BROWN: -- such that it's signed
16 off that the data -- and, I mean, the setup complies
17 with each -- like if there's -- say there's five setup
18 conditions.

19 MS. FLANAGAN: Yes.

20 MEMBER BROWN: You write down each one of
21 those and say, yes, it was supposed to be such and
22 such. This is it. It's signed off.

23 MS. FLANAGAN: Yes.

24 MEMBER BROWN: And there's a guy's name
25 there and the actual criteria. You know, it's

NEAL R. GROSS

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

1 supposed to be separated by this or the accuracy is
2 such and such, or whatever it was. If that's not
3 required as part of the reporting process, then you do
4 not know in the end whether you actually captured data
5 where the -- that the technique was actually followed.

6 MS. FLANAGAN: Right.

7 MEMBER BROWN: That's my only point.

8 MS. FLANAGAN: No, I understand.

9 MEMBER BROWN: When you're measuring small
10 quantities, it's very important that the technique is
11 documented and you don't just depend on art from the
12 guy that's done it, you know, 500 times.

13 MS. FLANAGAN: Yes.

14 MEMBER BROWN: I mean, he's a trustworthy
15 person, but you've got to have it documented if we're
16 going to trust it in these circumstances. That's all
17 I -- it's just something to be considered in terms of
18 how's this information reported and how's the actual
19 technique reported in terms of following that
20 technique?

21 CHAIRPERSON ARMIJO: Charlie?

22 MEMBER BROWN: Yes?

23 CHAIRPERSON ARMIJO: Particularly for any
24 kind of testing that people do in a fuel factory, they
25 have their qualified test procedures which includes

NEAL R. GROSS

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

1 things like calibration of thermocouples, water
2 purity, all these sorts of things. That's in their
3 quality assurance program.

4 MEMBER BROWN: No, I understand that.
5 Yes, I got that.

6 CHAIRPERSON ARMIJO: And particularly for
7 regulatory work, you know, that's -- they're pretty
8 diligent on running tests in conformance with a very
9 strict test procedure. So I would expect that that's,
10 you know, when the reg guides are issued and people
11 understand it and they have confidence that the tests
12 really work. And they are measuring small changes in
13 -- you know, a very small amount of residual ductility
14 that we're trying to measure here, so it's very
15 important to have test controls. So, I think there
16 will be qualified test procedures to comply with a
17 regulatory requirement.

18 MEMBER BROWN: Oh, I understand. I
19 understand. The point is actually recording the --

20 CHAIRPERSON ARMIJO: Oh, they do.

21 MEMBER BROWN: -- that the actual setup
22 was/is as specified in the test procedures, that's all
23 documented so that you know that people were aware of
24 that when they did it.

25 MEMBER SIEBER: Well, these are sort of

NEAL R. GROSS

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

1 standard tests, right?

2 CHAIRPERSON ARMIJO: Well, not
3 necessarily.

4 MS. FLANAGAN: Well, yes, I wanted to
5 speak to --

6 MEMBER BROWN: This is not a standard
7 tests. This is new.

8 CHAIRPERSON ARMIJO: You know, a steam
9 test. People do steam testing all the time, whether
10 they do it exactly this way or some other way, you
11 know? But ring compression tests are a tough thing to
12 do and do right. And so that's the whole purpose of
13 this round robin testing.

14 MEMBER BROWN: Okay.

15 CHAIRPERSON ARMIJO: And to make sure that
16 everybody getting the same sample, testing it in
17 different labs will get pretty much the same results
18 that meet the requirement.

19 MEMBER SHACK: I mean, we haven't normally
20 seen -- however, it's been a while since we've seen
21 reg guides with this much detailed guidance.

22 MEMBER SIEBER: Right.

23 MEMBER SHACK: I mean, that's normally bee
24 relegated to sort of consensus standards.

25 MS. FLANAGAN: Yes.

NEAL R. GROSS

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

1 MEMBER SHACK: Are the consensus standards
2 people working on standards for these kinds of tests?
3 I mean, obviously there's a need for it.

4 MR. CLIFFORD: This afternoon the industry
5 will present their recommendations or their
6 description of their round robin. One of the things
7 they're trying to do is to create an ASTM standard
8 using this reg guide. So, they're trying to get
9 endorsement from ASTM. I'll let them talk about it
10 this afternoon.

11 MS. FLANAGAN: And within these test
12 procedures there is relationship to established
13 standards. So for example, with thermocouple
14 calibration, there's a reference to what the
15 expectation is.

16 MEMBER SHACK: Yes, I mean, but that's
17 kind of a subsidiary.

18 MS. FLANAGAN: Yes.

19 MEMBER SHACK: I mean, the overall test,
20 you know, I mean, slow strain rate test, I can go to
21 an ASTM procedure and find, you know, a standard for
22 it and that's -- as I say, it's been awhile since I've
23 seen a reg guide this detailed.

24 MR. CLIFFORD: I think the ASTM approach
25 is probably the best approach, but that would take

NEAL R. GROSS

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

1 years.

2 MEMBER SHACK: Time, yes.

3 MR. CLIFFORD: So, but getting in on the
4 reg guide and implementing the rule. If it ever
5 happens that there's an ASTM standard created, then
6 great, but we don't need to wait for that.

7 MEMBER SHACK: Okay. But there is a
8 progress? At least people are thinking about that
9 approach?

10 MR. CLIFFORD: Correct.

11 MS. FLANAGAN: Okay. So, now I'll get
12 into the guidance that is sort of the outline of what
13 the guidance in the regulatory guide is. And so, for
14 establishing the onset of breakaway oxidation, the
15 guidance says to use the experimental procedure that's
16 provided in Appendix A of the regulatory guide. And
17 within that experimental procedure is a test matrix
18 defined which includes the tests of interest for this
19 phenomenon and the degree of replicate testing that's
20 expected to characterize variability. And then the
21 results of the experimental test would be provided;
22 this is just talking about the vehicle for providing
23 this to the staff, would be the staff's review and
24 approval for a new fuel design.

25 And then as far as periodic testing, again

NEAL R. GROSS

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

1 the experimental procedure is referring to that's in
2 Appendix A. And in this case a reduced test matrix is
3 identified which really focuses on the temperature
4 that was established originally as the most vulnerable
5 temperature, or the time at which the breakaway
6 oxidation time is the shortest. And then it also has
7 a comment about repeatability in the context of
8 periodic testing.

9 And then I'll discuss the analytical limit
10 in the third regulatory guide, but the periodic
11 testing really is related to the established
12 analytical limit. So in this case, whatever that
13 analytical limit that was established, the period of
14 testing is really designed to compare against that
15 established analytical limit.

16 CHAIRPERSON ARMIJO: Now, Michelle, you're
17 not going to go through -- I'm trying to understand
18 the agenda better, but you're not going to go through
19 the actual test procedures themselves, is that --

20 MS. FLANAGAN: Not in the slides. I can
21 certainly answer any questions that there are on
22 those, but I don't have slides that, you know, discuss
23 the language or --

24 CHAIRPERSON ARMIJO: Okay. Well, you
25 know, we've had them for review.

NEAL R. GROSS

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

1 MS. FLANAGAN: Yes.

2 CHAIRPERSON ARMIJO: So, I just wondered
3 if you were -- and many members may have questions; I
4 think Said raised one; I have a few, but it's kind of
5 clumsy to do it without your going through the
6 presentation of the actual draft guide itself, so --

7 MS. FLANAGAN: Yes, here these next three
8 slides are really high-level. What is the guidance
9 that is established?

10 CHAIRPERSON ARMIJO: I know that's the
11 issue.

12 MS. FLANAGAN: But, yes. So you'd like to
13 get into more of the finer details about what --

14 CHAIRPERSON ARMIJO: Yes, look, obviously
15 frequency of testing is a key thing.

16 MS. FLANAGAN: Right.

17 CHAIRPERSON ARMIJO: The number of repeat
18 tests. What does that mean?

19 MS. FLANAGAN: Yes.

20 CHAIRPERSON ARMIJO: You know, on
21 breakaway oxidation. Total five repeat tests at the
22 temperature at which minimum time is measured and so
23 on. You know, what is a repeat test? Does it start
24 from scratch, totally different autoclave --

25 MS. FLANAGAN: Okay. Yes, I understand.

NEAL R. GROSS

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

1 CHAIRPERSON ARMIJO: -- totally different
2 samples, totally different run, or is it five
3 different samples in the same autoclave? You know,
4 just --

5 MS. FLANAGAN: Okay. Yes, I understand.
6 I understand. Yes.

7 CHAIRPERSON ARMIJO: -- there's a lot of
8 those kind of detail stuff that maybe some people
9 wouldn't be interested in, but I find it interesting.

10 MS. FLANAGAN: Okay. Yes, so just to
11 answer a little bit about the repeatability, the
12 observation was that this phenomenon has some
13 variability and that you can have one test which does
14 not experience breakaway oxidation in your test time.
15 And if you just stop there, you might feel certain
16 that your material did not experience breakaway. In
17 another test you may find that it is experiencing
18 breakaway.

19 CHAIRPERSON ARMIJO: Well, typically what
20 you would do in a factory is you would have
21 standards --

22 MS. FLANAGAN: Yes.

23 CHAIRPERSON ARMIJO: -- of a material that
24 you always know has got good breakaway oxidation
25 resistance and another material which you always know

NEAL R. GROSS

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

1 has poor breakaway oxidation resistance and you run
2 them at the same time as the new batch of manufactured
3 cladding comes through.

4 MS. FLANAGAN: Oh, okay.

5 CHAIRPERSON ARMIJO: And you have these
6 internal standards that you're always tracking to make
7 sure that the test setup gives you the same results
8 day after day, week after week. And so, but you know,
9 and I don't know if the industry's going to comment
10 along those lines or not, but to me that's the kind of
11 questions I had, and maybe they're premature.

12 The other thing you --

13 MS. FLANAGAN: Yes, I mean, I understand
14 your question, and it's actually the -- in this case
15 we're assuming that the test procedure is valid and
16 that the variability is actually a function of some --

17 CHAIRPERSON ARMIJO: The material and the
18 fabrication process?

19 MS. FLANAGAN: Right. And so, but I
20 understand your question that there's also this other
21 range of variability that is confirming that you're
22 running the same test. So, I understand that.

23 CHAIRPERSON ARMIJO: Okay. And then the
24 other thing I wanted to ask you about: In the case of
25 breakaway oxidation life, you know, you're reporting

NEAL R. GROSS

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

1 out the need or requirement for single-sided testing
2 and two-sided testing. And I wanted to ask why would
3 you want two-sided testing?

4 MS. FLANAGAN: Sometimes just for
5 convenience. So, what the --

6 CHAIRPERSON ARMIJO: But it's not
7 something related to the fuel has failed and you're
8 getting oxidation and breakaway oxidation on the
9 inside, or -- it's really a test convenience? Is that
10 -- just so you can just put a little ring --

11 MS. FLANAGAN: In this particular -- yes.

12 CHAIRPERSON ARMIJO: Okay.

13 MS. FLANAGAN: Because welding of end caps
14 and as a level of complexity. And so, the regulatory
15 guide comments on what would be done if that just
16 wasn't what you wanted to do.

17 CHAIRPERSON ARMIJO: Yes.

18 MS. FLANAGAN: And how that relates to --

19 CHAIRPERSON ARMIJO: Because there are
20 some fuels where the inside is not the same as the
21 outside.

22 MS. FLANAGAN: Right.

23 CHAIRPERSON ARMIJO: Some cladding. And
24 so, okay. Well, I understand that.

25 MS. FLANAGAN: Yes.

NEAL R. GROSS

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

1 CHAIRPERSON ARMIJO: Well there are a
2 number of these detailed things -- and I guess I won't
3 belabor them, because you know, there was an issue on
4 stress reversals and triggering transformation of the
5 oxides.

6 MR. CLIFFORD: Do you want to pull up what
7 we actually got here?

8 CHAIRPERSON ARMIJO: You know, there were
9 a number of things, and maybe this is not the time to
10 talk about it. I was hoping that we'd get into that
11 a little bit more.

12 MS. FLANAGAN: Okay.

13 MR. CLIFFORD: Do you want us to pull up
14 the actually Appendix A here on the screen and then --

15 CHAIRPERSON ARMIJO: You know, I --
16 frankly I -- we're ahead of schedule. You know, you
17 went through the -- well, we're on DG-1261, right?
18 Michelle, are we on that?

19 MR. CLIFFORD: Yes.

20 CHAIRPERSON ARMIJO: Yes, so we're ahead
21 of schedule. So --

22 MR. CLIFFORD: So, let's do that.

23 CHAIRPERSON ARMIJO: So, why don't you
24 pull it up and let's just kind of walk through that.
25 We don't have to --

NEAL R. GROSS

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

1 MS. FLANAGAN: I don't know if they've
2 been loaded on here, actually.

3 MR. BROWN: No, I would have to get those.

4 MS. FLANAGAN: Okay. So, maybe what I'll
5 do is just continue with the presentation, but I do
6 acknowledge that, you know, a little bit level of
7 detail is of interest at this point. So, we'll --
8 hold on. I'm not used to this format here. Okay.
9 And then we'll look at some of the details of the test
10 procedure.

11 And so, in this case just to complete this
12 slide I'll say that in the objective -- I think I did.
13 I said that the objective of the periodic testing is
14 really to confirm performance relative to the
15 established analytical limit.

16 Okay. And then reporting results is
17 something that -- so this regulatory guide is
18 structured so that reporting would take place annually
19 and the objective of that reporting really is to
20 confirm that the cladding susceptibility to breakaway
21 oxidation has not been altered since the last reported
22 or since the established time. And then because that
23 is the objective, the report is very focused on
24 changes to the time of onset of breakaway oxidation.
25 And the vehicle for reporting in this case would be

NEAL R. GROSS

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

1 the annual reports outlined in 50.4, 52.3 and 21.21.

2 Okay. So that's the slides that I
3 prepared and it's clear that there's some interest in
4 some of the details, so --

5 MR. CLIFFORD: Maybe it would be a good
6 time to take a break while we wait for --

7 MEMBER BLEY: Let me get something real
8 minor in before we do that.

9 MS. FLANAGAN: Okay.

10 MEMBER BLEY: Can you go back to slide 13?

11 MS. FLANAGAN: Yes.

12 MEMBER BLEY: I've been struggling with
13 that since you talked your way through it.

14 MS. FLANAGAN: Okay.

15 MEMBER BLEY: Let me try to paraphrase
16 what you told us and --

17 MS. FLANAGAN: Okay.

18 MEMBER BLEY: These are your criteria for
19 success?

20 MS. FLANAGAN: Yes.

21 MEMBER BLEY: And to a stakeholder on
22 public comment the first one I can see how you get
23 that, the details and expectations. The next two
24 about using the test procedures produces repeatable
25 measurements in a laboratory and across laboratories

NEAL R. GROSS

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

1 you see that coming to you through stakeholder
2 interaction by the industry telling you what they've
3 accomplished.

4 MS. FLANAGAN: We've already been engaged
5 with industry to -- on particularly the breakaway
6 oxidation procedures. They actually have -- we have
7 engaged in discussions about tests that were
8 conducted.

9 MEMBER BLEY: Do you think you're already
10 at the point of seeing these repeatable and consistent
11 across labs? And then you get to the next one is
12 therefore the differences are all here. That's --

13 MS. FLANAGAN: Well, what it means is that
14 if --

15 MEMBER BLEY: I have real trouble with --
16 I can see why that would be a criteria for success.

17 MS. FLANAGAN: Right.

18 MEMBER BLEY: But I have a little trouble
19 seeing how you make that logically. But if you can go
20 ahead telling us what --

21 MS. FLANAGAN: Yes.

22 MEMBER BLEY: -- you've been getting from
23 industry on these experiments.

24 MS. FLANAGAN: Yes, so I think we'll hear
25 a little bit about it this afternoon. I'm not sure --

NEAL R. GROSS

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

1 MEMBER BLEY: But I guess my question goes
2 back to something somebody asked earlier.

3 MS. FLANAGAN: Right.

4 MEMBER BLEY: How do you get enough from
5 that kind of interaction to make that kind of
6 conclusion that things are --

7 MS. FLANAGAN: So, I --

8 MEMBER BLEY: -- you know all there is to
9 know?

10 MS. FLANAGAN: Yes. I just want to say
11 that the conclusion has not yet been made, but that --
12 if I could determine --

13 MEMBER BLEY: I'm sure that's true.

14 MS. FLANAGAN: -- those three steps were
15 complete, then it would -- then we could conclude that
16 the differentiation was a result of material
17 performance rather than --

18 MEMBER BLEY: Okay. Well, maybe I'll wait
19 until after we hear this afternoon's -- do you think
20 we're moving on that path?

21 MS. FLANAGAN: That's certainly the
22 objective and I think there is a little bit more work
23 to do.

24 MEMBER BLEY: Okay.

25 CHAIRPERSON ARMIJO: I would just put in

NEAL R. GROSS

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

1 front of your sentence No. 1 --

2 MS. FLANAGAN: Yes?

3 CHAIRPERSON ARMIJO: -- I'd just put an
4 "if."

5 MS. FLANAGAN: Okay.

6 CHAIRPERSON ARMIJO: That's really the --
7 because they're not there yet.

8 MS. FLANAGAN: Right. Yes, that's --

9 CHAIRPERSON ARMIJO: This is a work in
10 progress.

11 MS. FLANAGAN: Yes.

12 CHAIRPERSON ARMIJO: And that's the
13 expectation, but it's yet to be proven that all of
14 these things will work out the way --

15 MEMBER REMPE: Well, so then I guess I'd
16 like to go back to the point that Charlie raised on
17 how you receive this input. Is it down to the level
18 where you're looking at a -- we call them like
19 travelers when we manufacture like thermocouples, but
20 they've gone through, the thermocouple's mis-
21 calibrated and all this. And so you're looking at
22 those kind of level of details from the people who are
23 submitting reports from these various laboratories?
24 That they've, you know, checked their moisture
25 content, the purity of the water and things like that?

NEAL R. GROSS

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

1 I mean, are you just trusting what you're getting from
2 the various sources or how much in depth are you
3 looking at what you're getting?

4 MS. FLANAGAN: So, so far or in the --

5 MEMBER REMPE: So far in what you're
6 planning to do also.

7 MS. FLANAGAN: Right. So, I'm kind of
8 speculating here a little bit, but --

9 MEMBER REMPE: But saying that the
10 different labs are giving you consistent results. So,
11 when they come in with their consistent results, how
12 far down do you investigate what you're getting from
13 the different labs?

14 MS. FLANAGAN: Right. So, in the test
15 procedures there's an outline and requirements. And
16 if the results are submitted under the statement that
17 these were conducted in accordance with the test
18 procedure, then we would consider that they were done
19 in accordance with the --

20 MEMBER REMPE: So you believe them? You
21 don't go down and say please submit the QA --

22 MS. FLANAGAN: I mean, yes, but I should
23 say that within the test procedures there is a
24 requirement that says, you know, this must be verified
25 given this standard. And so, there is some

NEAL R. GROSS

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

1 interaction with verification.

2 MR. CLIFFORD: If it supports a licensing
3 amendment, it would have to be done in accordance with
4 10 C.F.R. 50 Appendix B QA procedures.

5 MEMBER REMPE: Okay.

6 MR. CLIFFORD: And the staff always has
7 the option of going and auditing each of the
8 calculations.

9 MEMBER REMPE: Yes, that's what I'm
10 wanting to hear.

11 MR. CLIFFORD: And I'm sure we would do
12 that --

13 MEMBER REMPE: Okay.

14 MR. CLIFFORD: -- when we would get a new
15 material or something significant as opposed to we're
16 going to use what's in the reg guide. I mean, if they
17 came in with a new material, I'm sure there would be
18 an audit that would be more detailed, more rigorous
19 investigation and make sure that they follow the reg
20 guide, or in at least the spirit of the reg guide, if
21 the reg guide wasn't so detailed to where they had
22 flexibility.

23 MEMBER BLEY: I guess that's why I was
24 having trouble with that slide. Stakeholder
25 interaction seems a little too informal --

NEAL R. GROSS

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

1 MS. FLANAGAN: Yes.

2 MEMBER BLEY: -- as a place to draw these
3 nice conclusions.

4 MS. FLANAGAN: No, I understand that, and
5 I think that we're kind of coming from some experience
6 of what stakeholder interaction has looked like so far
7 and that is probably not clear from the slides about
8 really how extensive and how frequent the discussion
9 has been on some particular topic. And so, I'd agree
10 that that's not clear in these slides what exactly we
11 mean when we say stakeholder interaction. But for
12 example, with some fuel vendors there's been exchange
13 of samples between laboratories, exchange of test
14 procedures, reports that were written. So, there's
15 been some detailed interaction and we have -- that
16 have revealed actual differences or that have revealed
17 some insight into what's going on and it's not
18 complete yet. So, that's why it's kind of --

19 MEMBER BLEY: For any of those have you
20 been able to understand why the differences have
21 occurred --

22 MS. FLANAGAN: In some cases --

23 MEMBER BLEY: -- or they just appear to be
24 random things.

25 MS. FLANAGAN: I wouldn't say random, but

NEAL R. GROSS

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

1 in some cases there's more work to do. I guess that's
2 what I'll say.

3 MEMBER BLEY: Okay. I guess the more we
4 hear about that, the more comfort --

5 MS. FLANAGAN: Yes. No, I understand.

6 CHAIRPERSON ARMIJO: We're done yet.

7 MS. FLANAGAN: Yes, I mean, you know, we
8 have to recall --

9 CHAIRPERSON ARMIJO: Cake's in the oven,
10 but it's not out.

11 MS. FLANAGAN: Yes. Okay. So now, we
12 have pulled up the actual -- the test procedure and
13 the regulatory guide. And so, maybe we can just have
14 direction to a particular section and then we'll go
15 there and we'll review the details and then maybe take
16 a certain amount of time and then we'll come back to
17 it if there's time at the end.

18 CHAIRPERSON ARMIJO: Yes, well, you know,
19 let me just ask about this stress reversal issue. I
20 didn't understand it, so -- and my question was if
21 this stress reversal is something that's important, is
22 it addressed in the testing procedure? Because the
23 testing is isothermal samples aren't stressed. Are
24 these stresses that occur just naturally as a
25 transformation of one kind of oxide to another, or is

NEAL R. GROSS

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

1 there stresses related to the loading on the cladding
2 during a LOCA or a quench? I didn't understand
3 what --

4 MS. FLANAGAN: Are you referring to a
5 particular part of the procedure, or are you just --

6 CHAIRPERSON ARMIJO: Yes, it's talking
7 about -- I forget what page it's on, but it says
8 stress reversals from compressive de-tensile and
9 chemical impurities --

10 MEMBER SHACK: A-2 background.

11 MS. FLANAGAN: Ah, okay.

12 CHAIRPERSON ARMIJO: Yes, and the question
13 was is this stress reversal issue important in the
14 testing?

15 MS. FLANAGAN: Ah, I see what you're
16 saying. Yes, right.

17 CHAIRPERSON ARMIJO: And the testing looks
18 to me like they're just basically isothermal
19 unstressed tubing samples.

20 MS. FLANAGAN: Yes.

21 CHAIRPERSON ARMIJO: And is stress a
22 variable that you've forgotten about, or does it occur
23 naturally?

24 MS. FLANAGAN: So, I can certainly try to
25 answer this question, but I think it would serve a

NEAL R. GROSS

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

1 little bit better -- if we have Mike Billone on the
2 phone, if he wanted to elaborate on this.

3 CHAIRPERSON ARMIJO: Sure.

4 MS. FLANAGAN: I think that that might
5 forward the conversation even more. So, is that
6 possible to --

7 CHAIRPERSON ARMIJO: Open up the line so
8 that Mike can talk or --

9 MS. FLANAGAN: Yes, because I think that
10 would be more direct and efficient if --

11 CHAIRPERSON ARMIJO: Or Ralph?

12 MS. FLANAGAN: And then the back and forth
13 of whatever comes out of that.

14 PARTICIPANT: So the lines aren't open?

15 MS. FLANAGAN: I think they're on mute.
16 So, I think he can hear us and he's anticipating our
17 turning it over to him, but I'm not sure that he's
18 able to speak yet.

19 CHAIRPERSON ARMIJO: I think Chris went to
20 do that.

21 PARTICIPANT: Sounds like he's on.

22 MR. BILLONE: Hello?

23 CHAIRPERSON ARMIJO: Hello.

24 MR. BILLONE: This is Mike Billone from
25 Argonne. May I address the issue of stress reversals

NEAL R. GROSS

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

1 real quickly?

2 MS. FLANAGAN: Yes, please.

3 MR. BILLONE: As you grow an oxide layer
4 on the cladding, there's a volume expansion that
5 results in the oxide layer being grown under
6 compressive stress because it wants to expand more
7 than the cladding because of volume expansion, the low
8 density. As you evolve in time, you start out with a
9 nice clean interface between the oxide and the metal
10 and at some point that develops into a scalloped
11 interface rather than a nice smooth layer. And that
12 scalloped interface where the oxide is thick, you have
13 regions of compression. Where the oxide is thin, you
14 have regions of tension at the oxide-metal interface.
15 So, it's not something you impose experimentally or
16 controlled. This is an isothermal test and you're not
17 adding any external stress. This is just internal
18 stress due to the phenomenon of the growth of the
19 oxide layer. And the precursor to breakaway oxidation
20 is always the development of that scalloped interface
21 between the oxide and the cladding.

22 CHAIRPERSON ARMIJO: Okay. Okay. So that
23 occurs naturally and --

24 MR. BILLONE: and it's a, yes, a
25 mechanistic natural phenomenon.

NEAL R. GROSS

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

1 CHAIRPERSON ARMIJO: Right, and the other
2 question I had, Mike, along those lines is all the
3 testing appears to be done on as-fabricated cladding,
4 not cladding that has some oxide on it.

5 MR. BILLONE: Well, we had an exchange
6 with Westinghouse where they put about a micron of
7 oxide layer on the cladding and we exchanged samples
8 and it made no difference.

9 CHAIRPERSON ARMIJO: Okay. So, you've
10 evaluated for the free oxidation, you know, let's say
11 some fuel that's been in there for 40,000 megawatt
12 days per ton or some, you know, substantial amount of
13 oxidation, but the difference in breakaway oxidation
14 behavior is unaffected by whether it's -- the
15 cladding's been in service or fresh out of the
16 factory?

17 MR. BILLONE: To be more precise, I would
18 say that we've evaluated the fresh fuel that's been in
19 the reactor just long enough to have enough of a heat
20 source to give you the high temperatures during LOCA.
21 So, it would be very low burnup fuel that we'd confirm
22 this for.

23 CHAIRPERSON ARMIJO: Okay. So, as far as
24 thicker oxides do you intend to resolve whether that
25 makes a difference?

NEAL R. GROSS

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

1 MR. BILLONE: Not within the Argonne
2 program because we're finished with our work, but
3 thicker oxides means higher hydrogen content and it
4 means it's going to kick you into the other reg guide
5 where the post-quench ductility and embrittlement due
6 to hydrogen that you pick up during -- in the reactor
7 is going to be more limiting than the breakaway; and
8 maybe that's too much of a personal opinion.

9 So, the breakaway that we studied is for
10 fresh cladding or very low burnup cladding and that's
11 where you don't have hydrogen that you've picked up
12 through the corrosion process. You get very, very low
13 hydrogen content. But breakaway is the phenomenon
14 that can result in high hydrogen pickup --

15 CHAIRPERSON ARMIJO: Yes.

16 MR. BILLONE: -- even during low burnups.

17 CHAIRPERSON ARMIJO: Okay. Well, that
18 answers that question, Mike. While I've got you
19 there, I want to ask about surface preparation,
20 cladding surface preparation.

21 MR. BILLONE: Right.

22 CHAIRPERSON ARMIJO: Many people, many
23 manufacturers use belt polishing techniques.

24 MR. BILLONE: Or wheel polishing, right.

25 CHAIRPERSON ARMIJO: Or wheel polishing,

NEAL R. GROSS

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

1 or something like that mechanically removing surfaces
2 rather than the old chemical etching procedures.

3 MR. BILLONE: Right.

4 CHAIRPERSON ARMIJO: And I wanted to make
5 sure that whatever gets tested is something that's
6 right off the manufacturing floor and does not then go
7 through a supplementary sample preparation that
8 changes that surface and I -- looking at --

9 MR. BILLONE: Yes, we tried to address
10 that knowing that what comes off the assembly line
11 after the polishing phase, that there's some
12 additional steps that may be taken in the fuel
13 fabrication plant. After you load the cladding with
14 fuel there's some additional cleaning that takes
15 place, and so we allow a whole variety of tests to be
16 conducted with the cladding that comes off the --
17 after -- let's say after belt polishing or wheel
18 polishing. But there's some confirmatory tests that
19 need to be done as a final product that's going to go
20 in the reactor.

21 CHAIRPERSON ARMIJO: Okay.

22 MR. BILLONE: We did try to address that
23 because we know that even dilute acid solutions
24 containing 1 percent hydrofluoric acid can result in
25 early breakaway oxidation, which is not --

NEAL R. GROSS

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

1 CHAIRPERSON ARMIJO: Yes.

2 MR. BILLONE: So, we wanted that all -- we
3 wanted to know what went into the reactor and how it
4 behaved.

5 MEMBER SHACK: Just scroll up a paragraph.
6 You sort of discuss that there in --

7 MS. FLANAGAN: Yes. Yes, there's some
8 discussion of it here at the beginning of the sample
9 selection that really the indention is that the
10 testing is conducted on material that's representative
11 of what's going to be loaded in the reactor. And then
12 you said it's even --

13 MEMBER SHACK: Well, page A-4.

14 MS. FLANAGAN: Okay.

15 CHAIRPERSON ARMIJO: Yes, but that's
16 harder to find.

17 MS. FLANAGAN: Ah. Well, okay.

18 MR. CLIFFORD: There's also discussion
19 about scratch dent.

20 MEMBER SHACK: Right.

21 CHAIRPERSON ARMIJO: But, you know, that
22 really --

23 MEMBER SHACK: Cladding surface
24 imperfections and scratches should be quantified and
25 simulated in the testing laboratory. A design basis

NEAL R. GROSS

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

1 scratch must be established.

2 CHAIRPERSON ARMIJO: Well, that's what
3 turned me off, because design basis scratches is a
4 little bit extreme. I think it should be the
5 fabricated product that is going to go into the
6 reactor is what should be tested.

7 MR. BILLONE: Right, but you're going to
8 scratch some of the cladding.

9 CHAIRPERSON ARMIJO: Well, yes, we know
10 that. We know that, Mike. But then if this testing
11 demonstrates that a -- let's say a longitudinal
12 scratch when you're loading a fuel rod through a bunch
13 of spacers creates such a vulnerability to breakaway
14 oxidation, then we got a serious, serious problem
15 because either we can't load fuel and meet the
16 requirements to keep the fuel where it's supposed to
17 be or we have, you know, a very susceptible material.
18 So, I'd like to know have you in your testing program
19 shown that a -- let's say a couple of scratches,
20 actual scratches along the cladding result in a
21 significant degradation?

22 MR. BILLONE: No. There's an easy answer
23 to that.

24 CHAIRPERSON ARMIJO: Okay.

25 MR. BILLONE: The U.S. alloys which are

1 basically -- I'll call them stable compared to the
2 Russian E110 alloy, they showed very little
3 susceptibility as far as the onset of breakaway
4 oxidation to scratches.

5 CHAIRPERSON ARMIJO: Okay.

6 MR. BILLONE: And, however, E110, if you
7 weld a thermocouple to it, you'll set off early
8 breakaway oxidation if you put a scratch on it. So,
9 I mean, the alloy has to be borderline unstable in
10 order for scratches to significantly accelerate the
11 process of breakaway oxidation. So, our research says
12 no in the sense that if 5,000 seconds is your smooth
13 cladding answer, then with scratched cladding you're
14 5,000 plus or minus 200 seconds, which is getting
15 significant.

16 CHAIRPERSON ARMIJO: Okay. Then the last
17 question before we take a -- the last question I have
18 before we take a break, and that was is the issue of
19 why ZIRLO in the draft guide had such a short
20 breakaway oxidation time compared to the other
21 materials. Is that still up in the air or is that a
22 final conclusion for --

23 MR. BILLONE: Those are the Argonne
24 results. And Westinghouse has a good set of data
25 which has a higher breakaway oxidation time. And

NEAL R. GROSS

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

1 that's the one alloy where we couldn't really get
2 agreement amongst -- between one lab and another lab,
3 whereas Zirc 4 we have excellent agreement with
4 different test techniques in France and CEA and
5 Westinghouse and Argonne. So, that material we have
6 good agreement. And with M5 we have good agreement
7 between Argonne and CEA. And then the one alloy in
8 which we have a couple of thousand seconds difference
9 is the ZIRLO.

10 CHAIRPERSON ARMIJO: Now, is that being
11 resolved?

12 MR. BILLONE: Well, that's tough to
13 resolve. I think the approach we're taking is if you
14 follow the reg guide and do all the benchmark testing,
15 then your results are acceptable. We've spent a lot
16 of time trying to resolve the differences and --

17 CHAIRPERSON ARMIJO: I don't understand
18 why it can't be resolved? If you test the same
19 material with the same test procedure, you ought to
20 get the same results plus or minus a smidgen. And so,
21 anyway, that -- I'll just hold that in --

22 MEMBER SHACK: Have you tested the same
23 material, Mike? Because, I mean --

24 MR. BILLONE: We swapped material, but the
25 apparatuses were different. And the differences in

NEAL R. GROSS

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

1 the apparatus didn't seem to matter for the other
2 alloys. And I can't say it matters for ZIRLO except
3 that Westinghouse does get higher results.

4 CHAIRPERSON ARMIJO: Okay. Well, we'll
5 just have to keep that in mind when we -- future
6 meetings, because we're not going to resolve it here.

7 MR. BILLONE: No. And my last comment I
8 want to make is that again you're dealing -- when
9 Michelle says repeatability, you have to understand it
10 in the context of an instability phenomenon. And when
11 you study instability phenomenon, you're not going to
12 get the same results from one test to the next test.
13 You're talking about like a test time plus or minus 10
14 percent or something like that.

15 CHAIRPERSON ARMIJO: No, Mike, believe me,
16 I don't disagree with you on that. And that's why
17 it's important that the -- if you have a criterion
18 that you've got to meet, that the material has plenty
19 of margin.

20 MR. BILLONE: Okay.

21 CHAIRPERSON ARMIJO: Because there is
22 going to be variability and -- no matter what you do.
23 And if you don't have margin, you're going to have a
24 terrible headache trying to --

25 MR. BILLONE: Right.

1 CHAIRPERSON ARMIJO: -- pass these tests.
2 So, are there any other questions from the
3 subcommittee?

4 (No audible response.)

5 CHAIRPERSON ARMIJO: If not, we're going
6 to take a break until -- let's make it -- how --
7 typically we -- 15 minutes. So, let's make it until
8 10:20. All right? Fifteen minutes.

9 (Whereupon, at 10:04 a.m. off the record
10 until 10:23 a.m.)

11 CHAIRPERSON ARMIJO: Okay. Let's get
12 started.

13 Michelle, let's -- I believe we finished
14 the 1261 --

15 MS. FLANAGAN: Yes.

16 CHAIRPERSON ARMIJO: -- presentation.
17 Unless members have any comments or questions, we're
18 ready for agenda item No. 6 on 1261.

19 MS. FLANAGAN: Okay.

20 CHAIRPERSON ARMIJO: And that would be an
21 EPRI presentation.

22 MR. CLEFTON: Let me address that, if you
23 would. My name is Gordon Clefton. I'm with NEI and
24 I'm representing the utilities, the vendors and the
25 industry consensus.

NEAL R. GROSS

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

1 We received these draft reg guides as
2 handouts for this meeting recognizing that they were
3 pre-decisional and were asked a couple of days ago if
4 we wanted to address the contents and the format and
5 such, the details of it, and chose not to because we
6 look at the fact that this is an integrated item with
7 the rule. We figure that it's going to take us 60 to
8 90 days to incorporate a consensus on the content of
9 the documents and we didn't figure that in three days
10 we were going to put a response together that would be
11 acceptable for what we wanted to talk about at today's
12 issue.

13 So, we're supportive of the idea. The
14 concept that we have of putting the details in the reg
15 guide is what we are looking for. Bigger picture in
16 the rule. Details in the reg guide. That's
17 supportive. There's actual specific words in here,
18 actual temperatures, details of the testing that will
19 come out of the laboratories, out of the three vendors
20 that we have and that will show up as comments that
21 Michelle and Paul will be able to work at changing the
22 draft guide into a reg guide. But as we've talked,
23 that's at a period after it comes out for public
24 comment.

25 So, right now the industry's looking

1 forward to 30, 60, 90-day response time to be able to
2 put a comprehensive set of comments back to the staff
3 so that they can refine the contents of these to
4 what's workable for the staff and the industry both in
5 terms of interface and in forms of webcast and
6 telecons, perhaps even workshops. And we have
7 industry support to --

8 CHAIRPERSON ARMIJO: Well, let me ask you
9 a question: Now, is that your position on commenting
10 on post-quench ductility and also the analytical
11 limits?

12 MR. CLEFTON: Yes, sir, all three of the
13 reg guides.

14 CHAIRPERSON ARMIJO: So, all three of
15 those you just are not prepared to comment today?

16 MR. CLEFTON: Today's not the appropriate
17 time to comment on that.

18 CHAIRPERSON ARMIJO: Okay. Okay. Well,
19 the invitation stood. How about the presentation on
20 test results and the round robin, and will there be --

21 MR. CLEFTON: Yes, we're real proud to
22 bring that in. We've got a comprehensive package for
23 you and we're ready to talk details on that. We have
24 the vendors in the audience representing all three of
25 the vendors. We have utility folks in here and many

NEAL R. GROSS

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

1 of the technical engineers ready to support questions
2 and answers that will come out of that presentation.
3 We'd look at that one scheduled for this afternoon
4 after lunch.

5 CHAIRPERSON ARMIJO: Okay.

6 MR. CLEFTON: And what it does is opens up
7 time for Michelle to talk details about the draft
8 guides this morning.

9 CHAIRPERSON ARMIJO: Yes, that does. And
10 maybe, Michelle, if you would, you know, in the post-
11 quench ductility testing, also the analytical limits,
12 kind of expand your comments to getting to the actual
13 reg guide. Some of us have questions anticipating it,
14 but often it's in the course of a presentation that
15 the questions come up. So, do your best on that.

16 MS. FLANAGAN: Okay. Maybe I could go
17 into like the contents of the reg guide and look at
18 what sections are on it.

19 CHAIRPERSON ARMIJO: Yes, you know,
20 exactly -- not exactly, but generally how are these
21 tests done?

22 MS. FLANAGAN: Right.

23 CHAIRPERSON ARMIJO: What are you trying
24 to accomplish with these tests? What are the
25 important variables and what do you know about it?

NEAL R. GROSS

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

1 You know, Argonne did a lot of testing and put to bed
2 a lot of the questions that we may have in our minds
3 about variability, for example.

4 MS. FLANAGAN: Okay.

5 CHAIRPERSON ARMIJO: So, that's the sort
6 of thing that I'm looking for; maybe the other members
7 would want to add to it. But it does free up quite a
8 bit of time, so you won't be pressed. So, I'd
9 appreciate if you would expand your presentation to
10 that.

11 MS. FLANAGAN: Certainly.

12 CHAIRPERSON ARMIJO: With that, let's go
13 onto item 7, post-quench ductility testing.

14 MS. FLANAGAN: Okay. So, Draft Guide 1262
15 is a test procedure for measuring post-quench
16 ductility through ring compression tests, and again,
17 I'll put this in perspective of the proposed rule
18 language. And this draft guide is an acceptable
19 experimental technique that can be used to develop --
20 to collect data to develop analytical limits.

21 So again, the objective is very similar.
22 It's really to provide a means of consistent
23 comparable data generation to establish regulatory
24 limits, and in doing so, simplify the staff's review
25 process and reduce regulatory uncertainty and minimize

NEAL R. GROSS

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

1 costs associated with the performance-based rule.

2 Again, the criteria for success are very
3 similar. It really is about that stakeholder
4 interaction and public commenting determining that
5 what we have accomplished in the regulatory guides is
6 clear communication of our expectations, effective
7 communication of our expectations and that we produce
8 a test procedure that produces repeatable measurements
9 within a laboratory and between laboratories. And
10 then if that is determined to be the case, we would
11 conclude that the differences that we see in the
12 future are actually a result of differences in
13 material behavior and not a result of differences in
14 experimental protocol. So, it's something to be
15 determined.

16 So again, the background for this one is
17 very similar to the breakaway oxidation test
18 procedures, and that is that it captures the
19 experimental technique that was used in NRC's LOCA
20 Research Program and it includes flexibility where
21 possible to allow for variations of equipment and
22 procedures that are already in use at other
23 laboratories, and the test procedures themselves.
24 Again, not the regulatory structure or the regulatory
25 position on the test procedures, but the test

NEAL R. GROSS

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

1 procedure itself was issued in conjunction with the
2 ANPR in August of 2009. And then in ANPR we received
3 comments and those have been considered as this draft
4 guide was developed. And then in some cases there's
5 changes that were made to the test procedures to
6 reflect the comments that have been received so far.
7 And then there's still room to do that in the draft --
8 in the public comment period for the draft guide.

9 So, the guidance on this one is very
10 simple: This guide says that you can use the
11 experimental technique that's in this guide to measure
12 the ductile-to-brittle transition for a zirconium-
13 based alloy. And it goes on to say that the technique
14 can be used to generate data for -- any zirconium
15 cladding alloy material can be used to generate data
16 at peak oxidation temperature less than 1200 degrees
17 C. And so the NRC's LOCA program really focused on
18 that value because it's the limit of ECCS performance.
19 And the test procedures can be used to investigate
20 performance at other lower temperatures. And then it
21 also -- the test procedure discusses the procedure in
22 terms of testing irradiated material.

23 MEMBER SIEBER: Now, the 1200 degrees C is
24 a maximum upper limit regardless of whether somebody
25 develops some super alloy that would be able to

NEAL R. GROSS

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

1 withstand temperatures greater than 2200 F?

2 MS. FLANAGAN: At this time in the
3 proposed rule that limit, that absolute limit has been
4 preserved.

5 MR. CLIFFORD: For zirconium only.

6 MS. FLANAGAN: For zirconium alloys only.

7 MEMBER SIEBER: Okay. Is there a reason
8 for that, or is that just to be in conformance with
9 the original acceptance criteria from the hearings in
10 1974?

11 MS. FLANAGAN: There was -- the research
12 that was done did not reveal that performance above
13 that temperature was acceptable. Does that make
14 sense? So, I mean --

15 MR. CLIFFORD: The time to reach
16 embrittlement above 1200 degrees C was so small that
17 it was impractical to allow a higher peak clad
18 temperature.

19 MEMBER SIEBER: Regardless of the
20 development of any new alloy or manufacturing
21 technique?

22 MR. CLIFFORD: No.

23 MR. LANDRY: Jack, Ralph Landry from the
24 staff.

25 MEMBER SIEBER: Hey, Ralph.

NEAL R. GROSS

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

1 MR. LANDRY: The 2220-degree F limit has
2 a lot more behind it than just embrittlement.

3 MEMBER SIEBER: Yes, I know.

4 MR. LANDRY: That's also a temperature
5 that ensures that you don't get into runaway
6 oxidation, auto-catalytic oxidation phenomena,
7 generation of excessive amounts of hydrogen and a lot
8 of other factors. So, there was nothing in the
9 testing that Argonne did that indicated a reason to
10 change the 2200, so we decided when redoing the rule
11 we wanted to preserve the 2200 because of all these
12 other factors that played into it in 1973 also.

13 MEMBER SIEBER: Okay. So, you're sticking
14 with the final acceptance criteria?

15 MR. LANDRY: Right.

16 MS. FLANAGAN: So, that's the last slide
17 that I have on this. It's really just an overview of
18 the contents of the regulatory guidance and
19 background. So, it sounds like there's interest in
20 looking at the regulatory guide and then going through
21 some of the details.

22 CHAIRPERSON ARMIJO: Well, I guess the
23 answer is yes, but it would be nice if the Committee
24 had some sort of idea how this testing is done, what's
25 important, what's not important. I'm glad we have

NEAL R. GROSS

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

1 Mike on the line. Maybe we could kind of walk through
2 that between yourself, Michelle, and Mike and --
3 because this is a test that is being used primarily
4 because a lot of experience with it, a lot of past
5 history. But the loading that during a quench the
6 fuel rod would experience, it is not a compressive
7 ring-type loading. In fact, the fuel might be in
8 bending, might be in tension, might be in compression,
9 but not in a ring compression type. So, we're using
10 this as kind of a technique to just measure a material
11 property, which is ductility.

12 MS. FLANAGAN: Yes.

13 CHAIRPERSON ARMIJO: Strictly for that.

14 MS. FLANAGAN: Yes.

15 CHAIRPERSON ARMIJO: And the trouble is
16 it's such a small amount of strain that we're trying
17 to -- that we think would be acceptable and we want to
18 measure it. Then your variability and your test
19 procedures, your materials, a lot of things can create
20 scatter that makes -- in the workplace can make a test
21 almost useless. And so that's why the round robin was
22 intended to help resolve that, that there was
23 repeatability. But also, Argonne did a lot of testing
24 to demonstrate that at least within one lab using one
25 procedure that they got very reproducible results.

NEAL R. GROSS

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

1 And, so I'd like to just get a summary-
2 type presentation on how the test is done, what's
3 really established as far as reproducibility from
4 these tests, what are the things that are really
5 sensitive that at least within the reg guide must be
6 controlled very well in order to get reliable test
7 data? So, that's kind of what I was hoping that we
8 would have been presented out of the reg guide as
9 opposed to an overview. The overview is good, but if
10 we have the time; and we do, I'd just like the staff
11 and maybe with Argonne to go over the reg guides test
12 procedure.

13 MS. FLANAGAN: Okay. So, let me see if I
14 can understand. Some of your questions are about how
15 this particular test procedure would generate a
16 performance characterization as compared to other
17 techniques?

18 CHAIRPERSON ARMIJO: No.

19 MS. FLANAGAN: Or no?

20 CHAIRPERSON ARMIJO: No, just within
21 itself.

22 MS. FLANAGAN: Okay. So --

23 CHAIRPERSON ARMIJO: You know, I mean, how
24 good is this test procedure and we've yet to get the
25 answer of, you know, how you can transport it to

NEAL R. GROSS

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

1 another lab --

2 MS. FLANAGAN: Okay.

3 CHAIRPERSON ARMIJO: -- and reproduce it.

4 But within the Argonne history what are the things

5 that Argonne has determined are really important?

6 What are the things that are unimportant, or not so

7 important that there's -- and how good is the test?

8 You know, how --

9 MS. FLANAGAN: Okay.

10 CHAIRPERSON ARMIJO: You know, how much

11 variability when everything is controlled as best you

12 can, how much variability do you get no matter what?

13 MS. FLANAGAN: Okay. Right. So, it's

14 kind of the lessons learned of --

15 CHAIRPERSON ARMIJO: Yes, exactly.

16 MS. FLANAGAN: -- actually working with

17 these test procedures? Okay. Then if that's really

18 the focus of the question, then I think it would be

19 beneficial to have my Mike Billone weigh in on that.

20 CHAIRPERSON ARMIJO: Okay.

21 MS. FLANAGAN: And then I can expand on

22 how that relates to the guidance.

23 MR. BILLONE: Okay. Can you hear me or am

24 I still on mute?

25 CHAIRPERSON ARMIJO: No, you're fine,

NEAL R. GROSS

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

1 Mike.

2 MS. FLANAGAN: We can hear you.

3 MR. BILLONE: Okay. I think the most
4 critical thing is temperature control and monitoring.
5 The literature in the past is filled with experimental
6 results related to oxidation and oxidation and post-
7 quench behavior, and the biggest problem with the
8 literature is poor temperature control. So, what
9 we've built into the procedure is a series of
10 benchmark tests. And not only do we require
11 thermocouples be calibrated and they have a
12 certificate along with -- we require what we call a
13 weight gain benchmark. Something like Zircaloy 4 is
14 highly predictable in terms of what the oxide layer
15 thickness is going to be as a function of time and
16 temperature and what the overall weight gain is.
17 So, before you start taking any data you need to
18 verify that the temperatures that you're measuring and
19 controlling are really the temperatures of the
20 material. So, I would say temperature control is the
21 most critical thing.

22 Then there's secondary things that should
23 be common sense. You need adequate steam flow. If
24 you have too little steam flow, you get steam
25 starvation and that's an artifact that you're

NEAL R. GROSS

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

1 introducing into the question, and that would be the
2 LOCA phase of the experiment. And there are other
3 factors that have to do with cooling rate and quench
4 temperature. We pretty much fix those for all of our
5 tests.

6 The second phase -- well, and I don't
7 know --

8 CHAIRPERSON ARMIJO: Well, there was --

9 MR. BILLONE: -- we're finished with the
10 LOCA phase, or we want do more with that?

11 CHAIRPERSON ARMIJO: No, Mike. One of the
12 questions that came up in the earlier subcommittee
13 meetings, and maybe full committee meetings, was the
14 issue of quench temperature, what temperature do you
15 quench from? And there was an issue of differences
16 between Argonne results and results from French tests.
17 have those things been resolved?

18 MR. BILLONE: Yes, that's been resolved
19 because the differences that were brought up; which
20 was scientifically fascinating, that -- our French
21 colleagues used a resistance furnace where you can't
22 get -- where the cooling rate is extremely slow.
23 We're talking thousands of seconds. And what results
24 you were seeing were the difference between thousands
25 of seconds cooling down to the quench temperature

NEAL R. GROSS

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

1 versus, you know, 50 to 100 seconds. So, the French
2 have added a new feature to their apparatus in which
3 they can do helium, force-flow helium cooling during
4 the cooling phase. So when their cooling rates are
5 comparable to our cooling rates we get the same
6 results.

7 CHAIRPERSON ARMIJO: Okay. And the quench
8 temperature, the temperature from which you quench
9 from, is that still around 800, or what --

10 MR. BILLONE: We chose 800 as a -- what we
11 thought was sort of a bounding temperature of, you
12 know, the highest temperature that you would bet
13 quench.

14 CHAIRPERSON ARMIJO: Okay. And I don't
15 remember whether I saw it in the reg guide. Is that
16 one of the specified test parameters in the reg guide?

17 MR. BILLONE: Yes, it is.

18 CHAIRPERSON ARMIJO: Okay.

19 MR. BILLONE: I don't know if I -- I'd
20 have to reread and see if -- usually when we have
21 these things like heating rates, cooling rates, quench
22 temperature, deviations from that need to be justified
23 by the vendor.

24 CHAIRPERSON ARMIJO: Okay. So, you put
25 acceptable numbers in and if they want to deviate they

NEAL R. GROSS

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

1 have to show you why that's okay.

2 MR. BILLONE: For their fuel design.

3 CHAIRPERSON ARMIJO: They have to show --

4 MR. BILLONE: Yes.

5 CHAIRPERSON ARMIJO: Okay.

6 MR. BILLONE: All right. And then just to
7 comment on the ring compression test, you're right,
8 we're doing a ductility screening test, but work by
9 our CEA colleagues in France and us at Argonne have
10 shown you could subject these samples to a three-point
11 bend test. There's your bending load.

12 CHAIRPERSON ARMIJO: Yes.

13 MR. BILLONE: And the ductile-to-brittle
14 transition from that type of test agrees quite well
15 with the ductile-to-brittle transition from the ring
16 compression test. But in one case you're bending is
17 in the circumferential direction and that's the ring
18 compression test, is you squeeze and it's the other
19 axial. And the material that embrittles at a certain
20 time and temperature it seems in the circumstantial
21 direction, let's call it, is also embrittled in the
22 axial direction. So, it wasn't -- we weren't planning
23 on that. We were planning on just using ring
24 compression as a screening test. But the agreement is
25 quite remarkable.

NEAL R. GROSS

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

1 CHAIRPERSON ARMIJO: Is that in a -- I'm
2 just trying to remember. We discussed that at the
3 prior subcommittee meetings, but I don't remember if
4 that had been resolved.

5 MR. BILLONE: That's fairly new.

6 CHAIRPERSON ARMIJO: That's new? Okay.
7 Is that in some sort of a NUREG or Argonne report,
8 or --

9 MR. BILLONE: No, CEA has a couple of
10 papers on that at ASTM meetings that are published
11 that I can --

12 CHAIRPERSON ARMIJO: Yes, I'd certainly
13 like to get a copy of those papers because that was
14 the thing that bothered me quite a bit is that, you
15 know, the tests we're doing is about the only way that
16 the fuel cladding can't be loaded during a quench.

17 MR. BILLONE: Right.

18 CHAIRPERSON ARMIJO: So, you know,
19 somewhere along the line there's got to be --

20 MR. BILLONE: It comes down to economy of
21 materials.

22 CHAIRPERSON ARMIJO: Sure.

23 MR. BILLONE: The French just tested as-
24 fabricated and pre-hydrided cladding which there's no
25 limit on sample size.

NEAL R. GROSS

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

1 CHAIRPERSON ARMIJO: Okay.

2 MR. BILLONE: But your three-point bend
3 test sample is 10 times longer --

4 CHAIRPERSON ARMIJO: Sure.

5 MR. BILLONE: -- than a ring compression
6 test. So, it came down to a matter of prime real
7 estate for high burnup cladding. And that's why we
8 went with the ring compression test. But later when
9 we -- well recently, last couple of years, when we've
10 been comparing test methods and our French colleagues
11 have been doing the same, that's when we found that
12 there was close correspondence between the axial bend
13 test with the longer sample and the ring compression
14 test. It just gave us a little more confidence and
15 fuzzy, warm feeling that we weren't testing -- that
16 the results weren't highly dependent on your loading
17 mechanism. And so, that's really over the last two
18 years that's come out.

19 CHAIRPERSON ARMIJO: Okay. Well, look,
20 that's new information and I think that's a good
21 finding, because it makes the tests a little more
22 relevant, too, to the actual kind of loading, that it
23 isn't -- the ductility we measure isn't just some
24 artifact of a particular kind of test. It doesn't
25 mean much --

NEAL R. GROSS

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

1 MR. BILLONE: Right.

2 CHAIRPERSON ARMIJO: -- in a real loading.
3 So, that's good.

4 MEMBER SIEBER: Are these French reports
5 specific enough to describe the actual geometry and --

6 MR. BILLONE: Yes.

7 MEMBER SIEBER: -- of --

8 MR. BILLONE: I mean, I could --

9 MEMBER SIEBER: -- the test samples?

10 MR. BILLONE: I could tell you. I mean,
11 they use -- for the ring compression test their
12 cladding is 10 millimeters long. And for the axial --
13 or the three-point bend test they're 90 millimeters
14 long.

15 MEMBER SIEBER: Okay.

16 MR. BILLONE: And the three-point bend is
17 kind of simple. You're just --

18 MEMBER SIEBER: Yes.

19 MR. BILLONE: -- loading at the mid-span.

20 MEMBER SIEBER: Right.

21 MR. BILLONE: And you have two supports
22 near the ends.

23 MEMBER SIEBER: Right.

24 MR. BILLONE: And I happen to remember all
25 those numbers, but I don't want to drag out your

NEAL R. GROSS

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

1 meeting, so --

2 MEMBER SIEBER: If they're in the paper,
3 then you don't --

4 MR. BILLONE: Yes, they're in the paper.

5 MEMBER SIEBER: Okay.

6 CHAIRPERSON ARMIJO: Yes, if you could
7 provide us with -- get Chris copies of those papers,
8 some of the members might be interested in --

9 MR. BILLONE: Yes, they're from the last
10 two zirconium conferences, the ASTM zirconium
11 conferences, and I'll provide those.

12 MEMBER SIEBER: Thank you.

13 CHAIRPERSON ARMIJO: Okay. Go ahead.

14 MR. BILLONE: All right. And then I don't
15 know if there's questions about how the ring
16 compression test is conducted, but we did a lot of
17 work to establish guidelines as to how much offset
18 strain, plastic strain, whatever you want to call it,
19 that you can determine from the load displacement
20 curves got you out of the noise of the uncertainty of
21 the test. And it's roughly -- you need roughly two
22 percent off that strain to know that you have
23 ductility.

24 CHAIRPERSON ARMIJO: Mike, in this test
25 does 2 percent offset strain -- is that equivalent to

NEAL R. GROSS

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

1 greater than 1 percent plastic strain?

2 MR. BILLONE: It --

3 CHAIRPERSON ARMIJO: Because that's your
4 acceptance criterion, right?

5 MR. BILLONE: Yes, and the 1 percent is
6 something you measure directly with a micrometer. You
7 measure the diameter before you squeeze and you
8 measure the diameter after you squeeze. And of course
9 what you're measuring after you squeeze is a sample
10 with a very tight through-wall crack. And that adds
11 some uncertainty. And that's why the -- the answer is
12 not zero. The answer is 1 percent based on
13 uncertainty analysis. And that's when you measure
14 directly. We call that permanent strain.

15 CHAIRPERSON ARMIJO: And what is the
16 acceptance? Is it that permanent strain number or is
17 it the offset strain you measure during the test
18 before the load drops?

19 MR. BILLONE: It's an easy thing to
20 answer. The way Argonne runs its tests are different
21 than anybody else in that we stop the test after the
22 first significant load drop, and most of our
23 colleagues run the test until the sample is completely
24 destroyed and you can get no information from it. So,
25 for the Argonne tests you can look at the directly-

NEAL R. GROSS

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

1 measured change in diameter and what you determine
2 from the load displacement curve. You have two
3 sources of data. Load displacement, you call that
4 offset strain, which is a traditional term.

5 But -- so the issue is are people willing
6 to run their tests the way Argonne runs their tests?
7 In other words, it's interactive. You see a
8 significant load drop of 40 percent or more. you stop
9 the test. You have an intact sample with a tight
10 through-wall crack most of the time and you can get a
11 legitimate diameter reading at the end. If you don't
12 want to do that, then you have to go with our offset
13 strain criteria.

14 CHAIRPERSON ARMIJO: Okay.

15 MR. BILLONE: Which is higher than the 1
16 percent.

17 MS. FLANAGAN: And then I've pulled up the
18 Appendix C of the regulatory guide, which discusses
19 specifically the relationship between offset strain
20 and permanent strain and it depicts --

21 CHAIRPERSON ARMIJO: Okay.

22 MS. FLANAGAN: -- what was observed in the
23 Argonne tests as far as the relationship between these
24 two parameters.

25 CHAIRPERSON ARMIJO: So, if someone wanted

NEAL R. GROSS

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

1 to run the tests differently, they'd have to
2 demonstrate to you that they effectively get the same
3 -- they've really measured the same ductility?

4 MS. FLANAGAN: Yes.

5 MR. BILLONE: Yes, and the only thing that
6 would be different would be to put in a fixed large
7 displacement and then continue to crush the ring until
8 you get like four cracks.

9 CHAIRPERSON ARMIJO: Yes.

10 MR. BILLONE: And then the only thing you
11 have is the load displacement curve --

12 CHAIRPERSON ARMIJO: Okay.

13 MR. BILLONE: -- to get data from. So,
14 we've allowed for that. We did a lot of work actually
15 to correlate the -- our permanent strain measurements
16 with our offset strain from the load displacement
17 curve knowing that most people were just going to use
18 the load displacement curve.

19 CHAIRPERSON ARMIJO: Okay. Okay. Now,
20 you also specify 135 degrees centigrade as the test
21 temperature for the ring compression test. Where did
22 that number come from and how important is it to run
23 it at 135 as opposed to 140 or 150, or even --

24 MR. BILLONE: I think my colleagues
25 probably at NRC can answer it better, but my

NEAL R. GROSS

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

1 understanding is that at the end of the quench phase
2 the pressure and the reactor is higher than
3 atmospheric pressure and the corresponding temperature
4 of the cladding would be -- or the steam would be 135
5 degrees.

6 CHAIRPERSON ARMIJO: So, that comes out of
7 a systems analysis that says that's --

8 MR. BILLONE: Yes.

9 CHAIRPERSON ARMIJO: So --

10 MR. CLIFFORD: It is sensitive to test
11 temperature.

12 CHAIRPERSON ARMIJO: But, yes, that's what
13 I was getting at. If you ran the test at 150, I guess
14 you'd get more ductility, but that's not what the
15 temperature's going to be based on the --

16 MR. BILLONE: Well, what you're doing is
17 you're testing at the minimum temperature at the end
18 of quench with total confidence that during quench
19 your temperatures are higher and you have more
20 ductility.

21 CHAIRPERSON ARMIJO: Okay. So, it's a
22 conservative -- you know, so if you --

23 MR. BILLONE: Right.

24 CHAIRPERSON ARMIJO: Because if you can
25 ask the question what if I tested at 100 centigrade?

NEAL R. GROSS

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

1 Would the 1 percent strain limit be met?

2 MR. CLIFFORD: It would be more
3 conservative.

4 MR. BILLONE: You keep the 1 percent
5 strain limit, but you're allowed less time at
6 temperature if you drop below that 1 percent.

7 CHAIRPERSON ARMIJO: Okay.

8 MR. BILLONE: We did limited testing at
9 room temperature, 100 degrees C and 135 degrees C,
10 very limited, just to get a feeling. And your
11 ductile-to-brittle oxidation level drops obviously as
12 your test temperature drops from 135 to room
13 temperature.

14 CHAIRPERSON ARMIJO: Okay. One other
15 question I had on the ring compression test. Is the
16 very precise 0.33 millimeters per second displacement
17 rate and --

18 MR. BILLONE: It's two millimeters per
19 minute, to make it easier.

20 CHAIRPERSON ARMIJO: Oh, well, that I feel
21 a lot better about. But you know, is it really -- so
22 it's two millimeters per minute plus or minus
23 something.

24 MR. BILLONE: Right.

25 CHAIRPERSON ARMIJO: And but is that the

NEAL R. GROSS

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

1 same number for independent of the cladding diameter,
2 cladding thickness? Not everybody has the same
3 dimensions.

4 MR. BILLONE: Yes, we used it for 15 by 15
5 cladding with the larger diameter and 17 by 17 with
6 the smaller diameter. It's in the range of what was
7 done in 1973 and it's roughly -- it's considered a
8 slow strain rate.

9 CHAIRPERSON ARMIJO: Okay. And so if
10 someone has -- so you don't really have a problem if
11 everybody uses the same strain rate independent of
12 their cladding dimensions?

13 MR. BILLONE: That's correct.

14 CHAIRPERSON ARMIJO: Okay. You don't
15 think that's --

16 MR. BILLONE: We didn't find a significant
17 -- and we're calling this a displacement rate.

18 CHAIRPERSON ARMIJO: Yes, I understand.

19 MR. BILLONE: Which means that there's a
20 slight difference in strain rate. It's not as
21 significant as you'd think. If you take cladding with
22 10.8 millimeter out diameter versus cladding with 9.5,
23 it's not -- you're not talking order of magnitude for
24 anything. You're not talking a significant difference
25 in strain rate for the two.

NEAL R. GROSS

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

1 CHAIRPERSON ARMIJO: Yes. Okay. I think
2 that covers a number of the specific questions I just
3 noted in reviewing the guide. But really my concern
4 is, you know, you're pretty satisfied with this test
5 and, you know, what leads you to believe that it's
6 really adequate from the standpoint of when everything
7 goes right as far as repeatability; you know, same
8 sample, hydrided the same way, tested exactly the same
9 way? What's the scatter in your test results?

10 MR. BILLONE: I would think the largest
11 scatter you would get would be with the real high
12 burnup cladding material, and that is because it's not
13 uniform. The hydrogen content is not uniform in the
14 axial direction or around the circumferential
15 direction. Yet, if all you're looking for is answers
16 plus or minus 1 percent ECR or oxidation level, then
17 you're not going to see a lot of scatter, meaning that
18 cladding with 550 to 660 ppm of hydrogen on the
19 average, it's going to embrittle between 4 and 6
20 percent. And so, if you're not looking at a measure
21 of plastic strain, you're just looking at where do you
22 transition between having some ductility and no
23 ductility, you don't get very much scatter at all.

24 CHAIRPERSON ARMIJO: Okay.

25 MR. BILLONE: If you're looking at, you

NEAL R. GROSS

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

1 know, is my ductility 30 percent strain or is it 10
2 percent strain, you'll get tremendous variability from
3 one lot of Zircaloy 4 made by one manufacturer to
4 another lot of Zircaloy 4 made by another
5 manufacturer. So, you'll get scatter in the absolute
6 ductility value at a particular oxidation level, but
7 you don't get the scatter in where the transition
8 occurs between ductile and brittle.

9 CHAIRPERSON ARMIJO: Okay. One other
10 question I had is on the testing of irradiated fuel
11 cladding. If a fuel supplier is using the -- let's
12 say the established Zircaloy 2, Zirc 4, ZIRLO, M5 --

13 MR. BILLONE: Right.

14 CHAIRPERSON ARMIJO: -- those alloys, does
15 this reg guide or -- and that's really to the staff,
16 require that additional testing of irradiated cladding
17 be performed?

18 MS. FLANAGAN: That requirement is in the
19 development analytical limits reg guide. So, in that
20 guide we really define our expectations for what type
21 of material and how extensive it will be tested. And
22 then this guide describes some of the important
23 characteristics of testing with irradiated material
24 and how to consider them in light of this test
25 procedure.

NEAL R. GROSS

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

1 CHAIRPERSON ARMIJO: Right, but -- so this
2 says if you're going to test, this is show to test?

3 MS. FLANAGAN: Yes.

4 CHAIRPERSON ARMIJO: The other one, which
5 we'll get to in a few minutes, is the analytical
6 limits. And this is whether you have to test
7 irradiated material --

8 MS. FLANAGAN: Yes.

9 CHAIRPERSON ARMIJO: -- or whether the
10 testing that's been done to date is sufficient to --

11 MS. FLANAGAN: Yes.

12 CHAIRPERSON ARMIJO: -- answer the --
13 satisfy the staff that irradiated material would not
14 have to be tested again? So, I'll just defer that
15 until later.

16 Those are most of my questions, but at
17 some point I think maybe we'd think about having
18 subcommittee meetings once we have the industry
19 comments and everything else that really get into the
20 guts of the testing, particularly where there is
21 differences and just major disagreements, things like
22 that. But it's probably premature now to try and do
23 that.

24 So, any other member? Charlie?

25 MEMBER BROWN: Yes, I have one other

NEAL R. GROSS

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

1 question, and it may not be a relevant one, so you can
2 tell me to -- number of samples. I presume you're all
3 doing a number of samples to come up with your set of
4 data and; and this is based again on past experience
5 that a set of qualifications has to be run for some
6 stuff. I was responsible to at least evaluate where
7 the requirement was. You run a certain set, you know,
8 four or five sets of data samples. You get results.
9 And if you fail the criteria, then what you had
10 required to do was to take three or four, five more
11 samples. Run the test again. Then you throw out the
12 highest and the lowest and then you take the resulting
13 ones and you come up and say am I okay or not? Is
14 this run like this or do you have to envelope all of
15 the samples?

16 MS. FLANAGAN: Yes. So, some of that
17 will --

18 MEMBER BROWN: That clear?

19 MS. FLANAGAN: Yes. No, I'm clear on what
20 the question is. Yes. So, your question is really
21 about following the test procedures and how many
22 samples do you have to reproduce in order to address
23 variability. And then also when does producing a lot
24 of variability call you into like a different set of
25 procedures to really get into the --

NEAL R. GROSS

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

1 MEMBER BROWN: Yes, are you allowed to
2 throw away data?

3 MS. FLANAGAN: Yes.

4 MEMBER BROWN: In other words, exclude it
5 from your --

6 MS. FLANAGAN: No.

7 MEMBER BROWN: -- from generating --
8 that's what happens in this case.

9 MS. FLANAGAN: Yes.

10 MEMBER BROWN: In other words, you take
11 those that appeared -- you get the additional samples
12 done and now you've got an array of data.

13 MS. FLANAGAN: Yes.

14 MEMBER BROWN: And now you're allowed to
15 can the highest one and can the lowest one. And then
16 you do your --

17 MS. FLANAGAN: Yes.

18 MEMBER BROWN: You determine whether you
19 pass based on the leftover data. And I'm --

20 MS. FLANAGAN: Right.

21 MEMBER BROWN: -- hoping that you all
22 don't do that.

23 MS. FLANAGAN: No, we do not.

24 MEMBER BROWN: Okay. Thank you. You've
25 answered my question then.

NEAL R. GROSS

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

1 MS. FLANAGAN: Okay. Okay. The other
2 part of your question about when you pass and when you
3 don't --

4 MEMBER BROWN: Yes.

5 MS. FLANAGAN: -- is actually in the
6 context of what your objective for testing is. So, in
7 some cases in the next test there will be a more
8 rigorous requirement if you're trying to just start
9 from scratch, set a new analytical limit that's alloy-
10 specific. And then there's a different level of
11 scrutiny that's required if you're just trying to
12 demonstrate that you are no different from the
13 proposed limit.

14 MEMBER BROWN: Okay.

15 MS. FLANAGAN: And that will be in the
16 next guide, but there's nothing in this guide that
17 says you can throw away your top and bottom.

18 MEMBER BROWN: Okay. I was just
19 interested in --

20 MS. FLANAGAN: Okay.

21 MEMBER BROWN: -- you know, making sure we
22 used all data from the test.

23 MS. FLANAGAN: Right. No, I --

24 MEMBER BROWN: As long as there wasn't
25 something really faulty, like you had --

NEAL R. GROSS

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

1 MS. FLANAGAN: Yes.

2 MEMBER BROWN: -- there's probably some
3 circumstance where --

4 PARTICIPANT: An invalid test.

5 MEMBER BROWN: Yes, it's an invalid test;
6 yes, exactly, where can make that -- no, I'm not
7 talking about that.

8 MS. FLANAGAN: Okay. Yes.

9 MEMBER BROWN: Thank you.

10 MS. FLANAGAN: Okay. So, we addressed
11 some of the details that are in this reg guide and --
12 okay. So, then I will move right along into the third
13 regulatory guide, which I think is where a lot of the
14 meat is and I think that this will be the place where
15 the questions are going to come up, because it's how
16 do we take the data that is generated in these two
17 regulatory guides and actually use it to identify the
18 limit. Like, where do we draw the threshold relative
19 to this data? It's in the same presentation. It's
20 just the following slides. I think it's already open
21 here.

22 CHAIRPERSON ARMIJO: Is it?

23 MS. FLANAGAN: Yes. Okay. So, again this
24 is where a lot of the meat is. Here our objective is
25 to enable the performance-based rule language by

NEAL R. GROSS

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

1 providing consistent means of using the experimental
2 data that was established with the protocols of the
3 two previous regulatory guides and then taking that
4 data to establish regulatory limits related to
5 cladding embrittlement and breakaway behavior. And
6 again, doing so would simplify the staff's review
7 process and reduce regulatory uncertainty and minimize
8 costs.

9 So, we want to establish an acceptable
10 analytical limit for the time at elevated temperature
11 for those materials which have already been tested in
12 NRC's program and we also want to provide guidance of
13 what our requirements would be if new cladding alloys
14 want to demonstrate that they are comparable to the
15 existing database. We want to provide guidance on
16 what would be required for new or existing alloys to
17 establish zirconium-alloy-specific limits other than
18 that which is provided in this guide. And we also
19 want to provide guidance on what would be required if
20 the desire was to establish an analytical limit at a
21 peak cladding temperature less than 2200 degree
22 Celsius.

23 And then finally, we want to provide
24 guidance in this regulatory guide about establishing
25 an analytical limit that's appropriate to demonstrate

NEAL R. GROSS

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

1 ECCS performance precludes the occurrence of breakaway
2 oxidation.

3 CHAIRPERSON ARMIJO: Michelle, what
4 reasoning or criteria do you use to determine whether
5 something is a new cladding alloy or not? You know,
6 there's a variety. You know, just because it's
7 labeled ZIRLO it could actually be some of ZIRLO or
8 grandson of ZIRLO. And same for M5 and all of these
9 other alloys, over time they change.

10 MS. FLANAGAN: Yes.

11 CHAIRPERSON ARMIJO: And generally for
12 very good reasons. And at what point do you say,
13 okay, this is really a new cladding alloy and you got
14 to go through the whole re-qualification of this
15 material? I don't care if it's labeled ZIRLO or not,
16 or M5 or Zirc 2, it's really different.

17 MR. CLIFFORD: When we approved -- first
18 of all, cladding alloys, if they're outside of the
19 ASTM spec, which would be Zirc 2 and Zirc 4 -- so I'm
20 dealing with say ZIRLO, M5, advanced cladding alloys
21 like that. When the staff reviews those materials, we
22 carefully define what the regulatory envelope of that
23 cladding alloy is. It would be specific to a nominal
24 chemical composition with a very tight window of
25 allowable deviations and it would be on heat treatment

NEAL R. GROSS

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

1 and structure, physical structure of the metal. So,
2 we define that. I mean, a good example is ZIRLO was
3 defined. And when Westinghouse came with optimized
4 ZIRLO, their first attempt was, well, it's close
5 enough. And then we didn't accept that argument and
6 it was then defined as a new cladding alloy.

7 So, it's -- we try to be -- we're getting
8 better at it. I would say years ago the windows --
9 the allowable chemical compositions. And we're very
10 large and we didn't even define what the heat
11 treatment was, whether it was fully recrystallized or
12 whether it was pressurized cold or stress-relieved.
13 But now we're doing a much better job trying to get
14 down to where we define the alloy where we feel
15 confident that if they stay within that window that
16 the material properties will be consistent.

17 CHAIRPERSON ARMIJO: Well, you know, for
18 example, the reason I brought it up is Zircaloy 2, the
19 standards, chemistry standards are pretty open.

20 MR. CLIFFORD: Yes. Yes, they are.

21 CHAIRPERSON ARMIJO: But many
22 manufacturers have much tighter restrictions on alloy
23 chemistry and that's where their experience base is.

24 MR. CLIFFORD: Yes.

25 CHAIRPERSON ARMIJO: And they could then

NEAL R. GROSS

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

1 relax to go still within the ASTM required to relax
2 those standards that they've used for a long time in
3 let's say one element or another and still be within.
4 Would that trigger or not trigger your definition of
5 a new alloy? And they change it because it makes a
6 difference in performance in let's say corrosion or
7 hydrogen pickup or something else and it might make a
8 difference on embrittlement. And, you know, if it
9 behaves differently, is it a new cladding alloy or
10 not? I guess that's what I'm --

11 MR. CLIFFORD: Right. Well, I guess in
12 the past we've accepted the ASTM specifications, so if
13 they stay within that window, even though that window
14 isn't very tight, then it's still considered their
15 version of Zirc 2.

16 CHAIRPERSON ARMIJO: Yes.

17 MR. CLIFFORD: So, if GE had Zirc 2 and
18 they're still within the spec, they're free to make
19 minor variations which are allowed by the standard and
20 not require a new licensing of the alloy.

21 CHAIRPERSON ARMIJO: Okay.

22 MR. CLIFFORD: But if they were to change
23 the final heat treatment, we do define -- for
24 instance, there is a fuel vendor; and I won't name
25 names, but who has a Zirc 2 who's going from, you

NEAL R. GROSS

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

1 know, cold work to fully recrystallized. Now, that's
2 a new material because of the significant effects that
3 it has on the material and mechanical properties.

4 CHAIRPERSON ARMIJO: But there are other
5 vendors that have used Zirc 2 fully recrystallized for
6 years and maybe they'd argue and say, hey look, if
7 they meet the requirements, this certainly does.

8 MR. CLIFFORD: Right, but their particular
9 fuel performance model has been tuned to the material
10 and mechanical properties of that alloy. So by
11 changing the final heat treatment and the composition;
12 not the composition, but the crystal structure of that
13 metal, then it would have invalidated their model.
14 Creep properties would change significantly, etcetera,
15 etcetera.

16 CHAIRPERSON ARMIJO: Yes. Yes. Okay.

17 MR. CLIFFORD: So in a sense we can
18 control the chemical composition and the final heat
19 treatment through the calibration of their fuel
20 performance models.

21 CHAIRPERSON ARMIJO: Okay. Go ahead.

22 MS. FLANAGAN: Okay. And again, the
23 criteria for success here is very similar, and that is
24 that we determined that we have communicated
25 effectively and completely what our expectations are

NEAL R. GROSS

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

1 and we do this through this public comment period and
2 stakeholder interactions.

3 So, there's a couple aspects of this
4 regulatory guide, so I'll go through each of them.
5 And it's really a particular fuel vendor is interested
6 in would send them to a particular sections of this
7 regulatory guide.

8 So to begin, for Zirc 2, Zirc 4 and ZIRLO
9 and M5, these are alloys that were tested in NRC's
10 LOCA Research Program. And so this guidance provides
11 unacceptable analytical limit that can be used by
12 these four fuels -- sorry, fuel claddings without
13 further testing. It's just this is a place to start
14 and it's based on the data that was generated in NRC's
15 LOCA Research Program, and the acceptable limit is
16 provided in the regulatory guide. And so, here it's
17 depicted as a line that transitions from ductile to
18 brittle behavior and it's a function of hydrogen. And
19 so, this limit could be adopted for the alloys in
20 which it is based that were tested in the program.

21 CHAIRPERSON ARMIJO: So, based on time and
22 temperature, you calculate percent ECR?

23 MS. FLANAGAN: Yes.

24 CHAIRPERSON ARMIJO: And then you measure
25 -- you have -- from measured tests with hydrogen-doped

NEAL R. GROSS

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

1 materials you measure ductility?

2 MS. FLANAGAN: Yes.

3 CHAIRPERSON ARMIJO: And if you fall in
4 this lower region, everything's just fine?

5 MS. FLANAGAN: Yes. Correct.

6 CHAIRPERSON ARMIJO: Okay.

7 MS. FLANAGAN: So, this is --

8 CHAIRPERSON ARMIJO: And that's a line.
9 Now, how much wiggle room do you have crossing that
10 line? Is there plenty of margin there, or is -- for
11 the materials that have been tested, you know, do you
12 have material that should be ductile that turns out to
13 be brittle and vice versa?

14 MS. FLANAGAN: So, margin can be described
15 in a couple ways. And in this case, this line marks
16 the determined transition from ductile to brittle
17 behavior. Now, to say a little bit more about that,
18 there was ring compression tests that were in the
19 brittle region that displayed an offset strain that
20 was consistent with ductile behavior. But as three
21 tests were conducted and the values were averaged, the
22 result is that that oxidation produces a brittle
23 result. And so there's some --

24 CHAIRPERSON ARMIJO: How about the other
25 way around? You know, you were supposed to be in the

NEAL R. GROSS

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

1 ductile range, but one of them turned out to be
2 brittle; one of three samples, and the other two
3 demonstrated ductility, what would you do then?

4 MS. FLANAGAN: So, there are some -- I
5 can't actually in this one remember if it's in this
6 guide or in the Test Procedures Regulatory Guide, but
7 there's no discussion about that. And it's the
8 discussion about why the need for three measurements
9 of a ring compression test really is necessary to
10 really inform behavior at a certain oxidation.

11 CHAIRPERSON ARMIJO: When everything turns
12 out, all three tests are in agreement, there's no
13 problem.

14 MS. FLANAGAN: Right.

15 CHAIRPERSON ARMIJO: But what happens when
16 there is a problem in something that should be
17 ductile, you have one test that -- with less than the
18 1 percent criterion?

19 MS. FLANAGAN: Yes.

20 CHAIRPERSON ARMIJO: Do you permit or
21 allow or require additional testing to show that that
22 was acceptable or not acceptable, or --

23 MS. FLANAGAN: In the case where there is
24 one measurement that would be determined to be brittle
25 and then two that are determined to be ductile, the

NEAL R. GROSS

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

1 average of that offset strain would be taken and then
2 the average would be evaluated against the criteria.
3 And so, in that case you could imagine a scenario in
4 which one brittle result was observe and the final
5 call would be that that oxidation level yielded
6 ductile results.

7 CHAIRPERSON ARMIJO: Yes.

8 MS. FLANAGAN: And in that case it's an
9 average of three tests. As the objective of what
10 there is to demonstrate is more rigorous, there's
11 times in which that would require nine tests. And so,
12 that -- does that make it clear?

13 MEMBER BLEY: Yes, but there's nothing in
14 there to account for the dispersion in that data. So,
15 if they were all three clumped close together and one
16 was on the brittle side and your average comes out
17 ductile --

18 CHAIRPERSON ARMIJO: You'd try retesting
19 it?

20 MEMBER BLEY: -- probably nobody -- well,
21 you might, but it might -- there might be an argument
22 for that. So, okay. But if one of them was severely
23 on the other side and the other two were kind of --
24 you know, if they were really desperate data, you
25 still just use the average?

NEAL R. GROSS

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

1 MS. FLANAGAN: You mean there's -- yes,
2 you're correct that there isn't a comment about an
3 unacceptable scatter.

4 MEMBER BLEY: Yes, that's true.

5 MS. FLANAGAN: That is correct, that the
6 measurement is an average. Let me --

7 MEMBER BLEY: That seems troublesome.

8 CHAIRPERSON ARMIJO: I thought you had to
9 be --

10 MS. FLANAGAN: I think you're getting into
11 something that I should really review before I --

12 MEMBER BLEY: Unless we never get much
13 scatter.

14 MS. FLANAGAN: Right.

15 CHAIRPERSON ARMIJO: I thought you had
16 something that's --

17 MS. FLANAGAN: Yes, let me go and make
18 sure then.

19 CHAIRPERSON ARMIJO: -- that can address
20 the issue of scatter.

21 MEMBER BLEY: I was just looking at and
22 didn't see it.

23 CHAIRPERSON ARMIJO: I didn't -- I don't
24 remember.

25 MEMBER BLEY: I don't.

NEAL R. GROSS

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

1 MS. FLANAGAN: Yes, I -- there's a part of
2 this that's me recalling what I remember and I'm
3 hesitant to make sure I'm saying what's actually in
4 the guide. So, I don't know if Mike is still on the
5 phone and if he can comment on this particular
6 question while I look for what has actually ended up
7 being said in this guide regarding that issue. Is
8 he --

9 MR. BROWN: Yes, I just have to turn it
10 on.

11 MS. FLANAGAN: Okay. Yes, because I just
12 can't recall if it's in the context of these -- of the
13 test procedures or --

14 PARTICIPANT: So his question is if you
15 have them run nine tests is there a window, they have
16 to stay within a certain range?

17 MS. FLANAGAN: Yes, it's kind of hard
18 because from this -- in this case, I mean, what you're
19 really interested in is when you get brittle behavior.
20 Okay?

21 CHAIRPERSON ARMIJO: Sure. Yes.

22 MS. FLANAGAN: So, for example, if you're
23 really in the ductile range, you're going to have huge
24 scatter. You might get one within an offset strain of
25 20 percent and one with 10 percent.

NEAL R. GROSS

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

1 CHAIRPERSON ARMIJO: That's not a problem.

2 MS. FLANAGAN: We're not concerned about
3 that.

4 CHAIRPERSON ARMIJO: That's borderline.

5 MS. FLANAGAN: What I'm concerned about is
6 when you start to get these really small values of
7 offset strain. And in that case, the offset means
8 something different. The variability is different.
9 Do you know what I mean? Like I would not be
10 concerned about 10 percent difference in offset strain
11 when I'm in a highly ductile region.

12 CHAIRPERSON ARMIJO: Yes, I agree with
13 you.

14 MS. FLANAGAN: But I start to get kind of
15 concerned if the variability is significant to 1 or 2
16 percent offset strain when I'm talking about
17 determination of brittle material. So, part of it is
18 that once we're really -- we're in the area where
19 we're concerned about, the values are closer to each
20 other. We haven't experiences where we'll see one
21 measurement of, you know, 1 percent and another of 10
22 percent, and then we have to deal with how to resolve
23 that kind of variability.

24 MEMBER BLEY: But, it just strikes me that
25 -- you know, and your story makes sense if that's the

NEAL R. GROSS

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

1 way it is, but if the next time somebody does a test
2 it really turns out to be very broad, it seems like
3 there ought to be something here that says don't just
4 average them if there's really something disturbing in
5 one of these results.

6 MS. FLANAGAN: Okay. Got it. So there's
7 a comment about --

8 MEMBER BLEY: I'm not quite sure how to
9 say that, but you know what I'm talking about.

10 MS. FLANAGAN: Okay. Yes, so I --

11 MEMBER BLEY: Because right now it says
12 doesn't matter.

13 CHAIRPERSON ARMIJO: The average is okay.

14 MEMBER BLEY: The average is okay.

15 CHAIRPERSON ARMIJO: Yes, and you know --

16 MEMBER BLEY: And if it's a skosh above,
17 it's good and if it's a skosh below, it's bad.

18 MS. FLANAGAN: Okay. So, you're talking
19 about --

20 MR. BILLONE: Hello?

21 CHAIRPERSON ARMIJO: Mike?

22 MS. FLANAGAN: Oh, I think Mike is going
23 to step in and answer --

24 MEMBER BLEY: Super.

25 MR. BILLONE: Oh, I wasn't sure if I was

NEAL R. GROSS

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

1 muted.

2 MS. FLANAGAN: Not anymore.

3 MR. BILLONE: Let me try to answer this
4 succinctly. When you talk about the 1 percent
5 permanent strain limit, the strain never goes to zero,
6 that permanent strain never goes to zero. So, you're
7 talking in numbers between 0.5 and 1 and 1.5. And
8 let's say you choose to average those and you come out
9 with 1, then you're okay. You're never going to get
10 huge scatter in the brittle regime because there's not
11 enough room to get a large number. Zero would be the
12 lowest value and most of your samples that are in the
13 brittle range are like 0.5 percent, 0.6 percent.

14 The subtlety comes in when you don't use
15 that method of measuring the diameter, that you
16 destroy the sample and you have to go to the load
17 displacement curve and then you have to use the offset
18 strain. And what we've built into that criterion to
19 make sure that we're guaranteeing 1 percent permanent
20 strain is we look at the average plus one sigma. We
21 had some statistics to the criteria for offset strain
22 such that it starts at a low value at low oxidation
23 and increases to almost 3 percent. So, any statistics
24 we have we have in the very large database comparing
25 offset strain to permanent strain. And then we

NEAL R. GROSS

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

1 require that the vendor use the average offset strain
2 to compare it with the criteria we develop.

3 So, there is some statistics in this.
4 It's in the relationship between measured -- between
5 the offset strain from the load displacement curve as
6 correlated with the 1 percent permanent strain limit.

7 MS. FLANAGAN: So, this --

8 MR. BILLONE: And we thought it was
9 punitive to require that your one sigma value was
10 within the ductile range and you're using a criterion
11 based on average plus one sigma.

12 MS. FLANAGAN: So, the discussion that
13 Mike is referring to here is in the test procedure for
14 post-quench ductility testing in Appendix C. And the
15 plot -- and the upper bound that Mike is referring to
16 is shown here in figure C-1. So here, it's the
17 relationship between permanent strain and offset
18 strain, and then really the scatter and the results.

19 MEMBER BLEY: This figure is in the reg
20 guide?

21 MS. FLANAGAN: This is in the regulatory
22 guide that defines the test procedure for post-quench
23 ductility.

24 MEMBER BLEY: But you go to the test
25 procedure to see how that's done. So, I'll have to

NEAL R. GROSS

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

1 look at that in some detail to see if it all comes
2 together for me.

3 CHAIRPERSON ARMIJO: Yes, I think we need
4 to understand that better because my issue is you have
5 -- you do three tests. Let's say two of them come out
6 1½ percent strain, plastic strain, measured the way
7 Mike described it, but for some reason or another
8 another one comes in at; I'll pick a number, 0.5.

9 MR. BILLONE: Yes.

10 CHAIRPERSON ARMIJO: To me that would be
11 a source of concern and I would not want to accept an
12 average. I'd want to say something's wrong here.

13 MEMBER BLEY: Figure it out.

14 CHAIRPERSON ARMIJO: Yes, figure it out.
15 And I'd expect anybody who's doing this on a good
16 faith basis would do the same, but it may not be
17 required in -- or it may be acceptable to just use an
18 average. And I'm just trying to find out would that
19 be acceptable as the reg guide is currently written?

20 MS. FLANAGAN: Yes.

21 CHAIRPERSON ARMIJO: So, yes, if we've got
22 two of them at 1 percent, 1½ percent, but one of them
23 was 0.5, but the average was still above 1, that would
24 bother me. You know, assuming that this is a very
25 important thing, that would bother me that it's not

NEAL R. GROSS

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

1 acceptable.

2 MS. FLANAGAN: Yes.

3 CHAIRPERSON ARMIJO: But maybe other
4 people feel differently.

5 MS. FLANAGAN: Well, no, I think --

6 CHAIRPERSON ARMIJO: And it may not
7 happen. You know, Mike's experience may be that, boy,
8 if we get over 1 percent strain, we -- you know,
9 that's -- we don't get these fliers that are really
10 very brittle.

11 I don't know, Mike, would you care to
12 comment?

13 MR. BILLONE: We've varied our approach.
14 Initially when we did this work if we had three to
15 five data points we would take the average minus one
16 sigma, one standard deviation, and that has to be
17 above 1 percent. That's how we started our work and
18 then eventually we compromised on that. I mean, you
19 would get variability because in the circumferential
20 direction you're hydrogen varies significantly. And
21 then there's no correlation between that and how you
22 would load the sample.

23 CHAIRPERSON ARMIJO: But in a furnace, if
24 you hydrided in a furnace, there's not going to be
25 circumferential variability.

NEAL R. GROSS

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

1 MR. BILLONE: Yes. Yes.

2 CHAIRPERSON ARMIJO: Something's wrong
3 there. Somebody should explain that. Because if it's
4 a --

5 MR. BILLONE: Well, I'm sorry, let me
6 start again. With high burnup fuel you get tremendous
7 variability.

8 CHAIRPERSON ARMIJO: Yes, that's in the
9 field. You know, that's --

10 MR. BILLONE: Yes.

11 CHAIRPERSON ARMIJO: Oxidation in the
12 reactors is -- you know, I don't disagree, but I'm
13 just saying if you're doing a laboratory hydrided
14 samples and you start getting these surprising results
15 where two are measured, there's plenty of ductility in
16 them, one is really low, all cooked in the same
17 furnace for the same amount of time and you get this
18 kind of variability, it just seems to me that
19 accepting an average would be --

20 MR. BILLONE: Well, no, that's a good
21 comment.

22 CHAIRPERSON ARMIJO: -- kind of sloppy
23 engineering.

24 MR. BILLONE: Our initial approach was
25 different. It was not the average. It was the

NEAL R. GROSS

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

1 average minus one sigma and compared to the 1 percent.

2 CHAIRPERSON ARMIJO: Okay.

3 MR. BILLONE: And we negotiated with our
4 RES and -- and interacted, not negotiated. We
5 interacted.

6 CHAIRPERSON ARMIJO: Yes.

7 MR. BILLONE: It was decided we would go
8 with an average. However, right now we are the only
9 lab in the world that uses this approach of stopping
10 the test so that you can even measure a permanent
11 strain.

12 CHAIRPERSON ARMIJO: Yes.

13 MR. BILLONE: I don't know if the new work
14 that EPRI's going to report is -- people have changed.
15 Everyone else uses the load displacement curve to
16 determine offset strain and there we do have
17 statistics built into that where our criterion is
18 higher. And so, on the average if you met that
19 criterion, then you have a good chance of, you know,
20 all your samples being ductile.

21 CHAIRPERSON ARMIJO: Yes. Yes. Well, you
22 know, I just --

23 MR. BILLONE: So the issue would really be
24 with anybody else in the world that would choose to
25 measure the diameter of the ring before the test and

NEAL R. GROSS

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

1 after the test without destroying the ring and without
2 creating large gaps. So, it's good to raise it
3 because we've done it both ways.

4 CHAIRPERSON ARMIJO: Yes. Okay. Well,
5 you know, I haven't heard the EPRI presentation yet,
6 but I kind of prefer something that I can physically
7 hold and measure and remeasure after somebody disputes
8 it and everybody says, yes, it definitely is deformed
9 and --

10 MR. BILLONE: Right.

11 CHAIRPERSON ARMIJO: -- whereas a strip
12 chart recording, differing guides can have different
13 opinions. I don't know, but it just seems that this
14 issue is something we'd want -- I'd want to hear about
15 some more, and maybe the rest of the subcommittee, on
16 -- and it may never occur. It may turn out that these
17 materials are so uniform that if you hydride it
18 properly and run the test with reasonable controls
19 that you'll get reasonably tight and consistent
20 results. So, I guess --

21 MR. BILLONE: No, but the example you gave
22 of -- and the one I gave, 0.5, 1, 1.5, that's -- there
23 is material -- varied validity. I'm not sure that
24 explains it.

25 CHAIRPERSON ARMIJO: Yes.

1 MR. BILLONE: But that is not an unusual
2 result.

3 CHAIRPERSON ARMIJO: Okay.

4 MR. BILLONE: So, that's something to deal
5 with. You go with the average or you can go with some
6 average minus one standard deviation. I'll leave that
7 one open because that goes beyond science and testing.

8 CHAIRPERSON ARMIJO: Okay.

9 MR. CLIFFORD: Right. So, we'll take the
10 action to evaluate this further and decide whether to
11 incorporate something specific in the final reg guide
12 before we come back to you guys.

13 MR. BILLONE: Yes.

14 CHAIRPERSON ARMIJO: Okay. Any other --

15 MEMBER SHACK: Well, it comes to the same
16 question of why one sigma -- I mean, you know --

17 CHAIRPERSON ARMIJO: You know, it's not
18 three sigma.

19 MEMBER SHACK: -- do we -- typically and
20 conservative, you know, we're somewhere around 95
21 percent, which is basically two sigma.

22 MR. BILLONE: Well, one sigma is better
23 than zero sigma.

24 MEMBER SHACK: Well, it's kind of -- you
25 know, it's the question where are you going to address

NEAL R. GROSS

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

1 uncertainty in this?

2 MR. BILLONE: You know, I guess we didn't
3 have enough data points --

4 MEMBER SHACK: That's a problem.

5 MR. BILLONE: -- overall and we chose to
6 explore a wide range of oxidation levels. And with --
7 there was only one cladding alloy where we did a
8 number of repeat tests just to see how it played out
9 and see how much difference it made.

10 CHAIRPERSON ARMIJO: What material was
11 that?

12 MR. BILLONE: It's an older variant of
13 Zirc 4. It's the kind they used to use in the H.B.
14 Robinson reactor.

15 CHAIRPERSON ARMIJO: Oh, okay.

16 MR. BILLONE: Fifteen by fifteen Zirc 4.

17 CHAIRPERSON ARMIJO: Okay. All right.

18 MR. BILLONE: But that was the only alloy
19 in the as-fabricated condition where we had enough
20 data points that we could do what you're talking
21 about.

22 CHAIRPERSON ARMIJO: Yes, and with time
23 with more people testing you'll see start seeing a
24 pattern --

25 MR. BILLONE: Right.

NEAL R. GROSS

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

1 CHAIRPERSON ARMIJO: -- that might give
2 you better statistics and -- but at this point where
3 you have very limited test data, that's an area where
4 I think you ought to rethink, the staff ought to
5 rethink that whether a simple average is really good
6 enough when you're in a borderline situation.

7 MR. BILLONE: I guess my last comment is
8 that if you accept that we're striving for transition
9 oxidation levels of let's say 17 plus or minus 1
10 percent, it may not make as big a difference as you
11 think because these ductility curves, they nose dive.

12 CHAIRPERSON ARMIJO: Yes.

13 MR. BILLONE: You go along with reasonable
14 ductility and you hit about 13 percent oxidation level
15 and then you come down very fast. The as-fabricated
16 tend to flatten out a little bit and that's where your
17 point would be well-taken. The pre-hydrided stuff --

18 CHAIRPERSON ARMIJO: Yes. Yes. Yes.

19 MR. BILLONE: -- nose dives very, very
20 fast. And within the plus or minus 1 percent
21 oxidation limit what we're talking about here may be
22 lost, or may be insignificant, but it's worth looking
23 at.

24 CHAIRPERSON ARMIJO: Yes. Yes. Okay.

25 Well, look, thanks a lot, Mike.

1 Any other Committee questions?

2 (No audible response.)

3 MS. FLANAGAN: Okay.

4 CHAIRPERSON ARMIJO: I think we can move
5 ahead, Michelle.

6 MS. FLANAGAN: Okay. So, the slide that
7 I was showing before is an acceptable analytical limit
8 that could be readily adopted for the materials that
9 were tested in NRC's LOCA program that were --
10 informed this line.

11 So then, for new cladding alloys there are
12 two options: One would be to adopt that limit that I
13 just showed, and the other would be establish a
14 material-specific one. So, first I'm going to talk
15 about what it would take for a new cladding alloy to
16 adopt the limit that I just showed.

17 Here the focus is really to confirm that
18 the transition to ductile-to-brittle behavior doesn't
19 take place at a lower ECR than the provided limit.
20 And, Sam, this gets into your question. This
21 methodology does include testing of as-received, pre-
22 hydrided and irradiated material.

23 CHAIRPERSON ARMIJO: So, for a brand new
24 material you would expect somebody to come with
25 irradiated material in their data package?

NEAL R. GROSS

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

1 MS. FLANAGAN: That is how this guidance
2 is set up, yes.

3 CHAIRPERSON ARMIJO: Okay.

4 MS. FLANAGAN: The methodology to develop
5 data to make this comparison would be referenced -- or
6 it would reference Draft Guide 1262 as an acceptable
7 way to generate that data. And then the vehicle for
8 submitting results would again be the staff's review
9 and approval of an new fuel design.

10 CHAIRPERSON ARMIJO: Okay.

11 MS. FLANAGAN: And so, the guidance
12 outlines this, but I wanted to make a figure that
13 would depict the extent of testing and kind of where
14 we're looking at testing. And so I'll walk through
15 this slide step-by-step and spend a little bit of time
16 on this.

17 So as I said, the objective -- or this
18 methodology includes testing of as-received, pre-
19 hydrided and irradiated material. And the extent of
20 pre-hydrided material and irradiated material, it
21 would really be informed by that particular material's
22 performance. So for example, what the expected end-
23 of-life hydrogen content is for that material would
24 really define the range of interest.

25 So for a cladding alloy that end-of-life

NEAL R. GROSS

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

1 hydrogen content is around 200 weight ppm, there would
2 not be a need to define the performance of a cladding
3 alloy at 600 weight ppm. It's really informed by the
4 end-of-life material performance. So in this case
5 I've done this depiction of the testing -- the extent
6 of testing assuming that this particular cladding
7 alloy that we're talking about has an end-of-life
8 expected hydrogen content of around 1200.

9 So, in this case the testing would start
10 with as-received material and oxidation tests would be
11 conducted at, just above and just below the proposed
12 limit. And in this method one oxidation test would be
13 conducted of each of these values and that oxidation
14 sample would be segmented into three ring compression
15 samples. Those samples would be tested and the
16 measured offset strain or permanent strain would be
17 used to determine if that material was brittle or
18 ductile at that oxidation level. And then the
19 comparison would be made to ensure that the ductile-
20 to-brittle transition is at or above the proposed
21 limit.

22 CHAIRPERSON ARMIJO: Right. So, there
23 would be a total of nine ring compression tests for
24 each hydrogen level that you're testing at?

25 MS. FLANAGAN: Correct.

1 CHAIRPERSON ARMIJO: For example, at 100
2 you'd have three sets of three samples?

3 MS. FLANAGAN: Yes, exactly.

4 CHAIRPERSON ARMIJO: Okay.

5 MS. FLANAGAN: And they would -- of those
6 nine three would be at the ECR level defined by the
7 proposed limit, three would be one ECR above, and
8 three would be one ECR below.

9 CHAIRPERSON ARMIJO: Okay.

10 MS. FLANAGAN: Okay. So, you'd begin with
11 that as-received sample and you'd be demonstrating
12 that for as-received material your performance was at
13 least as -- the transition was at least as high as the
14 proposed limit.

15 And then you would test pre-hydrided
16 material in increments no greater than 100 weight ppm.
17 And again, the procedure would be the same. You would
18 make -- you would test an oxidation level at, just
19 above and just below the proposed limit with the
20 objective of demonstrating that the transition is
21 taking place at or above the proposed limit.

22 And then as far as irradiated material,
23 the expectation would be you'd confirm that your pre-
24 hydrided material had been represented -- was
25 representative of your irradiated material by looking

NEAL R. GROSS

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

1 at the end-of-life, kind of the highest level of
2 hydrogen that you're looking at and then one hydrogen
3 level in between fresh and end-of-life. And so, in
4 this case it would be 200 and 400. So you'd test
5 irradiated material which had a hydrogen content of
6 200 and 400. And again, the same thing, you're
7 testing around the proposed limit.

8 CHAIRPERSON ARMIJO: Okay. But first
9 they'd have to demonstrate that based on post-
10 irradiation exam of actual fuel that had been in the
11 field did not exceed 400 as far as hydrogen pickup?

12 MS. FLANAGAN: Right.

13 CHAIRPERSON ARMIJO: Okay. So they'd have
14 that the prerequisite to start to set the test?

15 MS. FLANAGAN: Yes. And there's some
16 discussion of the hydrogen pickup models in this
17 regulatory guide also. And so --

18 MEMBER SHACK: Very little.

19 MS. FLANAGAN: It is very little; you're
20 right, yes.

21 CHAIRPERSON ARMIJO: But this is not a
22 model. This is actual test data.

23 MS. FLANAGAN: Correct.

24 CHAIRPERSON ARMIJO: You'd take irradiated
25 cladding and you measure the hydrogen content.

NEAL R. GROSS

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

1 MS. FLANAGAN: Correct.

2 CHAIRPERSON ARMIJO: Yes. Well, these are
3 numbers based on experiments, not the hydrogen level
4 that would be picked based on experimental post-
5 irradiation examination of irradiated cladding, right?

6 MS. FLANAGAN: Well, what I mean is that
7 you would find --

8 CHAIRPERSON ARMIJO: But is calculation
9 that it's going to be --

10 MR. CLIFFORD: No, this would be measured
11 hydrogen.

12 MS. FLANAGAN: Right. Yes. Okay. I see
13 your question. Yes.

14 CHAIRPERSON ARMIJO: Yes, for well-known
15 cladding I don't have a problem with that calculation
16 because you have a lot of data. But for brand new
17 cladding, you know, experiments are the only thing I'd
18 believe.

19 MS. FLANAGAN: Yes.

20 CHAIRPERSON ARMIJO: Okay.

21 MS. FLANAGAN: Okay. So, that depicts the
22 sort of extent of testing where the oxidation ranges
23 of interest are and depicts what are the expectations
24 for demonstrating and adopting the limit that's in
25 this regulatory guide for new cladding alloys.

NEAL R. GROSS

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

1 Another option would be to establish a
2 completely independent and material-specific limit.
3 And in this case, you don't take credit for any of the
4 proposed established limit and your objective is
5 really to characterize a cladding alloys embrittlement
6 behavior through an entire spectrum of conditions.
7 And when I say expected conditions here, I really just
8 mean hydrogen content that's expected during operation
9 and assume nothing, meaning that you assume -- you can
10 use that proposed limit as a starting point, but you
11 don't assume that that defines it. And so your
12 objective is more than just comparing that you're no
13 worse than that.

14 CHAIRPERSON ARMIJO: Let's say somebody
15 comes in and he's pretty sure that his end-of-life
16 hydrogen pickup is not going to be over 200 ppm.

17 MS. FLANAGAN: Yes.

18 CHAIRPERSON ARMIJO: But he says I don't
19 care. I'm going to test pre-hydrided samples all the
20 way out to 800 ppm and demonstrate it's okay. Would
21 that be acceptable to you that he wouldn't have to
22 test irradiated samples?

23 MS. FLANAGAN: Oh, no.

24 MR. CLIFFORD: He would have to test to
25 whatever he's asked the NRC to approve his alloy up

NEAL R. GROSS

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

1 to. Basically when we approve a new alloy, we approve
2 it up to a specific hydrogen content. So, if his end-
3 of-life is at 200, then he would need to define his
4 end-of-life regulatory limit at 200. And that would
5 not only be based on this, but it would also be based
6 on other mechanical testing requirements to license a
7 new alloy that you cannot use pre-hydrided as a
8 surrogate for irradiated. So, if the cladding only
9 absorbs 200, then that will be the extent of his
10 mechanical testing database. So, that will be his
11 regulatory limit. So, there would be no need to test
12 beyond that.

13 MS. FLANAGAN: Yes.

14 MEMBER SHACK: But he'll have to test at
15 200 using irradiated materials?

16 MS. FLANAGAN: Yes.

17 MR. CLIFFORD: Correct, for this and for
18 other reasons also.

19 MEMBER SHACK: Right.

20 MR. CLIFFORD: So, it's not just for this
21 reason.

22 CHAIRPERSON ARMIJO: Yes. Well, Michelle,
23 I don't understand the difference between the guidance
24 for this methodology and let's say the standard
25 methodology for new material.

NEAL R. GROSS

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

1 MS. FLANAGAN: Okay.

2 CHAIRPERSON ARMIJO: What's the big
3 difference? It seems to me like they're going to
4 do --

5 MS. FLANAGAN: Basically the extent of
6 testing. So, in this one really the only objective is
7 to prove that your transition is taking place at or
8 higher than a specific already established limit. In
9 the other case you're really saying that you know
10 nothing about the performance and therefore additional
11 repeatability is required, additional exploration of
12 maybe a wider range of ECRs is necessary. I mean,
13 it's really -- it may end up looking very similar as
14 far as ECR levels and the details may only be in the
15 extent of repeatability.

16 CHAIRPERSON ARMIJO: Okay.

17 MS. FLANAGAN: But for example, if you're
18 looking at developing a limit that's higher than this,
19 it wouldn't just be that you'd focus on -- you
20 wouldn't be informed or start with this proposed
21 limit. You'd be starting at a higher ECR and you'd be
22 exploring that range.

23 CHAIRPERSON ARMIJO: Okay.

24 MS. FLANAGAN: So, it's really the range
25 of interest of the ECR levels of what you're trying to

NEAL R. GROSS

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

1 demonstrate is the transition.

2 CHAIRPERSON ARMIJO: Okay.

3 MS. FLANAGAN: So the ECRs levels might be
4 higher. And then certainly the extent of repeat tests
5 will be higher.

6 I have some backup slides which have this
7 depicted for starting a new analytical limit and, for
8 example, what I've done in this slide takes four
9 slides in the other case. It's really like a lot more
10 iterations. So, first you'd do it as-received and you
11 sort of see where your transition is and you use that
12 to inform each subsequent level.

13 CHAIRPERSON ARMIJO: Did you give us
14 copies of those backup slides?

15 MS. FLANAGAN: No.

16 CHAIRPERSON ARMIJO: Why don't you do that
17 because --

18 MS. FLANAGAN: I said that very --

19 CHAIRPERSON ARMIJO: -- I don't -- you
20 know, everybody may not be interested --

21 MS. FLANAGAN: I listened to myself and I
22 was like whoa.

23 CHAIRPERSON ARMIJO: -- may not want to be
24 dragged through this and I --

25 MS. FLANAGAN: Yes.

NEAL R. GROSS

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

1 CHAIRPERSON ARMIJO: I'm interested, but
2 I think if you just give us those slides, we can look
3 at it and --

4 MS. FLANAGAN: Okay.

5 CHAIRPERSON ARMIJO: -- prepare ourselves
6 for some future meeting --

7 MS. FLANAGAN: Okay.

8 CHAIRPERSON ARMIJO: -- on that, because
9 I think it's for a brand new alloy and it's a subset
10 of the major guidance. It probably doesn't justify us
11 spending time unless some other member wants to
12 explore that. I don't see a lot of interest in doing
13 that, so just --

14 MS. FLANAGAN: Okay.

15 CHAIRPERSON ARMIJO: -- send us your
16 backup slides.

17 MS. FLANAGAN: Okay. Okay. Got it. So,
18 the backup slides which depict this, what would
19 really --

20 CHAIRPERSON ARMIJO: Yes.

21 MS. FLANAGAN: -- what it would like for
22 new materials?

23 CHAIRPERSON ARMIJO: Yes.

24 MS. FLANAGAN: And I don't need to go
25 through it now, but the intention is --

NEAL R. GROSS

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

1 MEMBER SHACK: I mean, you sort of have
2 that in Appendix B.

3 MS. FLANAGAN: Yes. Yes, it's outlined in
4 the regulatory guide and --

5 CHAIRPERSON ARMIJO: Yes, sometimes the
6 slides are easier to -- when you look at the slides
7 and you look at the appendix --

8 MS. FLANAGAN: Yes.

9 CHAIRPERSON ARMIJO: -- and the written
10 words just start to make sense.

11 MS. FLANAGAN: Okay. Okay. I understand.
12 So, I'm going to move on assuming that that will be
13 handled with follow-up.

14 Okay. Let me just review what I have
15 here. Okay. So, again the objective for establishing
16 a alloy-specific limit is different and therefore the
17 testing expectations are more rigorous. And the
18 methodology is designed to characterize the range of
19 hydrogen content, assuming no known reference points.
20 And again, the methodology that's outlined here
21 includes testing of as-received, pre-hydrided and
22 irradiated material and it refers to Draft Guide 1262
23 as an acceptable way to generate this data. And
24 again, the results would -- the vehicle for submitting
25 the results would be in the staff's review and

NEAL R. GROSS

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

1 approval of a new fuel design.

2 And I just want to clarify that this is
3 not only alloy-specific limits, but this is any limit
4 that wants to be established for an alloy-specific or
5 a temperature-specific criteria. So, there are some
6 instances in which that would provide value to
7 different vendors, and in that case this establishes
8 how that could be done.

9 MEMBER SHACK: I mean, he could have
10 different curves for large LOCAs and small LOCAs,
11 right?

12 MR. CLIFFORD: Right.

13 MEMBER SHACK: I mean, so it would --
14 because he'd want to maximize his oxidation for the
15 small LOCA.

16 MR. CLIFFORD: Or he could have different
17 curves for different peak oxidation temperatures and
18 apply them to different regions of the core.

19 MEMBER SHACK: Core.

20 MS. FLANAGAN: Yes.

21 CHAIRPERSON ARMIJO: But it's the same
22 material, so I mean, it's not going to be --

23 MEMBER SHACK: But if it never sees the
24 same -- you know --

25 MR. CLIFFORD: Right, sensitive to the

NEAL R. GROSS

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

1 maximum --

2 MEMBER SHACK: Temperature.

3 CHAIRPERSON ARMIJO: Yes, okay.

4 MR. CLIFFORD: -- temperature.

5 MEMBER SHACK: I see. But that's right,
6 he'd do it -- just even within the core he could be
7 doing this.

8 MR. CLIFFORD: Burnup effects.

9 MEMBER SHACK: Burnup effects, yes.

10 MR. CLIFFORD: Core location. Break size.
11 Sure.

12 MS. FLANAGAN: Okay. So, the last
13 analytical limit that is defined and provided --
14 guidance is provided on is how to set an analytical
15 limit for breakaway oxidation. So in this case the
16 experimental results for breakaway oxidation behavior
17 would be provided through the initial licensing of a
18 cladding alloy. And then again, it's referencing the
19 experimental procedures of Draft Guide 1261 as an
20 acceptable way to generate that data.

21 I'm pretty sure there's going to be
22 questions on this next bullet, which is about how that
23 testing is evaluated against ECCS performance. So,
24 here, let me see if I can explain this from sort of
25 using without the slide and then see what questions

NEAL R. GROSS

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

1 arise.

2 Let's say that the testing of a particular
3 alloy reveals that breakaway oxidation is experienced
4 at the minimum time, is experienced at 1000 degrees
5 Celsius and after 5,000 seconds breakaway is shown to
6 begin. The analytical limit can be set to evaluate
7 ECCS requirements to prevent sitting at 1000 degrees
8 Celsius for 4,000 seconds, so you can introduce margin
9 there from where your material performed to where
10 you're going to evaluate time relative to ECCS
11 performance.

12 What is established in this test procedure
13 is that with the data that we have available right now
14 breakaway oxidation is a phenomenon that has been
15 shown to exist as low as 650 degrees Celsius. And so,
16 times above 650 degrees Celsius couldn't be excluded
17 from the time that is relevant to this evaluation of
18 this phenomenon. However, it is a temperature -- it
19 is affected by the temperature. And so, right now
20 this requirement that the ECCS evaluation really be
21 linked to time above 650 is a result of the inability
22 to say anything else, and as data would be produced
23 that could be revisited.

24 So, having said what I've said, are there
25 -- does that make sense? Am I clear about where the

NEAL R. GROSS

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

1 650 comes from and where the opportunity to introduce
2 margin would be relative to cladding performance?

3 (No audible response.)

4 MS. FLANAGAN: Okay.

5 MEMBER SHACK: He would just break it into
6 different regions and he would have sort of -- you'd
7 somehow have to set up allowable times at different
8 temperatures?

9 MS. FLANAGAN: Well, for example, what I
10 mean is that if the material was demonstrated to have
11 breakaway oxidation within 5,000 seconds -- or sorry,
12 not before 5,000 seconds. At 5,000 seconds you
13 experience breakaway oxidation. And then you go and
14 evaluate the ECCS performance and say am I going to
15 experience breakaway oxidation during a LOCA? You
16 would look at the time at which you're above 650 and
17 evaluate that against 4,000 seconds if you chose to
18 introduce that margin. So, ECCS performance is
19 related to your observed behavior and it's not to say
20 I'm going to conduct an isothermal test called a LOCA
21 that sits at this temperature for 1000 degrees
22 Celsius. It's somewhere in between that. ECCS
23 performance is treated as one thing and then material
24 performance is treated as another thing and then the
25 link is as described there.

NEAL R. GROSS

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

1 MR. CLIFFORD: Yes, we don't have an
2 inaccurate calibrated correlation that properly
3 integrates time and temperature which captures each --
4 the sensitivity of breakaway to different
5 temperatures, because it's not always the maximum
6 temperature. It's whatever the material is sensitive
7 to, which could be an intermediate temperature. And
8 because we don't have that, the only way you can
9 really implement this would be -- a conservative way
10 would be find out what the minimum time to breakaway
11 and whatever that temperature is and don't go above a
12 ceiling -- or not a ceiling, but a lower threshold for
13 more than that period of time.

14 CHAIRPERSON ARMIJO: So, you know, it
15 seems like you'd just do a whole series of -- at
16 different temperatures of time to reach breakaway and
17 find them in time and then go through your systems
18 analysis to determine whether or not you exceeded
19 those -- if your temperatures were such that you had
20 to live with a minimum time --

21 MR. CLIFFORD: Right.

22 CHAIRPERSON ARMIJO: -- then that's it.

23 MS. FLANAGAN: Yes.

24 CHAIRPERSON ARMIJO: But if your
25 temperatures never get to that minimum time, you'd

NEAL R. GROSS

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

1 have margin --

2 MS. FLANAGAN: Yes.

3 CHAIRPERSON ARMIJO: -- somewhere, you
4 know? Whether you could use it or not, I don't know,
5 but these aren't the particular -- these aren't very
6 difficult tests to do. They're isothermal tests and
7 steam.

8 MR. CLIFFORD: Right.

9 CHAIRPERSON ARMIJO: And the -- so, you
10 know, I just think we can just do time temperature
11 experiments and demonstrate what this material -- how
12 it behaves and then see if you're exposed to those
13 kinds of times and temperatures in your -- through
14 your LOCA analysis.

15 MS. FLANAGAN: Yes.

16 CHAIRPERSON ARMIJO: And this one I think
17 is straightforward, but I'll wait to hear from the
18 industry guys, see if they agree with that.

19 MS. FLANAGAN: Okay. Yes, so the material
20 performance is really evaluated with that first
21 regulatory guide that we discussed here today. And
22 here it's really a discussion about how to evaluate
23 ECCS performance in light of that observed
24 performance.

25 Okay. So in this one, I'm going to get

NEAL R. GROSS

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

1 into a little bit more of the details of the
2 regulatory guide and talk about other topics that are
3 covered by this regulatory guide.

4 CHAIRPERSON ARMIJO: Okay.

5 MS. FLANAGAN: As I said, it really has a
6 lot of the meat of how this performance base will be
7 implemented.

8 And so, within this regulatory guide there
9 is a discussion about the qualifications of hydrogen
10 pickup models and it provides the vehicle for doing --
11 for qualify a hydrogen pickup model and it's through
12 post-irradiation examination data and observations of
13 hydrogen pickup, the development of a hydrogen pickup
14 model, and all of that would be part of the
15 documentation supporting the NRC's review and approval
16 of a new or existing fuel design.

17 CHAIRPERSON ARMIJO: For new materials I
18 understand, but for existing or established alloys
19 don't we already have sufficient hydrogen pickup data
20 and models --

21 MR. CLIFFORD: No.

22 CHAIRPERSON ARMIJO: -- for the Zirc 2,
23 Zirc 4, M5?

24 MR. CLIFFORD: None of our current
25 regulations are correlated to cladding hydrogen

NEAL R. GROSS

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

1 content, so we haven't really enforced that type of
2 information. What we do have is we have end-of-life
3 maximums. They can say, well, I'll stay below 400 ppm
4 for this particular Zirc 2, and they have data to 400.
5 But I don't know they arrive at 400, whether they
6 slowly increase and then there's an exponential
7 increase with burnup or residence time. So we don't
8 have that fuel duty versus hydrogen pickup.

9 CHAIRPERSON ARMIJO: Well, you know, I
10 suspect the data exists and you have required it for
11 regulatory purposes.

12 MS. FLANAGAN: That could be.

13 MR. CLIFFORD: Right, the data exists. We
14 just haven't approved those models yet.

15 MS. FLANAGAN: Yes. Yes. Okay. So,
16 another aspect of that hydrogen pickup model is
17 accounting for the uncertainty and variability in
18 hydrogen content. And so, here's another place that
19 hydrogen content is a place where you can have that
20 variability, and then when you're going back to
21 evaluate as a function of hydrogen, where your
22 variability is. It's why it can get kind of tricky.
23 There's a lot of places and a lot of ways that we can
24 talk about variability. There's variability in the
25 hydrogen pickup model, variability in the ring

NEAL R. GROSS

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

1 compression test results. You know, so this part of
2 the regulatory guide discusses a little bit about what
3 is expected regarding quantification of uncertainty
4 and variability.

5 CHAIRPERSON ARMIJO: Well, if you really
6 have a lot of hydrogen pickup variability,
7 circumferential variability on irradiated fuel
8 cladding, it just makes the problem very difficult.
9 And that's going to be a function again of the
10 nuclear design of the fuel --

11 MR. CLIFFORD: Exactly.

12 CHAIRPERSON ARMIJO: -- because the
13 material's homogeneous, I hope.

14 MS. FLANAGAN: Yes, this guidance provides
15 a way to handle that as the ECR should be evaluated
16 against the peak circumferential average hydrogen
17 content. Now, we might get public comments on this
18 and discuss about is the best --

19 CHAIRPERSON ARMIJO: Peak circumferential
20 average -- oh, so you go up the axial -- axially up
21 the rod and then you measure hydrogen around the
22 circumference?

23 MR. CLIFFORD: Yes.

24 CHAIRPERSON ARMIJO: And where the average
25 peaks? I don't understand that terminology. I don't

NEAL R. GROSS

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

1 really need to I guess at this point, but it's a
2 little confusing. Because the weakest point will be
3 where you have the highest hydrogen and --

4 MR. CLIFFORD: Right. Yes, the
5 circumferential average of all your measurements
6 around the circumference and it would be the peak at
7 the location of the fuel rod.

8 CHAIRPERSON ARMIJO: But it's going to
9 crack at the weakest point. So the average doesn't
10 make --

11 MEMBER SHACK: But his argument is that it
12 moves around a lot circumferentially. It just doesn't
13 move around axially, which is why you --

14 CHAIRPERSON ARMIJO: No, it's more likely
15 to move axially.

16 MR. CLIFFORD: It's more of an axial
17 variation --

18 CHAIRPERSON ARMIJO: Right.

19 MR. CLIFFORD: -- rather than a
20 circumferential variation.

21 MEMBER SHACK: Right, but you get a small
22 circumferential, which makes them do all right then on
23 the peak.

24 CHAIRPERSON ARMIJO: If you have a lot of
25 circumferential variability, there's a reason for it.

NEAL R. GROSS

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

1 We may not understand it, but -- I hope that's not the
2 case, but -- because that's where you're going to
3 crack where you've got your peak hydrogen in -- after
4 a LOCA. So, and axially, you know, there's going to
5 be some variation, but that's pretty straightforward.
6 So I'm just hoping that there's not too much
7 circumferential variability in the hydrogen.

8 MS. FLANAGAN: And some of that
9 circumferential variability may be the reason that the
10 measurements for ductility would vary between repeat
11 tests. And so, here we're kind of addressing the --
12 given the different ways that circumferential hydrogen
13 content would impact ring compression test results and
14 given our hydrogen pickup models, this was a way to
15 address those phenomenon as they're related to each
16 other and that could be a subject to look into
17 further.

18 CHAIRPERSON ARMIJO: Okay. But you
19 address it?

20 MS. FLANAGAN: Really how to best do that.

21 CHAIRPERSON ARMIJO: You address it and
22 they have to address it and --

23 MS. FLANAGAN: Yes.

24 CHAIRPERSON ARMIJO: -- satisfy you that
25 the variability is understood, or it's not much there.

NEAL R. GROSS

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

1 And if it's there, they have to test them a certain
2 way.

3 MS. FLANAGAN: Yes.

4 MR. CLIFFORD: Right, I mean, you could
5 also look at it as viewed -- if you had no testing on
6 irradiated cladding and you didn't have built into
7 your ductility measurements the circumferential
8 variability, then you would need to account -- maybe
9 you would want to have your peak local hydrogen
10 content as opposed to any sort of averaging.

11 CHAIRPERSON ARMIJO: Yes.

12 MR. CLIFFORD: Because it wouldn't be
13 caught somewhere else.

14 CHAIRPERSON ARMIJO: Okay. Go ahead.

15 MS. FLANAGAN: Okay. Another topic that's
16 addressed in this draft regulatory guide is how to
17 apply these criteria in a ruptured region. And so, in
18 this draft guidance what is the methodology that's
19 established is that the -- and this is very much how
20 the current regulations are set up. The cladding
21 thickness in a rupture region is defined as the
22 cladding cross-sectional area dividing by the cladding
23 circumference. So, it's basically an average wall
24 thickness in that minimal -- in that minimum wall
25 thickness region of the burst. And then the criteria

NEAL R. GROSS

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

1 to calculate double-sided oxidation once that rupture
2 takes place is also outlined in this regulatory guide.

3 CHAIRPERSON ARMIJO: See, I don't
4 understand that at all. You've already ruptured
5 there, right?

6 MS. FLANAGAN: Right.

7 CHAIRPERSON ARMIJO: And it's super thin.
8 It's ballooned. And so, you're saying, well, now it's
9 going to get -- this thin region that's already
10 ruptured is now going to get embrittled by oxidation
11 and hydrogen pickup from both sides. And so, where do
12 you go from there? Is that the limit?

13 MR. CLIFFORD: What we've defined here in
14 the reg guide is the current requirement that's in
15 50.46 today. In June; correct if I'm wrong -- in the
16 June ACRS briefing we will be providing the empirical
17 database supporting the continued application of this
18 approach.

19 MS. FLANAGAN: So for example, in the
20 current regulation the ACS -- sorry, the oxidation
21 limit is 17 percent for any fuel, no matter what
22 burnup it is, and across the whole rod.

23 CHAIRPERSON ARMIJO: Right.

24 MS. FLANAGAN: And so, then when you look
25 at saying, well, how do I determine if I'm above or

NEAL R. GROSS

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

1 below 17 in the rupture region, you use these two
2 methods that you look at the average wall thickness
3 since ECR is a percent of the cladding reacted.

4 CHAIRPERSON ARMIJO: Okay.

5 MS. FLANAGAN: So, you actually care what
6 the wall thickness is.

7 CHAIRPERSON ARMIJO: Okay.

8 MS. FLANAGAN: And then you also say that
9 the calculation is a double-sided oxidation
10 calculation. And so, that 17 percent is evaluated
11 against -- in the balloon region in that manner. And
12 this maintains that approach, that given a particular
13 observation of an oxidation limit you use it in the
14 balloon region by accounting for the wall thinning and
15 the double-sided oxidation.

16 MR. CLIFFORD: And in June we'll provide
17 test results that show by using these analytical
18 requirements you achieve an objective.

19 CHAIRPERSON ARMIJO: Okay. I'll wait and
20 see from that, because seems to me that's a very,
21 very, very -- it'll be tough to pass -- to meet your
22 criteria because the rate of oxidation and hydriding
23 doesn't realize how thin the cladding is. So you're
24 going to be pumping hydrogen --

25 MR. CLIFFORD: That's currently what's

NEAL R. GROSS

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

1 done today and the -- you're right, if you model -- if
2 you have a ballooning model and you predict that your
3 cladding is going to balloon and burst, then most
4 likely your limiting ECR will be in that region
5 because of the double-sided oxidation and the wall
6 thinning.

7 CHAIRPERSON ARMIJO: Yes.

8 MR. CLIFFORD: And that's in the currently
9 approved models and methods.

10 CHAIRPERSON ARMIJO: Okay.

11 MEMBER SHACK: And how do you compute the
12 cladding circumference in the current model?

13 MR. CLIFFORD: There are approved cladding
14 strain models that have --

15 MEMBER SHACK: Okay.

16 MR. CLIFFORD: -- basically a critical
17 temperature and critical pressure which determine
18 strain, the degree of strain which is based on NUREG-
19 0630?

20 MS. FLANAGAN: Well, that's one guidance.
21 And I think vendors have --

22 MR. CLIFFORD: Yes.

23 MEMBER SHACK: I mean, that's the old
24 Powers and Myer thing on ballooning?

25 MS. FLANAGAN: Yes.

NEAL R. GROSS

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

1 MR. CLIFFORD: Yes.

2 MS. FLANAGAN: Yes.

3 MR. CLIFFORD: Yes.

4 MS. FLANAGAN: The old Power and Myer,
5 yes.

6 MEMBER BROWN: If you've ruptured how do
7 you have any thickness at all in that area, if there's
8 a hole, I mean, as you say, taken at a horizontal
9 plain at the elevation of the rupture?

10 MS. FLANAGAN: Yes.

11 MEMBER BROWN: And so, you've got a hole
12 you're looking in. There is nothing there. That's my
13 definition of a rupture. Maybe I've got the wrong --

14 MS. FLANAGAN: Well, it's like --

15 CHAIRPERSON ARMIJO: Right. There's a
16 hole there.

17 MS. FLANAGAN: Yes, so --

18 CHAIRPERSON ARMIJO: A tear.

19 MS. FLANAGAN: -- it's looking at the
20 cross-section and dividing the area by the
21 circumference. And that's the wall thinning.

22 MEMBER BROWN: So, it's kind of an average
23 cladding.

24 MEMBER BROWN: Zero. I mean, if there --

25 MS. FLANAGAN: There's a -- yes, right,

NEAL R. GROSS

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

1 the reason --

2 MEMBER BROWN: Or you're talking about the
3 -- oh, so you're talking about an average?

4 MR. CLIFFORD: Right.

5 MS. FLANAGAN: Yes, maybe --

6 MEMBER BROWN: You're talking about wall
7 thickness clear around?

8 MR. CLIFFORD: Yes.

9 MEMBER BROWN: -- as opposed to just a
10 local point?

11 MR. CLIFFORD: Yes.

12 MEMBER BROWN: So you're defining a --
13 maybe that's where I --

14 CHAIRPERSON ARMIJO: It's an average.

15 MS. FLANAGAN: Yes.

16 MEMBER BROWN: Okay. So, all right. All
17 right.

18 MR. CLIFFORD: You go from zero to --

19 MEMBER BROWN: I didn't think about that
20 real quick.

21 MS. FLANAGAN: Yes, I have a picture that
22 I can depict it, but I think, yes, that's what it is.

23 Okay. Another topic that's covered in
24 this regulatory guide is the expectation of
25 calculating double-sided oxidation due to the fuel-

NEAL R. GROSS

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

1 cladding bonding layer. So, this was a finding of the
2 research program that an oxide layer can actually
3 develop on the inside cutting surface not because of
4 in the burst region there -- that region is actually
5 exposed to steam, but actually because for high burnup
6 cladding when you develop a fuel bonding layer the
7 interface can actually pass oxygen. And because
8 zirconium has affinity for oxygen, that oxide layer
9 can develop not because of steam, but actually as the
10 fuel is the source. And so, that was a research
11 finding that we wanted to address in the revisions to
12 the regulations and it's defined about -- a method to
13 do so is defined in this draft guide. And so --

14 CHAIRPERSON ARMIJO: Yes, the problem I
15 have with that is that fuel to cladding bonding is --
16 there's a lot of variability there.

17 MS. FLANAGAN: Right.

18 CHAIRPERSON ARMIJO: And it depends a lot
19 on the fuel design, the way it's -- the fuel's
20 handled, the way it's operated.

21 MS. FLANAGAN: Yes.

22 CHAIRPERSON ARMIJO: And is your basic
23 assumption that all fuel above a certain burnup will
24 have fuel-clad bonding so you must treat it that way,
25 or do you --

NEAL R. GROSS

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

1 MS. FLANAGAN: No.

2 MR. CLIFFORD: No.

3 CHAIRPERSON ARMIJO: Or if someone can
4 show you that it's a rare event but it does happen
5 once in awhile --

6 MS. FLANAGAN: Yes. So, the way that it's
7 set up is to establish a burnup limit where if no data
8 was available or no -- the vendor chose to provide no
9 data, there is a minimum that could be established,
10 and that is extremely conservative in that sense, and
11 it's set at 30 gigawatt-days per ton. However, it is
12 clear in the regulatory guide that a different
13 threshold can be supported by metallographic images,
14 of bonding layers as a function of burnup and things
15 that are more performance-specific and really take
16 into account how the material is operated, how the
17 material behaves. And all of that is within the
18 context and the guidance that's provided how to -- how
19 one would do that to establish a material-specific
20 burnup limit that's appropriate given this phenomenon.

21 CHAIRPERSON ARMIJO: Okay. That's going
22 to be tricky. You know, it depends what the fuel
23 suppliers have available. And I'm sure they have a
24 lot of information available, but --

25 MR. CLIFFORD: As you know, this would

NEAL R. GROSS

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

1 require a hot cell, so --

2 CHAIRPERSON ARMIJO: Well, you know, if it
3 hasn't been done up to now, it's going to take forever
4 to do it. But I think whenever you do a PIE, you get
5 that information and --

6 MR. CLIFFORD: Right.

7 MS. FLANAGAN: Yes. Well, because it may
8 not be practical to go forward with a lot of -- and
9 support it, we did establish an acceptable limit so
10 that if that data wasn't readily available or there
11 wasn't a value in doing that, a limit could be
12 provided which would define sort of a conservative
13 space to operate.

14 CHAIRPERSON ARMIJO: The problem is, you
15 know, the pellets aren't actually lined up with a gap
16 uniform, or, you know -- and one -- they'll be -- you
17 have to be in contact. The pellet and the cladding
18 has to be in contact for the bond to form.

19 MS. FLANAGAN: Yes.

20 CHAIRPERSON ARMIJO: Which means -- and it
21 may be that that's the most important region simply as
22 far as oxidation. And that may all you -- but most of
23 the cladding is -- it doesn't have a bond.

24 MR. CLIFFORD: Right.

25 CHAIRPERSON ARMIJO: As you go around the

NEAL R. GROSS

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

1 circumference, it's -- so is your idea that that will
2 be the weak link where there is a fuel-clad bond and
3 therefore it's justified?

4 MS. FLANAGAN: Well --

5 MR. CLIFFORD: I think it's more than it
6 can't be ruled out.

7 MS. FLANAGAN: Yes.

8 MR. CLIFFORD: If you've shown that it
9 could exist in a certain location, I mean, unless --
10 I mean, it's going to be a function of burnup, so --
11 and this -- you know, and the hydrogen's also going to
12 be a function of burnup.

13 CHAIRPERSON ARMIJO: Yes.

14 MR. CLIFFORD: So, I mean, I don't think
15 you could say categorically that you're not going to
16 get the bonding layer above a certain burnup, you
17 know, at a region of interest with respect -- that
18 would also have high hydrogen. Would also see high
19 temperatures during a LOCA.

20 CHAIRPERSON ARMIJO: Well, everybody
21 calculates there's going to be gaps, you know, a real
22 nice gap and all that. But in reality, it's
23 stochastic stacking of the pellets and the gaps are
24 variable as you go around the circumference. So, this
25 is going to be tricky. I look forward to seeing the

NEAL R. GROSS

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

1 fuel suppliers' comments on this approach.

2 Continue, Michelle.

3 MS. FLANAGAN: Okay. So, the last -- one
4 of the other topics that's identified is further
5 comments on breakaway oxidation analytical limits.
6 And so, what the regulatory guide expands to say, that
7 identifying the limiting combination of break size,
8 break location and initial conditions is part of
9 identifying the maximum total accumulated time above
10 the temperature of interest. So, I think to just sort
11 of give some background on this, the criteria to
12 maximize time above a certain temperature may be
13 different than otherwise would be revealed with
14 looking for your highest ECR. So, some areas where a
15 breakaway could be a concern may not be the same areas
16 in which your highest ECR is a concern. So, this is
17 just establishing that looking for both is part of
18 what is intended from this opinion analytical limit.
19 And it also comments that operator actions can be
20 credited. So, those are some of the other topics that
21 are discussed in this regulatory guide. It gets into
22 a little bit further detail about the contents.

23 And that is the last slide that I have
24 prepared on this. I can also go into this regulatory
25 guide and we can look at some particular language or

NEAL R. GROSS

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

1 particular sections, if that's of interest.

2 CHAIRPERSON ARMIJO: Well, first of all,
3 I'd like to ask the committee members if they have any
4 more questions or if they'd like you to do that.

5 I think, Michelle, I'm fine with it. I
6 think what we should do is take our lunch break.

7 MS. FLANAGAN: Okay.

8 CHAIRPERSON ARMIJO: And then that will
9 give the industry folks as much time as they need to
10 go over their testing program, the round robin. Don't
11 anticipate any public comment, so after lunch we'll
12 have the EPRI presentation.

13 MR. CLIFFORD: There is somebody at the
14 mic.

15 CHAIRPERSON ARMIJO: Oh, yes. Go ahead.

16 MR. RODACK: Tom Rodack from Westinghouse.
17 Before Michelle and Paul depart the center stage here,
18 could you just clarify the timetable for issuing the
19 reg guides and the rule language for public comment?
20 Both of you talked about that this morning, but I was
21 just confused because it sounded like the rule
22 language wasn't going to come out until February, but
23 the reg guides were going to come out soon. So, could
24 you just clarify, because I want to make sure we have
25 the resources available when you need to comment.

NEAL R. GROSS

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

1 CHAIRPERSON ARMIJO: It's really your
2 slide 8.

3 MS. FLANAGAN: Yes.

4 CHAIRPERSON ARMIJO: This is the opening
5 thing.

6 MS. FLANAGAN: I guess --

7 CHAIRPERSON ARMIJO: Put some dates on
8 that.

9 MR. RODACK: Yes, on Paul's slide.

10 MR. CLIFFORD: yes, our schedule to get
11 the proposed rule package to the EDO is the end of
12 February 2012. I think the -- so, the public comment
13 period would begin some time after that. It would go
14 up to the Commission. The Commission would determine
15 the speed at which they go out for public comment.
16 The draft reg guides will be available before that.

17 The question we have is do we want to send
18 the draft reg guides out before for comment. I mean,
19 I think our target would be no matter what we would
20 want to have an overlapping window. In other words,
21 you wouldn't want to send the draft reg guides out,
22 close that public comment period and then send out the
23 draft rule language. It really wouldn't make sense.
24 So, if the draft reg guides were to out earlier, that
25 window would be extended so that it would encompass

NEAL R. GROSS

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

1 the same time span for the draft rule.

2 MS. FLANAGAN: Yes, I think what Paul is
3 pointing to is that these regulatory guides could be
4 available to put out for public comments before the
5 rule, but there may not be a benefit in doing that if
6 the evaluation is really integrated. The evaluation
7 of the rule and the reg guides is so closely linked
8 that the public comment period is just all in the
9 same. Then there may not be a benefit for us putting
10 the public comment period beginning for the regulatory
11 guides as soon as they're available. But, you know,
12 we're open to feedback on that. If that would provide
13 something, then -- did I just make that more
14 confusing?

15 MR. RODACK: Well, I guess my question is
16 between -- we have -- there are draft rule reg guides
17 that are available right now. I mean, we --

18 MS. FLANAGAN: Well, they're still in
19 interoffice concurrence. So, what we're discussing
20 here is somewhat pre-decisional. But they are
21 expected to be out of that process and would be ready
22 for public comment before we currently anticipate the
23 rule would be ready for public comment.

24 CHAIRPERSON ARMIJO: When do they
25 officially get issued for public comment?

NEAL R. GROSS

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

1 MS. FLANAGAN: Following this process,
2 it's when the interoffice concurrence is complete.
3 Then there's the -- there's a couple steps and
4 there --

5 CHAIRPERSON ARMIJO: Yes, well roughly
6 what date?

7 MS. FLANAGAN: I think it's the end of the
8 summer. If everything goes forward as expected --

9 CHAIRPERSON ARMIJO: Okay.

10 MS. FLANAGAN: -- the necessary steps
11 would be complete by the end of the summer.

12 CHAIRPERSON ARMIJO: So, something like
13 maybe August or something?

14 MR. CLIFFORD: Right.

15 MS. FLANAGAN: Yes, so that's when it
16 would be possible.

17 MR. RODACK: If I may, I guess when the
18 reg guides are in final for -- or after you've
19 completed internal concurrence, I think it would be
20 valuable if you could release them to the public so we
21 could begin to review them even if you haven't opened
22 the official comment period. If you're satisfied that
23 they're at a point that they're fit to release to the
24 public, I think it would be good to release them in
25 advance because it's going to -- believe it or not, it

NEAL R. GROSS

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

1 takes time to review these and, you know, come up with
2 meaningful comments. And there's typically, you know,
3 stakeholders that you need to engage and, you know,
4 the more time we have, I think the better quality
5 comments you'll receive.

6 MS. FLANAGAN: Okay. I understand. Yes.

7 CHAIRPERSON ARMIJO: Okay.

8 MEMBER BLEY: Let me just ask a question
9 in that light. Once you've released the reg guides;
10 I think you mentioned earlier, one of you did, that
11 you anticipate some public workshops and those sorts
12 of things, might you have those before the rule is
13 out, or would you hold those public meetings until
14 after the rule?

15 MS. FLANAGAN: Well, I'll say that we're
16 not -- the public meetings are certainly an option for
17 if that's going to be of value. They're not currently
18 planned, but that --

19 MEMBER BLEY: Okay. I thought I heard
20 somebody say that earlier.

21 MS. FLANAGAN: Yes, I think we mentioned
22 that that's a good tool to use if that --

23 MEMBER BLEY: Okay. A tool.

24 MS. FLANAGAN: -- is appropriate. I think
25 what we're struggling with here is that in some way

NEAL R. GROSS

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

1 the regulatory guides are understood in the context of
2 the rule. So, at some point we have to recognize that
3 what is required by the regulatory guides is impacted
4 by what the rule says. And so, we don't want to get
5 them so separated that we forget why they exist and
6 how they'll be enacted.

7 And in addition, there may be something
8 that shows up in the rule language that would have to
9 be reflected in the regulatory guide.

10 MEMBER BLEY: So you might have to revise
11 the guides, yes, just on that. Yes.

12 MS. FLANAGAN: Right. So, they're so
13 closely linked and we're trying to provide the maximum
14 value and maximum time for public comment and really
15 have the best regulatory guides developed as a
16 function of stakeholder interaction. And that we're
17 also cognizant of the relationship and trying to see
18 what is most beneficial given that integral
19 relationship.

20 CHAIRPERSON ARMIJO: Well, you know, the
21 sequence of review should be the rule followed by the
22 reg guides.

23 MS. FLANAGAN: Right.

24 CHAIRPERSON ARMIJO: And the rule should
25 be settled so that the reg guides can be settled.

NEAL R. GROSS

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

1 MS. FLANAGAN: Right.

2 CHAIRPERSON ARMIJO: And but I understand
3 they are closely linked and you can't -- and it almost
4 seems impossible to separate them, but it's -- I think
5 for the ACRS we probably need to understand the rule
6 a lot more before we get too -- I'm happy that we're
7 reviewing the reg guides. At least we get an
8 understanding of what's in them and everything else,
9 but in the final analysis I think the rule is the law
10 and that's what we've got to focus on.

11 MS. FLANAGAN: Yes.

12 MR. BAHADUR: It looks to me like a number
13 of options are being discussed here and that's exactly
14 what was the object of this meeting was, to share with
15 the Committee the development of the reg guides. The
16 process from the efficiency point of view and from the
17 effective point of view would be to have the rule
18 developed, get the rule and the reg guides together in
19 a package, bring it to the Committee, get a letter
20 from the Committee, go to the Commission if you have
21 to, or to EDO, and then propose -- then publish it for
22 the public comment. If the public feels that 90 day
23 would not be sufficient for reviewing the three reg
24 guides and the rule, maybe we can think about
25 extending the rule.

NEAL R. GROSS

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

1 But it looks to me like settling the reg
2 guide now, because the public would not find
3 sufficient time to review the time the rule is out
4 there, is going to erode the effectiveness of the
5 entire process. My suggestion would be if we take
6 this meeting for what it was meant for to bring the
7 working document of the reg guides, the reg guides
8 which are still going on the inter-office concurrence,
9 the Office of Research has developed that. The
10 licensing offices haven't had a chance to review that
11 and look that and have not been able to go to the EDO
12 for the EDO's concurrence. The best thing for us
13 would be to use your feedback, go back and revise the
14 reg guides based on what were the open items we are
15 carrying with us. We come back to you with the reg
16 guide and the rulemaking package together and then
17 follow the process.

18 CHAIRPERSON ARMIJO: But, Sher, the issue;
19 and I'm just strictly speaking about ACRS, it's a big
20 pill to swallow a rule, three reg guides, potential
21 new issues all in one two-hour meeting for full
22 Committee. So, we're going to have to break this up
23 into manageable pieces for our review, you know. And
24 the industry guys have got the draft of the reg guides
25 which may or may not change and you've committed -- or

NEAL R. GROSS

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

1 you expect; not committed, that by August you'd issue
2 them for public comment. Is that --

3 MS. FLANAGAN: No, we haven't committed to
4 that. I'm just saying that if everything goes
5 forward, that is when --

6 CHAIRPERSON ARMIJO: No, I didn't mean to
7 say you'd committed.

8 MS. FLANAGAN: Okay.

9 CHAIRPERSON ARMIJO: But they could be
10 ready to be issued by August?

11 MS. FLANAGAN: That might -- that would be
12 better.

13 MR. BAHADUR: That is a possibility.

14 CHAIRPERSON ARMIJO: Okay.

15 MR. BAHADUR: Right now the reason why the
16 public had the opportunity of looking at these draft
17 reg guide was essentially because we came to you for
18 this meeting.

19 CHAIRPERSON ARMIJO: Yes.

20 MR. BAHADUR: We come to you this meeting.
21 It's a public meeting and therefore we have made an
22 exception to make it public.

23 CHAIRPERSON ARMIJO: Sure.

24 MR. BAHADUR: But this is still a pre-
25 decisional from the point of view of Commission hasn't

NEAL R. GROSS

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

1 had a chance fay weighing into it. EDO hasn't had a
2 chance to look into it. So, we are alter the process
3 just to reflect as to what you just -- this is such a
4 big pill. We're trying to break it into smaller bite
5 size. And the idea was while the rule is being
6 developed, let these reg guides go out in the public.
7 We come to you and we present that to you and we'll
8 take back the feedback from you.

9 CHAIRPERSON ARMIJO: So, this is really --
10 as far as the industry, it's kind of unofficial
11 familiarization, just like your workshops and all the
12 other things you've been doing. But for us it's a
13 briefing on where you stand.

14 MR. BAHADUR: Exactly.

15 CHAIRPERSON ARMIJO: And later today we'll
16 -- the committee members will discuss, you know, how
17 we want to structure the full committee presentation
18 and what we think we should do about it. So, we're
19 not there yet.

20 So, why don't we just take a break and
21 reconvene at 1:15 if there's no other issues? 1:15
22 for sure. Got to come back, Charlie.

23 (Whereupon, the hearing was recessed at
24 12:14 p.m. to reconvene at 1:15 p.m. this same day.)

25

1 A-F-T-E-R-N-O-O-N S-E-S-S-I-O-N

2 1:15 p.m.

3 CHAIRPERSON ARMIJO: Okay. Well, why
4 don't we just start? Mike Corradini has arrived and
5 will be here shortly, so let's get going.

6 And I think we start out with Ken Yueh.
7 Did I pronounce that correctly, Ken?

8 MR. YUEH: Yes.

9 CHAIRPERSON ARMIJO: Okay.

10 MR. YUEH: Thank you for giving us an
11 opportunity to present our research findings.

12 Before I start the presentation, I just
13 want to say a few words why we're doing this work. I
14 think regulatory bodies, the research sponsored by
15 regulatory bodies in general I think, including
16 international regulatory bodies, have mostly been
17 focused on evaluating limiting conditions and it's
18 more conservative. And because of that, certain
19 things are not fully evaluated. So the work the
20 industry has sponsored is geared towards evaluate more
21 realistic conditions.

22 And today we present results in two areas
23 and our LOCA round robin test plans. Okay. In the
24 three areas that we're going to present test results
25 includes preliminary high-temperature oxidation tests

NEAL R. GROSS

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

1 that we've been conducting. It's meant to supplement
2 ANL database. And I'm going to present a very
3 comprehensive investigation of the ID oxygen pickup,
4 two-side oxidation.

5 We will start with a little background in
6 fuel pellet interaction. And, you know, we do have
7 hypothesis. That's just the amount of oxygen on the
8 inside of the fuel rod is limited. So, we want to
9 present results that quantifies the impact of limited
10 ID oxygen source on post-quench ductility.

11 Okay. We'll talk about the high-
12 temperature oxidation test, the preliminary results.
13 We started this project primarily because ANL test
14 data of Zircaloy-4 indicates that the embrittlement
15 ECR can be higher with a low oxidation temperature.
16 So with that we wanted to generate data that supports
17 alternative acceptance criteria, you know, other than
18 the limiting 1200 degrees Celsius condition.

19 And what you see on the chart here is
20 where we're trying to generate different temperatures.
21 And we hope the result we get is -- will be consistent
22 with what's observed with ANL test data.

23 Early on the NRC recommended acceptance
24 criteria 1200 Celsius terminates at 600 ppm hydrogen.
25 So that time we were wanting to expand the database to

NEAL R. GROSS

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

1 beyond 600 ppm so that it does not go to zero.

2 And our last goal for this project is to
3 collect sufficient data to be able to determine if
4 it's feasible to develop a mechanistic embrittlement
5 model.

6 So, our tests, rather than focusing 1200
7 Celsius when evaluating other conditions so it's
8 complementary to the ANL tests, in our test matrix we
9 start with 1050 Celsius and then we have another
10 temperature, 1125, and then a limited number of tests
11 at 1200 Celsius just to be able to benchmark to the
12 ANL test data.

13 For hydrogen content we plan to test from
14 as-built to 1000 ppm in 200 ppm increments.
15 Unfortunately, hydrogen charging still not precise.
16 You know, it's not precise. It's almost like art.
17 But, you know, things are improving. So we end up
18 with different hydrogen levels. So, I mean, it may
19 not necessarily be on target.

20 The test procedure used is mostly
21 consistent with ANL guidelines. It's a indirect
22 resistance heating.

23 Okay. Following the actual post-quench
24 ductility test we were planning to use the samples
25 generated from these tests and plus some additional

NEAL R. GROSS

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

1 tests to establish basis to develop an embrittlement
2 model. And with this package we're thinking of doing
3 this in three different steps. The first step is to
4 evaluate the oxygen profile before the sample cooled.
5 So we will do this by heat up a sample to -- and hold
6 it for the desired amount of ECR and quench it. So we
7 will have frozen state of oxygen distribution and
8 concentration in the material.

9 And after that, past test samples that we
10 examined from ANL indicates that during cooling there
11 are chemical changes, you know, very small chemical
12 changes locally within the sample that may be
13 happening. And our data indicates local segregation
14 of oxygen. And this may have some dependence on the
15 cooling rate. So we would evaluate that and try to
16 correlate that, too.

17 Also the final metallurgical condition
18 where it is at the critical ductile-to-brittle
19 transition.

20 MEMBER SHACK: Sort of hydrogen seems to
21 be added to that model. I assume that it's really in
22 there.

23 MR. YUEH: Yes, it will be in there. We
24 will -- the samples will have hydrogen in there, you
25 know. Right now, the hydrogen is variable. We cannot

NEAL R. GROSS

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

1 charge it to precisely where we want it. But the
2 samples we'll be looking at will be from the samples
3 used to generate the different --

4 MEMBER SHACK: Do you have an idea how
5 you're mechanistically going to incorporate the
6 effective hydrogen?

7 MR. YUEH: The hydrogen, if there's an
8 effect, it would translate to observable changes in
9 microstructure; the oxygen level, for example,
10 locally. Earlier presentation talked about the
11 diffusion coefficients and solubility increase with
12 hydrogen. So this will show up in our measurements of
13 oxygen. Right now it's very difficult to measure
14 hydrogen directly. There's no easy method to do that.

15 This slides shows preliminary results for
16 the test at 1050 Celsius. The testing has not
17 completed at this temperature indicated by the
18 highlighted areas. So there's still generated data to
19 fill the gaps and we're hoping to complete that later
20 on in the summer. The existing database is showing
21 that there is a significant change to the
22 embrittlement ECR. And if you look at this chart,
23 it's not a shift sideways. The difference would be,
24 you know, it's a vertical shift. It would -- you
25 know, the actual difference is larger than by looking

NEAL R. GROSS

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

1 at the curve shifting sideways.

2 So, you know, if we look at this way, you
3 know, this data point here, the difference would be
4 here. So, it's a quite big change in improvement in
5 the embrittlement of the cladding.

6 CHAIRPERSON ARMIJO: Ken, in the marginal
7 ductile data points one as low as, you know, probably
8 the order of 50 ppm hydrogen, what do you mean by
9 marginal? Does that represent the average of three
10 tests or --

11 MR. YUEH: No, the --

12 CHAIRPERSON ARMIJO: -- that's an
13 individual test?

14 MR. YUEH: These are all individual tests.
15 The marginal ductility are -- with the offset strain
16 is between 1 to 2 percent.

17 CHAIRPERSON ARMIJO: And so, you actually
18 fractured the sample and broke it, so you can't do the
19 post-test diameter measurement?

20 MR. YUEH: That is correct. Very few
21 sample stayed intact so we were not able to measure
22 the permanent strain on most of the samples.

23 CHAIRPERSON ARMIJO: Okay. So, do you
24 meet the letter of the guide using the offset strain?

25 MR. YUEH: If we are to use the previous

NEAL R. GROSS

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

1 version of the guideline, which you know, some of
2 other testing, including the LOCA round robin, some of
3 these samples would meet -- you know, would be
4 classified as ductile. Some of them may change
5 position into brittle. Most likely the data points --
6 we have large ECR within the definition of the
7 uncertainty. You know, it may fall out and become
8 brittle.

9 CHAIRPERSON ARMIJO: Yes.

10 MR. YUEH: But the data points in this
11 region where the uncertainty is small, some of them
12 may, you know, stay classified as ductile.

13 CHAIRPERSON ARMIJO: Okay. And you're
14 going to do more testing in these temperature ranges,
15 or is that it?

16 MR. YUEH: We will still -- we're going to
17 do testing in the shaded areas.

18 CHAIRPERSON ARMIJO: Okay.

19 MEMBER ABDEL-KHALIK: What's the error bar
20 on the hydrogen concentration measure?

21 MR. YUEH: I have not done a statistical
22 study of that, but in the LOCA round robin program we
23 plan to do a mini round robin of the hydrogen
24 evaluation techniques. The uncertainty, I think it
25 will depend on what kind of standard you use.

NEAL R. GROSS

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

1 MEMBER ABDEL-KHALIK: Do you have a
2 reasonable intuition as what the order of magnitude of
3 that uncertainty might be?

4 MR. YUEH: You know, the number I get will
5 be a guess, because I do not know what standard was
6 used, what's the hydrogen, what the calibration range
7 is. So, I think, you know, as a guess, you know, it
8 should be within plus or minus 25.

9 CHAIRPERSON ARMIJO: Ppm?

10 MR. YUEH: Ppm, yes.

11 CHAIRPERSON ARMIJO: Where were these
12 measurements done?

13 MR. YUEH: These measurements were done at
14 Western Zirconium.

15 CHAIRPERSON ARMIJO: That includes the
16 hydrogen? I'm talking about the hydrogen.

17 MR. YUEH: The hydrogen. Yes, measurement
18 hydrogen. Western Zirconium.

19 CHAIRPERSON ARMIJO: They know how to
20 measure hydrogen? Okay.

21 MR. YUEH: This chart shows the 1125
22 degrees Celsius test. The amount of improvement has
23 decreased a bit, but I think there is most likely
24 still a difference, especially near the low region
25 where we have -- 400 ppm region where we have quite a

NEAL R. GROSS

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

1 few data points showing ductile above the line. Okay.
2 And once again, we are going to do two more tests
3 trying to fill some of the gaps to better define the
4 line.

5 The 1200 Celsius test, as I mentioned
6 earlier, we're going to do a limited number. This
7 temperature is left to the end because, you know, we
8 haven't generated as much data because at these higher
9 temperatures the tube used in the test tend to crack.
10 So we like to generate as much data as we can at the
11 lower temperatures before we complete the test matrix
12 at 1200 degrees Celsius.

13 Now, the test data that we have collected
14 so far seemed to yield data more restrictive than the
15 published irradiated ANL test results. We generate a
16 few data points. The embrittled samples sort of sit
17 on the line.

18 But one of the other tests where we
19 evaluated the ID oxidation where we pre-oxidized some
20 samples showed that pre-oxidation can potentially
21 influence this transition. And the three charts shown
22 here are samples tested with two-sided oxidation,
23 okay, oxidized for 475 seconds, 22 percent ECR. And
24 the first chart shows this. It's a clean surface.
25 White metal. Okay? The sample is clearly brittle.

NEAL R. GROSS

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

1 It failed before you reached, you know, the yielding
2 point. On the right-hand side we have two other
3 samples where they were pre-oxidized at 5 microns and
4 10 microns of oxide. They still show some ductility.

5 CHAIRPERSON ARMIJO: How were they
6 oxidized? Were they in a laboratory? Were they in a
7 steam test? Were they in water? You know, how were
8 they -- there are different kinds of oxides.

9 MR. YUEH: They were oxidized in steam at
10 800 degrees Celsius.

11 CHAIRPERSON ARMIJO: But that's not the
12 same oxide you get in reactor at lower temperatures.

13 CHAIRPERSON ARMIJO: It is not, but we
14 have plans to evaluate the pre-existing oxide using
15 corrosion samples.

16 CHAIRPERSON ARMIJO: From reactor?

17 MR. YUEH: From normal water corrosion
18 test.

19 CHAIRPERSON ARMIJO: Okay. I might as
20 well ask it now, because I'm -- why do you not use the
21 ANL procedure to just stop the test when you first see
22 a load drop so that you can measure the post -- pre
23 and post-diameter mechanically?

24 MR. YUEH: When you are looking at brittle
25 material, the difference between just initial fracture

NEAL R. GROSS

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

1 and multiple fractures, the time is very small. It's
2 very difficult to stop the test and capture right
3 there, You know, with samples with more ductility you
4 could potentially do that, but then those samples, you
5 know, don't necessarily have issues in determining,
6 you know, whether it's ductile or brittle. But the
7 ones that are really brittle, you know, there's not a
8 lot of time between the first fracture and subsequent
9 fractures.

10 CHAIRPERSON ARMIJO: So, why can Argonne
11 stop the test when they see a load drop and not
12 fracture the sample completely and your test can't?

13 CHAIRPERSON ARMIJO: Yes, but I don't know
14 if they can stop --

15 MR. SCOTT: So it's that area?

16 MR. YUEH: Yes.

17 MR. SCOTT: Mike has a better ear.

18 PARTICIPANT: Harold? Harold, go to the
19 microphone.

20 CHAIRPERSON ARMIJO: Mike?

21 MR. SCOTT: Mike Billone has better ears,
22 so he and the technician listen for that crack.

23 CHAIRPERSON ARMIJO: Literally? Is that
24 what you're saying? It's -- or it's not off -- it's
25 not some sort of a load that once it senses a drop in

NEAL R. GROSS

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

1 the load you're test machine doesn't just stop
2 applying the load or I mean, this test shouldn't
3 depend on somebody's hearing.

4 PARTICIPANT: Especially if somebody's
5 getting older.

6 CHAIRPERSON ARMIJO: Mike's in pretty good
7 shape, but --

8 MR. YUEH: Well, you could if you have a
9 feedback control of your test instrument. Right now,
10 you know, the equipment doesn't have that.

11 CHAIRPERSON ARMIJO: Yes.

12 MR. YUEH: So, you know, if you have to
13 depend on the person that conducting the test, it's
14 difficult to stop it in time.

15 CHAIRPERSON ARMIJO: But if you could stop
16 the test automatically with the machine, you would
17 stop it? Is that --

18 MR. YUEH: You --

19 CHAIRPERSON ARMIJO: So, you don't have a
20 philosophical objection to stopping the test when the
21 first crack appears and then measuring the diameter
22 before and after the test and use that as a plastic
23 strain?

24 MR. YUEH: I personally don't, but you
25 know, I work for a research organization, so I

NEAL R. GROSS

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

1 don't --

2 CHAIRPERSON ARMIJO: Well, I'd like to
3 hear --

4 MR. YUEH: -- comment on that.

5 CHAIRPERSON ARMIJO: -- from anybody who
6 wants to comment on that because --

7 MR. YUEH: Oh, you don't? Okay.

8 PARTICIPANT: Is Bob here? There he is.

9 MEMBER SIEBER: You have a comment back
10 here.

11 CHAIRPERSON ARMIJO: Yes. Microphone.

12 MR. COMSTOCK: I'm Bob Comstock from
13 Westinghouse and I'm the one who did the tests. So,
14 we do stop the test immediately when we see a load
15 drop. Even then a lot of the samples still fall apart
16 and we can't do a post-test measurement. I'd have to
17 go back and count my samples, but probably 80 percent
18 of the samples, if they're brittle, are going to fall
19 apart. We only have a very small number where we can
20 measure permanent strain. That's why when Ken
21 presented the data he presented it as offset strain
22 because we can get that on all of our samples.

23 CHAIRPERSON ARMIJO: Is it because you
24 have simultaneous cracking in more than one
25 location --

1 MR. COMSTOCK: Lot of times we have --

2 CHAIRPERSON ARMIJO: -- since, you know,
3 you're pressing down?

4 MR. COMSTOCK: That's right. After the
5 load drops about 30 percent, which is Mike's
6 guidelines for stopping the test, on a lot of our
7 samples we have a crack at the top and bottom, or most
8 of them, occasionally at 3:00 and 9:00 positions. So,
9 they taking the samples out, a lot of them just fall
10 apart.

11 CHAIRPERSON ARMIJO: Okay.

12 MR. COMSTOCK: So, we don't have a
13 philosophical reason for not doing it. We try.
14 Reality is a lot of them aren't available to post-test
15 measurement.

16 CHAIRPERSON ARMIJO: Okay. That clears
17 that up. I just wanted to make sure that there wasn't
18 something different in your approach, that you did it
19 purposely.

20 Okay. Go ahead, Ken.

21 MR. YUEH: Just to summarize, I think we
22 have demonstrated that at a lower temperature clearly
23 the embrittlement ECR increases. And this would be
24 useful to plants that do not have PCTs that -- you
25 know, close to 1200 Celsius, because a lot of them

NEAL R. GROSS

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

1 have temperatures significantly less than 1200
2 Celsius. Okay?

3 Now, even if we take credit for the lower
4 PCT, I think the ring compression-based ductility test
5 is still very conservative, because in a typical LOCA
6 the temperature profile, you know, is very short time
7 is your clad spent at the peak cladding temperature.
8 So, a lot of the ECR accumulated will still be below
9 the PCT that you conduct the isothermal test.

10 So, our recommendation then is -- I think
11 if this is already captured in the draft reg guide, is
12 to allow the industry to generate a family of curves
13 at different PCTs and to also allow interpolation of
14 the acceptance criteria. So, if people generated the
15 criteria at multiple temperatures to be able to
16 interpolate and apply it even to specific pin PCT, I
17 think, you know, it may be conceivable that there may
18 be methodology developed where you actually have to go
19 to down to that level detail. I think earlier on we
20 heard NRR talking about region-wide application of
21 specific, you know, PCTs.

22 And if we are able to successfully develop
23 a model; and I think there's also interest from IRSN;
24 I think they have spent quite a bit of time developing
25 the mechanistic model to be able to predict

NEAL R. GROSS

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

1 embrittlement, that you know, we should be allowed, I
2 guess, to apply such a model as an acceptance
3 criteria.

4 CHAIRPERSON ARMIJO: So, you're saying,
5 you know, it's kinetics-controlled, lower
6 temperatures, lower kinetics --

7 MR. YUEH: Yes, we --

8 CHAIRPERSON ARMIJO: -- less damage for a
9 given --

10 MR. YUEH: Yes.

11 CHAIRPERSON ARMIJO: For any given
12 hydrogen level you'll have less damage because the
13 oxidation isn't going as fast?

14 MR. YUEH: Yes. So, this model, we would
15 capture the information we generated with a
16 temperature-specific -- you know, the different PCTs
17 and we would try to model the phenomena from that.

18 CHAIRPERSON ARMIJO: Okay. So, you're
19 thinking maybe certain classes of reactors where you
20 can demonstrate to the staff that the peak clad
21 temperature will be no higher than a certain value and
22 no longer than a certain time, that would be the
23 criteria that would govern as far as your testing
24 is --

25 MR. YUEH: That's one set of criteria.

NEAL R. GROSS

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

1 We're proposing the family curves criteria. Now, with
2 a model, you know, we hope to be able to do away with
3 those fixed limits. Then with the model, if we can
4 demonstrate the model predicts the embrittlement, you
5 know, through verified tests, then that should be as
6 correct as the original curves.

7 CHAIRPERSON ARMIJO: Okay.

8 MEMBER CORRADINI: Can I ask you a
9 question? Can you go back to slide No. -- the one
10 where there's that cartoon, slide 5?

11 So, your point is that if -- I'm just
12 repeating kind of what Sam asked you, but I want to
13 make sure I understood it. So, if somehow you're
14 going to come up with a combination of core design and
15 clad material such that you can show with uncertainty
16 that you're never above 1050, then you would use --
17 you would propose to use the blue line?

18 MR. YUEH: Yes.

19 MEMBER CORRADINI: So, there's an
20 uncertainty in the blue line. And when will you
21 document what that uncertainty is, because it's the
22 intersection of the two wings that you really care
23 about, right?

24 MR. YUEH: Well, this morning we talked
25 about using the best estimate. And then I think

NEAL R. GROSS

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

1 there's a lot of conservatisms in the assumption, in
2 your LOCA analysis, where you assume the worst
3 possible break size and the other variables. I think
4 that --

5 MEMBER CORRADINI: On the thermal
6 hydraulic side, I'm with you. Well, at least I think
7 I understand it. Here I'm kind of fishing to try to
8 understand how are you going to document the
9 uncertainty on the blue line, the blue dashed line?
10 Because if you're saying I got a peak clad temperature
11 of 900 C and with the 95/95 it does -- with 95 percent
12 confidence I'm not above 1050. So, now I've got that
13 wing. Now, I want to match that wing with the
14 materials uncertainty and I'm still struggling to
15 figure out how you determine the uncertainty of the
16 blue dashed line.

17 CHAIRPERSON ARMIJO: Yes. We talked a
18 little bit about that this morning --

19 MEMBER CORRADINI: This morning? Okay.

20 CHAIRPERSON ARMIJO: -- when we talked
21 about the testing, the variability and test results,
22 everything. Under best control how much variability
23 do you --

24 MEMBER SHACK: Well, but it's even more
25 interesting if you go back and you look at that curve

NEAL R. GROSS

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

1 on the equivalent cladding reacted and the strains
2 where, you know, you look at the one -- the best
3 estimate and then the one sigma and you try to see
4 what that means in terms of ECR, which is actually the
5 thing that really -- you know, we're going to come out
6 here and compute when we're all said and done is the
7 ECR that this thing sees in the accident. And the one
8 sigma gives you about 2 or 3 percent rulemaking
9 strain. You know, so the -- if you went plus or minus
10 two sigma, you know, you have an enormous range of ECR
11 to cover.

12 MR. YUEH: Yes, that will depend also how
13 many test you run.

14 MEMBER CORRADINI: Well, it's kind of --
15 I view it like critical heat flux. The more precise
16 want the answer, the more tests you better run.

17 MR. DUNN: This is Burt Dunn from AREVA.
18 I said I wasn't going to enter the conversation, but
19 I think your question is how will you couple this type
20 of criteria to best-estimate LOCA predictions as
21 opposed to how would you couple this to Appendix K-
22 type LOCA predictions. Appendix K is going to be
23 considered 100 percent.

24 MEMBER CORRADINI: Yes, that's one way of
25 framing it. I guess my only point was that if you're

NEAL R. GROSS

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

1 going to start looking at criteria that depend upon
2 another model prediction, then I want to make darn
3 sure I understand the margin between the failure point
4 and the predicted parameter that I'm going to compare
5 to the failure points. That's all.

6 MEMBER ABDEL-KHALIK: Can you go to slide
7 8, please? I presume that you're planning to do
8 additional testing in these oval regions because you
9 sort of don't trust the brittle transition experiments
10 within these regions, or what?

11 MR. YUEH: Well, there is -- you notice
12 that there's no data nearby where we have samples that
13 are actually ductile. And when we began the test, we
14 were going to charge the samples to a known -- to a
15 target hydrogen level, but we were not able to hit
16 that hydrogen content. So, it's almost like the
17 initial bunch of tests were shotgun approach. You
18 know, we charged the material and then, you know, we
19 did the test. But at the end it turned out there was
20 a lot of a gradient -- hydrogen concentration gradient
21 around the samples that we charged. So, the actual
22 ring compression test sample didn't have the hydrogen
23 level that we were targeting, so we couldn't generate
24 data. For example, you know, the specific location,
25 we don't a sample where it's ductile.

NEAL R. GROSS

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

1 MEMBER ABDEL-KHALIK: But all the samples
2 have gradients, don't they?

3 MR. YUEH: All the sample, they do, but
4 with the -- the samples were charged nine inches long.
5 So and depending on the furnace condition, we charged
6 this. There could be a gradient around the sample.
7 So, what I did before was just the sample, maybe the
8 ends of the big piece that you charge, and then you
9 cut them into little samples. Well, we find that
10 after you cut them into little samples you do the
11 test. The hydrogen in there is not at the target
12 level, so the ECR that we were targeting is no longer
13 valid. Because, you know, let's say if you think you
14 have 200 ppm, then you would try to target, you know,
15 usually at 12 percent and then one at 14 percent and
16 one at, you know, 15-16 percent.

17 MEMBER ABDEL-KHALIK: Well, what is the
18 independent variable in this experiment?

19 MR. YUEH: Well, initially we want -- in
20 this case the hydrogen will be the independent
21 variable we would put in, but --

22 MEMBER ABDEL-KHALIK: Whatever you have,
23 you test it and this is the results you get?

24 MR. YUEH: Yes.

25 MEMBER ABDEL-KHALIK: Doesn't matter what

NEAL R. GROSS

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

1 your target was?

2 MR. YUEH: Well, in order to be able to
3 generate data where you bracket the embrittlement
4 threshold, you know, we need to know precisely where
5 the hydrogen is so that you know what ECR to oxidize
6 the sample to.

7 MEMBER SHACK: Yes, if he's missed the
8 hydrogen, yes, that's why he ends up with too many
9 blue and too many open. And he's looking for that
10 transition so he has to hit it right. You know, if he
11 thinks he's got 400 hydrogen, then he thinks he should
12 be testing at an equivalent ECR of 4. Whereas if he
13 really has 200 hydrogen, he's got a useless test.

14 MR. YUEH: Yes, that's why we have what we
15 have.

16 MEMBER SHACK: That's right.

17 MR. YUEH: And going forward we are going
18 to test --

19 CHAIRPERSON ARMIJO: Ken, I still don't
20 understand. Your data there just says for these
21 conditions once you get above 600-700 ppm hydrogen
22 independent of what the ECR is, you've got pretty
23 brittle material. And adding a few more data points
24 out there, what good is that going to do you?

25 MR. YUEH: We do want to generate a few

NEAL R. GROSS

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

1 data points, perhaps a little bit lower ECR, that
2 shows the material in a ductile condition.

3 CHAIRPERSON ARMIJO: So, you're saying
4 that there is some ductility no matter what? Is that,
5 you know --

6 MR. YUEH: Oh, no, no, no. I'm not
7 saying --

8 CHAIRPERSON ARMIJO: -- who cares if it's
9 half a percent?

10 MR. YUEH: I'm not saying that. What we
11 want to do is generate a data point about the dark
12 line, you know, below the brittle sample to define
13 what the embrittlement threshold is for this
14 temperature.

15 CHAIRPERSON ARMIJO: Okay.

16 MEMBER ABDEL-KHALIK: So, let's say you're
17 going to run some more experiments, right? What are
18 you going to do with the data points that you think
19 are questionable?

20 MR. YUEH: We're not questioning those
21 data point right -- you know, classified as brittle.
22 We're not hoping to change that. We're hoping to
23 generate data in that area. You know, generate data.
24 Hopefully show that we can have test samples that are
25 ductile a little bit below where we have the data

NEAL R. GROSS

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

1 point, you know, right now brittle.

2 So, what we want to do is, for example, if
3 we test the data point here just below this, right, we
4 want to be able to show -- you know, determine bracket
5 what -- you know, what the embrittlement threshold is,
6 essentially this line. Where will we place this line?

7 MEMBER SHACK: But I mean, your current is
8 short of showing the NRC curve is non-conservative,
9 because you're at 1125. You're falling below the
10 curve.

11 CHAIRPERSON ARMIJO: Right. When you've
12 talked about the marginal ductility ones, you know?

13 MEMBER SHACK: Well, no, I'm talking about
14 the dark blue ones. If I extend that line out from
15 600, instead of cutting it off there, if I extend it
16 out the way the NRC curve goes, I'm going to have
17 ductile failure at 1020 -- 1125 below the 1200 degree.

18 MR. YUEH: Yes, but the NRC line, you
19 know, is also best estimate and you also have data
20 points below the line. So, right now there -- you
21 know, most -- all of the data points are classified as
22 entirely brittle above the line.

23 CHAIRPERSON ARMIJO: Okay. There was a
24 comment here.

25 MR. EICHENBERG: This is Tom Eichenberg,

NEAL R. GROSS

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

1 TVA. I think one of the things that isn't entirely
2 clear is why it's important that we be able to control
3 our target hydrogen concentration. And just looking
4 at the data, it seems like if we take the example of
5 the 800 ppm oval, we don't have anything at 800 ppm or
6 even its immediate neighborhood which is a ductile
7 sample. So, if all of our samples are starting to
8 move away from our targets, we could end up with no
9 way to fully appreciate what the uncertainty is over
10 the entire range of this correlation because all of
11 our ductile samples may be all skewed and clouded in
12 one area, whereas you can see the actual brittle
13 samples are more distributed through the range. So,
14 our ability to control the hydrogen concentration is
15 going to really impact how well we can control the
16 uncertainty that we come up with.

17 MEMBER ABDEL-KHALIK: But ultimately, I
18 mean, you know, you're going to use this data to
19 generate the limit line of some sort, right? And I'm
20 just wondering whether whatever limit line you're
21 going to generate would be impacted by having more
22 experiments.

23 MR. YUEH: Well, you know, I think what
24 you are getting at is, you know, this space here, the
25 difference is so close, right? We're generating

NEAL R. GROSS

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

1 brittle samples so close to the limits.

2 CHAIRPERSON ARMIJO: Right.

3 MR. YUEH: But I think the curves should
4 be looked at. You know, vertically there's still
5 quite a bit of a gap here. Because when we look at
6 the acceptance criteria, you know, given what
7 temperature and calculated ECR we have, and we come
8 back to this curve, we would read off the hydrogen.
9 If you look at this, there's several percent
10 difference if you're looking vertically.

11 CHAIRPERSON ARMIJO: I see what you're
12 trying to say, but it just doesn't jump across as a
13 grabber that --

14 MEMBER CORRADINI: Yes, I think visually
15 it looks a hell of a lot closer than --

16 CHAIRPERSON ARMIJO: Yes.

17 MEMBER CORRADINI: -- you're saying it
18 works.

19 MR. NISSLEY: Could you go back to slide
20 7, please?

21 I think the key is that we're seeing --
22 this is Mitch Nissley, Westinghouse. I think a key
23 point here is we're seeing something that's definitely
24 noticeable at 1050. But at 1125 it's close.

25 CHAIRPERSON ARMIJO: Right. Yes. And I

NEAL R. GROSS

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

1 don't see a problem with that. The closer you get to
2 the --

3 MR. NISSLEY: The point -- right. I think
4 it's a little easier to appreciate trying to fill in
5 the cloud areas --

6 CHAIRPERSON ARMIJO: Yes.

7 MR. NISSLEY: -- at the 1050 than it is at
8 1125.

9 MEMBER ABDEL-KHALIK: Correct. Correct.

10 MR. NISSLEY: And a key point is that
11 typically in LOCA calculations, as you get later in
12 life and the hydrogen starts becoming more
13 significant, the power production is also dropping
14 off. So, you have competing effects here such that
15 1050 is a pretty high temperature for a high burn-up
16 fuel rod.

17 CHAIRPERSON ARMIJO: Right. So, the time
18 at temperature that you could experience would give
19 you an ECR that's very, very low and if you can
20 demonstrate that even with a lot of hydrogen you still
21 have ductility.

22 MR. NISSLEY: Right.

23 CHAIRPERSON ARMIJO: That's a good thing
24 to be able to show.

25 MR. NISSLEY: Yes, clearly this figure is

NEAL R. GROSS

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

1 more compelling.

2 CHAIRPERSON ARMIJO: Yes, the other one
3 looks like it's demonstrating that at those
4 temperatures you're going to have a brittle material
5 of over 600 ppm hydrogen, pretty much independent of
6 the ECR unless you do a lot more testing. And I don't
7 know what it's going to buy you.

8 MEMBER ABDEL-KHALIK: I mean, those limit
9 lines are going to be fuzzy anyway.

10 CHAIRPERSON ARMIJO: Yes.

11 MEMBER ABDEL-KHALIK: Right? And looking
12 at the curve at 1125, I'm not sure you can slice the
13 salami any finer than what it is.

14 MR. YUEH: Well, that may be the case, so,
15 you know, that's why we're doing the test.

16 MR. SCOTT: Mr. Chairman, could I make a
17 -- could you go to the diagram again, Ken?

18 We think sort of theoretically that as you
19 move to the right of there with hydrogen, those lines
20 are going to collapse because there's no evidence that
21 I know of that's going to maintain the separation.
22 So, I think from a theoretically standpoint we have
23 some evidence that those lines will become sort of --
24 I guess I would -- the dotted line, the red line would
25 drop down and match the black line at 300, 400, 500,

NEAL R. GROSS

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

1 600 ppms.

2 CHAIRPERSON ARMIJO: Based on what kind of
3 theoretical --

4 MR. SCOTT: The fact that the mechanism
5 with hydrogen is because it increases the oxygen
6 solubility, and the more oxygen you get, the sooner --
7 and so it doesn't really take the high -- the fact
8 that you're at high temperature isn't helping you
9 anymore because you have too much oxygen in there.
10 So, though that -- a shorter time --

11 CHAIRPERSON ARMIJO: Okay. Even though
12 the --

13 MR. SCOTT: -- even though the temperature
14 is less --

15 CHAIRPERSON ARMIJO: -- the diffusion
16 rates are lower --

17 MR. SCOTT: Yes.

18 CHAIRPERSON ARMIJO: -- the oxidation
19 rates are lower, but the solubility is fixed by
20 temperature?

21 MR. SCOTT: The solubility of the oxygen
22 is greater at higher hydrogen and so you have less
23 chance to -- for the temperature effect and the time
24 effect help you.

25 CHAIRPERSON ARMIJO: Okay.

1 MR. SCOTT: You're closer to being brittle
2 right off the bat.

3 MR. YUEH: You know, we do have data
4 points at 1050. You know, even though right now it's
5 classified as marginally ductile, but you know, if we
6 down by ECR a little bit, I think they would be
7 ductile. Yes, we have a whole bunch of data points
8 here right now classified as marginal. And I suspect
9 that if we look at the offset strain, even with the
10 new criteria, because the ECR is so low, they'd still
11 be classified as ductile.

12 CHAIRPERSON ARMIJO: Yes. Okay. Any
13 other questions?

14 (No audible response.)

15 CHAIRPERSON ARMIJO: No. Why don't you go
16 ahead?

17 MR. YUEH: Okay. Change of topic. Move
18 onto ID oxygen pickup. For this, the work has been
19 divided into different stages. You know, I'd like to
20 first give a little background on why we're doing this
21 and then what we did initially to evaluate the
22 phenomenon, and later on the quantification of the
23 difference with limited amount of ID oxygen source on
24 post-quench ductility.

25 So, early on the NRC announced inclusion

NEAL R. GROSS

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

1 of two-sided oxidation away from the ballooned and
2 burst region. Okay. The reference cited was the
3 Halden IFA650.5 test. So that test reached a PCT of
4 1050 degrees Celsius. The photo micrographs you see
5 are from that test basically showing around, you know,
6 28 and 26 microns of oxygen-stabilized alpha. So 28
7 on the inside; 26 on the outside. Okay. But based on
8 simple, you know, math, essentially 3 microns of oxide
9 has sufficient oxygen to generate this layer. So,
10 this would sort of run counter to the claim made in
11 the Halden test report which stated that the oxygen
12 came from bounded fuel. Okay.

13 CHAIRPERSON ARMIJO: Was there any
14 metallographic examination of the fuel before the test
15 was done to determine if or if not -- if you had a
16 bonded fuel to the cladding, you know, from a
17 different segment or something like that so you'd know
18 for sure? Because after the test you don't see any
19 fuel bonded to the ID, do you?

20 MR. YUEH: There may be, but I do not have
21 that information, but I do have pictures of bonded
22 fuel later on that I can show you how it looks like.

23 CHAIRPERSON ARMIJO: For that burnup for
24 that particular fuel is 3 microns typical for the ID
25 zirc oxide?

NEAL R. GROSS

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

1 MR. YUEH: Well, 3 micron is what I
2 calculated to contain enough oxygen.

3 CHAIRPERSON ARMIJO: Yes, but --

4 MR. YUEH: This oxygen stabilized alpha
5 layer. Now, in --

6 CHAIRPERSON ARMIJO: -- 3 microns is
7 fairly thick for an ID oxide, isn't it?

8 MR. YUEH: Once you have fuel-clad bonding
9 takes place, I think the oxide on the inside is around
10 10 microns.

11 CHAIRPERSON ARMIJO: so, that's your
12 argument, that all of the alpha phase is governed by
13 -- well, it's caused by pre-existing ID oxide?

14 MR. YUEH: It could. it's a hypothesis.

15 CHAIRPERSON ARMIJO: That's an argument.

16 MR. YUEH: Yes.

17 CHAIRPERSON ARMIJO: But you can't really
18 say there wasn't any fuel bonding there to begin with.

19 MR. YUEH: I cannot, that's right.

20 CHAIRPERSON ARMIJO: It would be good to
21 find out if there was or was not, because I think
22 that's the whole argument, that --

23 MR. YUEH: I do not remember the burnup of
24 this fuel rod. I don't know if somebody else --

25 MR. SCOTT: Eighty.

NEAL R. GROSS

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

1 MR. YUEH: Eighty? Okay. If it's 80,
2 there would have been fuel bonding layer there.

3 CHAIRPERSON ARMIJO: Yes, I would think
4 so. Yes. So, you know, the argument is a stretch
5 that it's all caused by just pre-existing zirc
6 oxide --

7 MR. YUEH: Okay. Well, I --

8 CHAIRPERSON ARMIJO: -- at that burnup.

9 MR. YUEH: Yes, the follow-up slides, you
10 know, we have done tests to evaluate this and, you
11 know, the follow-up slides hopefully will give a
12 better picture of what is happening.

13 MR. NISSLEY: Yes, Mitch Nissley,
14 Westinghouse. I think one of the points here is that
15 we believe that if there is bonding that there's not
16 an unlimited oxygen source on the ID as there is on
17 the OD, that the oxidation on the OD, provided the
18 steam is there and the temperature is there, will
19 continue we believe at a higher kinetics rate than on
20 the ID.

21 CHAIRPERSON ARMIJO: Yes, I think it's on
22 -- you know, it's a very complicated thing --

23 MR. NISSLEY: Yes.

24 CHAIRPERSON ARMIJO: -- because the
25 oxygen, the UO₂ has to dissolve into the bonding

NEAL R. GROSS

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

1 layer. And before oxygen can transport through the
2 zirc oxide a lot of things have to happen. And but,
3 if you've got a big chunk of UO2 bonded to that zirc
4 oxide, there's plenty of oxygen there. The question
5 is how fast can it diffuse? And it's got to go
6 through a very complicated -- I have a picture from
7 old work I did at GE years ago showing large pieces of
8 UO2 bonded to a cesium-uranium-zirconium oxide layer,
9 which is in turn bonded to the zirc oxide and with
10 islands of UO2 that are just simply dissolving that
11 will -- I can show you the picture later. But so, it
12 says, hey, there's stuff that's bonded. It's a
13 beautiful diffusion bond. So the question is how fast
14 does the UO2 dissolve? How fast does the oxygen
15 transport through the cesium-zirconium bond? How fast
16 does it transport through the zirc oxide and finally
17 into the cladding? And I don't know those -- what the
18 kinetics are.

19 MR. YUEH: Based on our evaluation on the
20 slide on that later, if fuel-clad reactions take
21 place, there's evidence of that afterwards where you
22 actually form into metallics.

23 CHAIRPERSON ARMIJO: Well, I don't know.
24 I don't know if you'd -- you know, this happened.
25 This particular stuff was just high burnup fuel, no

NEAL R. GROSS

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

1 LOCA testing or anything else, and it's very well
2 bonded. But it was -- you know, it's highly variable.
3 You know, you got another location around the
4 circumference, no bonding. Up the length of the rod,
5 no bonding. So, but I think you could address it by
6 -- if you knew something about the kinetics of the
7 dissolution of the oxide UO₂ and then transport
8 through the various layers you might have an argument,
9 but -- or you just do some tests, diffusion --

10 MR. YUEH: We have done tests on here.

11 CHAIRPERSON ARMIJO: Okay.

12 MR. YUEH: And I have a picture of that.
13 So, our alternative hypothesis is that because of the
14 IP oxygen source may be limited that the ID surface
15 oxygen pickup may not necessarily occur the same rate
16 or to the same extent as the OD surface. And the
17 reason that we think the oxygen on the inside is
18 limited because both Limerick conducted at ANL and the
19 Halden test does not show significant evidence of
20 fuel-clad reaction. And the literature data also
21 suggests that contact is needed for oxygen transfer.
22 And we do have test designed I will show later, you
23 know, with and without contact pressure where we have
24 non-irradiated pellets and clad, you know, held in
25 close proximity to each other. Okay. So, we go on

NEAL R. GROSS

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

1 the premise that the internal oxygen source may be
2 limited to the pre-transient oxide. And that's
3 basically the evaluation and qualification of the
4 impact of the limited internal oxygen source on the
5 post-quench ductility.

6 This photo micrograph shows one of the
7 samples tested in the ANL program. And from this you
8 can see that there's very little evidence of oxygen-
9 stabilized alpha on the ID. It is quite thick on the
10 outside. Okay? And there's very little evidence of
11 fuel-clad reaction. And I will show a picture of how
12 that looks like later.

13 CHAIRPERSON ARMIJO: And it would be good
14 if you would just show everybody what the alpha layer
15 is and -- you know, not everybody knows what these
16 structures look like.

17 MR. YUEH: Oxygen-stabilized alpha layer
18 on the outside, there's oxide. Oxygen-stabilized
19 alpha layer on the inside, there's very little
20 evidence of that.

21 CHAIRPERSON ARMIJO: And that's a very
22 high burnup BWR fuel and there was bonding of the fuel
23 to the cladding?

24 MR. YUEH: There may be some bonding, but
25 I was --

NEAL R. GROSS

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

1 MR. LIN: This is Yin-Pi Lin, GNF. Yes,
2 there was some bonding before the test. If you look,
3 the bond layer existed prior to the test.

4 CHAIRPERSON ARMIJO: You actually saw UO2
5 particles bonded to the zirc oxide?

6 MR. LIN: Yes, according to the NUREG
7 reports, that's -- they did do some tests and show
8 that there was a bond layer prior to the test. And
9 this is after the test.

10 CHAIRPERSON ARMIJO: Okay.

11 MR. YUEH: And this -- these photo
12 micrographs show the typical fuel-clad bonding. And
13 in every case there's an oxide layer between the clad
14 and the bonded fuel. Our hypothesis is that this
15 oxide layer, the oxygen from the oxide layer is
16 involved in the LOCA event where the oxide becomes
17 absorbed into the clad. And potentially the fuel,
18 there's no evidence of the fuel actually react with
19 the clad, you know, where the oxygen would be transfer
20 from the fuel to the clad.

21 So, we then proceeded to do some fuel-clad
22 interaction tests. And our goals were to verify
23 Hoffman's observation basically shows that if there's
24 no contact, there's very little; it's almost
25 immeasurable, oxygen transfer from the fuel to the

NEAL R. GROSS

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

1 clad. And a second goal is to evaluate the extent of
2 reaction if you have a contact pressure and with pre-
3 oxidation.

4 The test articles were short rodlets about
5 6½ inches long. Were filled with I think around five
6 non-irradiated fuel pellets. Some of the samples were
7 pre-oxidized at 1650 degrees Celsius. And then the
8 amount of pressure, contact pressure between the
9 pellet and clad is introduced by using oversized
10 pellets so that you can insert the pellet at room
11 temperature, but once you get the right temperature,
12 the pellet would expand more than the clad and you
13 would have contact pressure.

14 In addition, there is an external pressure
15 applied on the outside that balances the pressure
16 increase from the internal gas, which is helium in
17 those cases. We conduct the test at 1000 and 1100
18 Celsius. Exposures from one to three -- thirty
19 minutes. Most of the samples were I think exposed to
20 around 10 minutes. So, that defines the limit of the
21 LOCA for the temperature in question.

22 Most of the samples were tested in the horizontal
23 position. We did test one sample in the vertical
24 orientation.

25 Now, we did a special test where we pre-

NEAL R. GROSS

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

1 oxidized the cladding to about seven microns of oxide
2 without fuel. And then we tried to take the samples
3 through a LOCA cycle similar to the Halden test where
4 it was pointed out that you saw the oxygen-stabilized
5 alpha phase. Okay? With this test the photo
6 micrograph showing the inner diameter, we sort of
7 replicated what they have seen in the Halden test.
8 So, you know, this verifies the theoretical
9 calculation that this can't happen.

10 This is the photo micrograph that I've
11 been talking about a few minutes ago. Okay? This is
12 -- the picture shows pellet-to-clad reaction. And
13 there is a lot of evidence left if the reaction does
14 take place. And I don't have in this presentation,
15 but I do have scanning electron microscopy work done
16 on this and it shows, you know, metallic phases
17 similar to what Hoffman have seen before in his tests.

18 Of the tests that we have conducted, about
19 half of them, independent of contact pressure and the
20 pre-oxidation are totally free -- at least the cross-
21 section we looked at are totally free of fuel-clad
22 reaction. Okay? But half of them showed like this
23 one very limited reaction, very localized.

24 CHAIRPERSON ARMIJO: So, your argument is
25 even if the fuel is bonded to the cladding, it really

NEAL R. GROSS

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

1 doesn't contribute to the growth of the alpha
2 stabilized?

3 MR. YUEH: That's our hypothesis.

4 CHAIRPERSON ARMIJO: That's your argument?

5 MR. YUEH: That's our argument.

6 CHAIRPERSON ARMIJO: And you've got some
7 data that says you can reproduce what happened in
8 Halden by just starting with a pre-oxidized ID
9 surface --

10 MR. YUEH: Yes.

11 CHAIRPERSON ARMIJO: -- no fuel at all,
12 and still get that same thickness as that Halden
13 test?

14 MR. YUEH: Yes. And then none of the
15 tests conducted by Halden or at ANL have shown this
16 kind of reaction where you actually have some
17 evidence.

18 CHAIRPERSON ARMIJO: So, if -- once the ID
19 zirc oxide disappears, is dissolved into the
20 zirconium, then what happens to the bond between the
21 UO₂ and the what used to be ZrO₂? Does that separate?
22 Do you wind up with a gap, you know?

23 MR. YUEH: I think that's what the
24 Limerick and Halden test is showing, there is no fuel
25 attached to the oxygen-stabilized alpha phase.

NEAL R. GROSS

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

1 CHAIRPERSON ARMIJO: Well, I think you
2 could come up with an analytical model, but you really
3 have to know the details of those interfaces between
4 the UO₂, the bond layer, which is cesium-uranium-
5 zirconium oxide, the zirc oxide, and finally the
6 zirconium and understand what the solubilities are and
7 what the diffusivities are before you can make that
8 claim. It may be true, but if you stick a big chunk
9 of UO₂ onto that ID surface, there's plenty of oxygen
10 there. So, you have to prove that it doesn't go
11 anywhere.

12 MR. YUEH: Well, you know, I think the
13 existing data -- you know, it's more like Halden test
14 and integral test. You know, it's irradiated fuel.

15 CHAIRPERSON ARMIJO: Yes.

16 MR. YUEH: It's realistic with the bonded
17 fuel as well, and after the test there's no evidence
18 of reaction.

19 CHAIRPERSON ARMIJO: Yes. Okay. Any
20 other questions on this?

21 (No audible response.)

22 CHAIRPERSON ARMIJO: Go ahead. Keep
23 going, Ken.

24 MR. YUEH: So having done the work, just
25 to evaluate potentially how much oxygen source there

NEAL R. GROSS

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

1 could be inside the fuel clad, and then we want on to
2 initially, as a quick test, evaluate what would be the
3 impact of such limited oxygen source. And we did this
4 by evaluating test samples with unrestricted double-
5 sided oxidation and then in restricted OD, restricted
6 ID oxidation. This is done by putting end plugs to
7 the ends, essentially sealing the ID. So, we pre-
8 oxidized the tube on an open stage and then we put an
9 end cap on the ends and we sealed it so the amount of
10 oxygen on the inside would be limited.

11 Okay. So, we did this with five and ten
12 microns per-oxidation at 800 Celsius.

13 CHAIRPERSON ARMIJO: So, ID and OD both
14 had the same --

15 MR. YUEH: Same amount of oxygen.

16 CHAIRPERSON ARMIJO: Okay.

17 MR. YUEH: We tested the samples at 1100
18 and 1200 Celsius, two ECR levels. We did post-quench
19 ductility tests.

20 This work was performed at AEKI in
21 Hungary. This is a schematic of the test apparatus.
22 It's a horizontal furnace. Both steam and argon, you
23 know, passes through a quartz tube where the sample
24 sits. The argon gas is used as a carrier gas for --
25 once the steam is condensed it is used to carry the

NEAL R. GROSS

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

1 hydrogen onto an external detector where they actually
2 measure the hydrogen generation live so they can
3 actually detection regular oxidation live.

4 So, in our test the samples would be first
5 inserted in this pre-heated zone and then into the
6 tube furnace with a temperature. And after the
7 prescribed amount of time, it would be withdrawn to a
8 third heated section to control the cooling rate to
9 800 degrees. And after that it's withdrawn and
10 quenched in air.

11 CHAIRPERSON ARMIJO: Okay. So, you
12 actually just pull the sample back into --

13 MR. YUEH: Pull it out of the heater, yes.
14 So, the heating -- the cooling rate maybe is a little
15 bit lower compared to the other techniques.

16 This chart shows the difference between
17 one-sided with a limited amount of oxygen and two-
18 sided oxidation. The top chart shows, you know, where
19 the ends are closed, but they both have same amount of
20 pre-oxidation. You know, you can probably noticeably
21 see for the similar amount of time exposure the sample
22 with -- you know, and pre-fixed amount of oxygen
23 source on the inside maintains ductility all the way,
24 you know, throughout. But I think the difference
25 decreases as expected with amount of pre-oxidations

NEAL R. GROSS

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

1 level.

2 So, this demonstrated to us that given
3 that you have a limited amount of oxygen on the ID,
4 the impact, you know, from oxygen ingress into the
5 clad on the ID is limited. You know, it's less than
6 OD.

7 CHAIRPERSON ARMIJO: Unless the argument's
8 made that you have fuel-clad bonding and that's and
9 infinite supply of oxygen. And so --

10 MR. YUEH: Yes, but you know, our test --

11 CHAIRPERSON ARMIJO: So, that's a key
12 issue to resolve?

13 MR. YUEH: Yes. But you know, our test,
14 you know, shows if you had such a reaction how it will
15 look like, and we have not seen that, I think in any
16 of the tests with irradiated clad and fuel.

17 MEMBER SHACK: Yes, but I'm not sure. You
18 know, your fuel-interaction test where you had the
19 contact pressure, you're still without the bond that
20 would form and I don't know that they're really, you
21 know, as far as --

22 CHAIRPERSON ARMIJO: Yes, but they haven't
23 had time to form the natural bond that forms, and that
24 takes a long time. Because, you know, you just got
25 just a diffusion couple where you're just assuming

NEAL R. GROSS

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

1 that pressure will create the -- a region where things
2 can transport.

3 MEMBER SHACK: Okay.

4 CHAIRPERSON ARMIJO: And in a real reactor
5 bond, you have this -- like I say, you have this
6 complex layer. And once that's there, you've got
7 perfect conditions for transport of oxygen if once --
8 unless the ZrO₂ just dissolves so quickly that -- and
9 the cesium-zirconium-oxygen thing is so stable that
10 nothing more will happen, or the kinetics are so slow
11 that nothing more will happen, that's where -- but in
12 your accelerative or your little laboratory test you
13 just haven't had time to form the bond that would form
14 in reactor.

15 MR. YUEH: No, that is correct there's no
16 bond, but we are not taking credit for that. From
17 that test, you know, we show that the reaction can
18 take place. And if reaction does take place, there's
19 evidence left behind. That's what we want to show
20 from that.

21 Now, the real evidence comes from
22 irradiated fuel. With the tests of Halden and ANL
23 where you do have bonded fuel there is no residual
24 evidence for fuel-clad reaction.

25 CHAIRPERSON ARMIJO: Well, I think

NEAL R. GROSS

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

1 experimentally you really need to get good
2 metallographic data on what was there before the test
3 was done and what was there after the test was done,
4 and that would help you make your case. And, you
5 know, the laboratory diffusion couples kind of thing
6 is interesting, but I don't think it's -- like Bill
7 says, you haven't really formed a bond that occurs in
8 reactor.

9 MEMBER SHACK: We have a limited database
10 of high burnup fuel that's gone through LOCA cycles.

11 CHAIRPERSON ARMIJO: Well, we have recent
12 examples in Japan.

13 MR. YUEH: Yes. Okay. And then the last
14 phase that we did was to try to quantify, you know,
15 what the difference is if you had this limited oxygen
16 source. And we pretty much did the same thing except
17 we extended the pre-oxidation to 20 microns. Now,
18 incidently to generate the 20 microns of oxide at 800
19 Celsius it took 18,000 seconds. Okay? That's five
20 hours. So, we know for Zircaloy-4, you know, the
21 breakaway at this temperature after 18,000 seconds has
22 not taken place.

23 This is the results from that test. And
24 on top you have two-sided and limited oxidation --
25 oxygen source. And as expected, it shows a fairly

NEAL R. GROSS

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

1 flat trend. There's very little difference between
2 the no pre-oxidation versus pre-oxidation. However,
3 at the 20 microns one of the samples that you expected
4 to be brittle stayed ductile. So, this correlates
5 with the chart I've shown earlier where the -- when
6 you have a pre-existing oxide, it may be protected and
7 sort of extend the embrittlement threshold a little
8 bit, increase a little bit.

9 On the bottom where we have the samples
10 sealed. And you know, as you can see, if you have
11 more pre-oxidation, more oxygen source, the difference
12 decreases. So, by the time you get to 20 microns pre-
13 oxidation, it's almost the same as unrestricted two-
14 sided oxidation. You know, the beginning the
15 difference is huge. So, you're looking at few hundred
16 seconds to, you know, almost 2,000 seconds.

17 So with that, just to summarize, I think,
18 you know, we have verified that what's observed at --
19 in the Halden test can be generate from a thin, you
20 know, pre-transient oxide, the oxygen-stabilized alpha
21 layer.

22 The potential for pellet-clad reaction I
23 think it's limited. We have not -- of all the tests
24 of irradiated-clad people have done, I have never seen
25 evidence of this reaction. The impact of limited ID

NEAL R. GROSS

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

1 oxygen source on the post-quench ductility has been
2 quantified and up to 20 microns of pre-oxidation there
3 seems to be quite a bit of difference. And from
4 examination of the high burnup fuel, it appears that
5 once fuel-clad contact takes place, you know, once you
6 develop an oxide layer, that oxide layer appears to be
7 stable actually at close to 10 microns all the way to
8 very high burnup. And I have looked at pictures of
9 fuel burnup in the '60s and '70s. They are over
10 around 10 microns. And lastly, the pre-oxidation
11 seems to slightly improve the clad post-quench
12 ductility performance.

13 CHAIRPERSON ARMIJO: Have you or do the
14 industry people have data on the thickness of the ID
15 zirconium oxide layer in regions where there is fuel-
16 to-clad bonding and in regions where there is not?
17 And, you know, if you can find that the zirc oxide
18 thickness where there's bonding is the same as the
19 zirc oxide thickness where there is no bonding, then
20 you can say that the bond, you know, which supplies a
21 lot of oxygen, doesn't really supply oxygen. You
22 know, because the zirc oxide should have been thicker
23 underneath the bonded region because it had a bigger
24 source of oxygen if the oxygen was mobile, you know?

25 MR. YUEH: I did see one hot cell report

NEAL R. GROSS

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

1 where when you have the bonding, you know, underneath
2 the pellet there is this 10 microns or oxide. And
3 then even in the space between the pellets, there is
4 no oxide there. And maybe my colleagues have seen
5 more than I have, but --

6 CHAIRPERSON ARMIJO: Well, I have just --
7 this was not particularly high burnup fuel. It was
8 old GE data. I believe it was published; I don't
9 recall where. But it was a very nice bond, but the
10 zirc oxide in between the cesium-zirconium-uranium
11 bonding layer and the cladding was the order of five
12 microns thick. I don't remember, you know, what the
13 thickness was where there was no bonding, because it
14 was spotty.

15 MR. YUEH: Yes.

16 CHAIRPERSON ARMIJO: But it wasn't
17 particularly thick. And if it was a source of oxygen,
18 I would have expected to have some greater thickness
19 if it had more supply than -- through the gas space.
20 So, if you can find from your hot cell exams the
21 various fuel suppliers, they may have -- be able to
22 demonstrate that bonding really doesn't really supply
23 oxygen. It just provides a bond.

24 MR. YUEH: Yes.

25 CHAIRPERSON ARMIJO: But it doesn't supply

NEAL R. GROSS

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

1 oxygen for what -- that you need to stabilize the
2 alpha phase.

3 MR. YUEH: Yes.

4 MEMBER SHACK: Yes, but you really need to
5 look at that after it's been through a LOCA cycle.

6 CHAIRPERSON ARMIJO: No, actually you do
7 it before, Bill.

8 MEMBER SHACK: Yes, but --

9 CHAIRPERSON ARMIJO: If it's already
10 bonding and it's been sitting there for thousands of
11 hours, okay, or bonded, and the zirc oxide is still
12 the same thickness where it's bonded and where it's
13 not bonded, then you've got an argument that says the
14 UO2 is not supplying oxygen into the zirconium.

15 MEMBER SHACK: Even if I raise the
16 temperature dramatically?

17 CHAIRPERSON ARMIJO: Well, no, I'm just
18 saying for a fixed temperature. Now, I'm not arguing
19 yet about whether you could go up in temperature. The
20 thermodynamics can change.

21 MEMBER SHACK: No, but that's my point is
22 that, you know, what you need is a database of things
23 that have formed the bond and then have gone through
24 a high-temperature cycle of which we have one, I
25 think.

NEAL R. GROSS

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

1 CHAIRPERSON ARMIJO: That's why they
2 got --

3 MR. YUEH: Oh, no, no. No, we have more
4 than one of that. Halden has conducted probably a
5 dozen tests; I don't know how many. But right now --

6 MEMBER SHACK: Okay. Well --

7 CHAIRPERSON ARMIJO: Those are the ones
8 you've got to look at really carefully.

9 MEMBER SHACK: Okay. I mean, and
10 everybody seems to be talking about one of them as far
11 -- I mean, I haven't seen the data. I'd really like
12 to see the data from those 12 tests because that
13 sounds like the database of interest. The rest of
14 this is all kind of -- you know, we can all wave our
15 hands, but those sound like the 12 tests that mean
16 something.

17 MR. YUEH: And the NRC, I think, is a
18 participant in that program, so we should be able to
19 get that.

20 MEMBER REMPE: So, in addition --

21 CHAIRPERSON ARMIJO: Okay. Well, we just
22 got -- yes?

23 MEMBER REMPE: Well, in addition to that
24 data the test that your reporting will it be a
25 document and will it be submitted that we can review

NEAL R. GROSS

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

1 it?

2 MR. YUEH: I do not plan to submit this
3 unless one of the vendors want to pursue this,
4 because --

5 MR. DUNN: Well, we'll see whether it's
6 interesting or not when --

7 MR. YUEH: Yes, I think you have to --
8 yes, you have to decide whether you need this or not.

9 CHAIRPERSON ARMIJO: Okay. This is an
10 EPRI presentation representing work for both BWRs,
11 PWRs and all kinds of fuel from different suppliers,
12 so you're trying to get a general argument here.

13 MR. YUEH: Yes.

14 CHAIRPERSON ARMIJO: So, we're not looking
15 at anything that's proprietary to any one of the fuel
16 suppliers. Okay.

17 MR. YUEH: Okay. And our recommendation,
18 you know, based on what we have seen, you know, the
19 reg guides, you know, that addresses the ID oxidation
20 I think, you know, should -- it would be good to make
21 some allowances for reduced impact from ID oxidation
22 under some conditions.

23 CHAIRPERSON ARMIJO: Well, that's only
24 good until the cladding fails, right?

25 MR. YUEH: Yes. Well, even after the --

NEAL R. GROSS

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

1 CHAIRPERSON ARMIJO: If you burst it, then
2 you have plenty of steam.

3 MR. YUEH: Steam I think is only limited
4 to the region which burst. There's still no
5 communication to the rest of the rod.

6 CHAIRPERSON ARMIJO: That's the argument?

7 MR. YUEH: Well, that's what they have --

8 CHAIRPERSON ARMIJO: That's a weak
9 argument, but go ahead. Give it a try.

10 MR. YUEH: Well, that's what they have
11 seen in the Halden test, I think.

12 CHAIRPERSON ARMIJO: Really? Okay. Like
13 to see that.

14 MR. YUEH: Yes, because imagine in the
15 burst region -- yes, because if you have steam going
16 up, you wouldn't have steam starvation. You wouldn't
17 have the -- you know, lot of hydrogen waiting around
18 the burst region. So, the steam doesn't survive, it
19 appears, to ingress into the rest of the --

20 CHAIRPERSON ARMIJO: Well, it will tend to
21 be consumed as it --

22 MR. YUEH: Yes.

23 CHAIRPERSON ARMIJO: -- you know, as it
24 goes away from the burst region.

25 MR. YUEH: Yes, if it lasts very long,

NEAL R. GROSS

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

1 yes, I think it will.

2 CHAIRPERSON ARMIJO: Okay. Let's move on.

3 MR. YUEH: Okay. The last topic, LOCA
4 round robin. So, we start on this, you know, because
5 of concerns raised about variations, beginning labs
6 and experimental variations. And at the same time,
7 you know, the industry has expressed interest to
8 generate an independent test standard sanctioned by
9 ASTM.

10 So, we started out to solicit labs to join
11 this effort. We have seven labs agreed to join this
12 and I will identify them -- a listing later on in my
13 presentation. You know, these labs are all voluntary
14 to join this effort. There is no money involved, so
15 people -- the labs agreed to cover their own costs.
16 So, in terms of scheduling, you know, we only
17 coordinate the efforts. We may not necessarily have
18 a lot of control on the schedule when things will be
19 completed.

20 CHAIRPERSON ARMIJO: If you're not paying
21 them.

22 MR. YUEH: Yes, we're not paying them.
23 So, at the start we established a framework. You
24 know, it is an ASTM requirement that we have a minimum
25 of five labs, you know, in order to be able to

NEAL R. GROSS

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

1 establish a test procedure. Okay. In this framework,
2 each lab agreed to do a set of post-quench ductility
3 and breakaway oxidation tests, okay, using a common
4 set of agreed test parameters. These will be high-
5 level parameters like a temperature profile, heat up
6 and cooling rates. And at the same time we agree that
7 the labs should use their own test procedures, because
8 in the initial run we like to be able to establish
9 that even with this flexibility, you know, we could
10 generate repeatable results. You know, obviously that
11 will lead to a looser test procedure. Okay. And if
12 this doesn't work out, it may be possible that we have
13 to redo some tests at more refined, more restrictive
14 parameters.

15 All of the sample preparations at this
16 point are being conducted by the individual labs,
17 except for hydrogen charging. Okay. Two of the labs
18 doesn't have the facility to do hydrogen charging and
19 EPRI is supplying the hydrogen pre-charged material.
20 And the test data generated from each lab, you know,
21 at the end of the test the individual labs will
22 generate a test report and EPRI will combine the data
23 into a single report, and that will be shared with all
24 the participating members.

25 The common parameters, as was mentioned

NEAL R. GROSS

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

1 earlier, majority of them consistent with ANL
2 recommendations. You know, some of them may be
3 slightly different, like the water quality in the
4 original ANL draft test procedure requires specific
5 rate of water. For example, people are just using
6 normal grade to satisfy the ASTM standard. And there
7 are some other minor exceptions. The major parameter,
8 the temperature, the heat-up rate and cooling rates
9 are with the specification.

10 The post-quench ductility test, we are
11 talking an ANL-like temperature profile at 1200 C
12 setpoint. Okay. Testing will be conducted at as-
13 built 200, 400 and 600 ppm hydrogen levels. The
14 values listed there are just targets. People may
15 choose different values, but they need to bracket
16 where the transition is and determine, you know,
17 embrittlement ECR.

18 CHAIRPERSON ARMIJO: Are you going to test
19 all the different cladding materials?

20 MR. YUEH: We are only testing Zircaloy-4.

21 CHAIRPERSON ARMIJO: You're not going to
22 test MF, ZIRLO or anything else, while the fuel
23 suppliers may do their own and keep that proprietary,
24 or is there, you know --

25 MR. DUNN: Bert Dunn. Keep in mind we're

NEAL R. GROSS

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

1 doing groundwork to establish a --

2 CHAIRPERSON ARMIJO: A test procedure?

3 MR. DUNN: -- test procedure.

4 CHAIRPERSON ARMIJO: Yes, but you'd want
5 to -- you would kind of hope that the test procedure
6 would work for all the materials.

7 MR. DUNN: Transfer in the materials, yes.

8 MR. YUEH: Our goal is not to get useful
9 data out of this. Our goal is to evaluate, you know,
10 variability.

11 CHAIRPERSON ARMIJO: Yes, but I'd be -- I
12 don't know if you'd want to label cladding A, B, C, D
13 and not say which is which, but it seems to me that
14 you'd want to -- what you -- that you'd to not
15 necessarily do all of the tests with all of the
16 materials, but you would do at least for some of the
17 tests all of the materials to make sure that there's
18 no surprises there, that the test is very repeatable
19 for one material, but not very repeatable for another.

20 MR. YUEH: Another reason we are limiting
21 the number of samples even is because the labs, you
22 know, they're doing this on a volunteering basis and
23 they cover their own costs.

24 CHAIRPERSON ARMIJO: Well, it may be more
25 costly not to do it than to do it, but that's a

NEAL R. GROSS

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

1 commercial decision.

2 MEMBER SHACK: I worry a little that
3 you'll get so much scatter in the hydrogen content
4 it'll be difficult to compare the tests.

5 MR. YUEH: That is a concern I raised with
6 ASTM, because we're not able to -- you know, right off
7 it's very difficult to do statistical evaluation
8 between different labs. So, that issue still need to
9 be discussed.

10 CHAIRPERSON ARMIJO: Are you working on
11 methods, experimental methods to get better control of
12 your hydrogen charging?

13 MR. YUEH: I think, you know, Westinghouse
14 has been doing the high-temperature oxidation test for
15 us. Since this start at the beginning, I think their
16 technique has improved. And going forward, we would
17 first measure the hydrogen level before we do the
18 high-temperature oxidation test. That way we would
19 know where we need to target. So, in that sense maybe
20 has become less important in the high-temperature
21 test, but in the round robin, you know, it will be
22 more important. Right now the procedures for doing
23 hydrogen charging of the individual labs are not known
24 to us. Well, the framework, you know, they are
25 allowed to follow their own procedures. You know,

NEAL R. GROSS

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

1 they have been requested to document the procedure
2 they used for the work.

3 MEMBER SHACK: But that's okay if they
4 were actually out generating data, because you know,
5 whatever they put in they measure it when they're done
6 and they're done. But here you're actually trying to
7 get a set of tests that you can sort of correlate
8 across the five labs. And if they're all done at --
9 instead of three hydrogen contents, fifty hydrogen
10 contents, you'll have fewer -- I mean, the alternative
11 is to supply it with charged samples from
12 Westinghouse, for example, and at least look at the
13 lab-to-lab variability in the mechanical part of the
14 tests rather than the lab-to-lab variability in their
15 ability to charge hydrogen. I mean --

16 MR. DUNN: I think in the end though you
17 have to look at both.

18 CHAIRPERSON ARMIJO: I think in the end
19 you have to look at both, but I think at the beginning
20 of this program the fewer variables you have, and
21 hydrogen is a key one, to have --

22 MEMBER SHACK: Yes, it's --

23 CHAIRPERSON ARMIJO: -- master hydrogen-
24 charged sample would be a good idea.

25 MEMBER SHACK: Yes, it's certainly an

NEAL R. GROSS

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

1 arguable point. I mean, I agree.

2 MR. YUEH: Yes, but you got to remember
3 even if the samples are charged in a single location,
4 it's -- there are still variations.

5 CHAIRPERSON ARMIJO: Well, I understand
6 that.

7 MR. YUEH: So, I think as long we measure
8 it -- now, as a second follow-up to this, we were
9 considering for one lab to supply hydrogen-charged --
10 pre-charged material to a few number of labs to do,
11 you know, a limited number of tests.

12 CHAIRPERSON ARMIJO: Yes.

13 MR. YUEH: We discussed it initially, but
14 at that time we decided to complete this part first
15 before we'd consider that.

16 CHAIRPERSON ARMIJO: Well, as long as all
17 of the people doing the testing realize how
18 significant that hydrogen variability problem is,
19 they'll do their best.

20 MEMBER SHACK: Like I say, it wouldn't be
21 the first time you've recognized you've got a problem
22 without solving it.

23 CHAIRPERSON ARMIJO: Yes, that's right.
24 You wouldn't have had anyway.

25 MR. YUEH: Now, I think at the end, you

NEAL R. GROSS

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

1 know, there's clearly some kind of trend in the line.
2 So, I think if everybody fall close to the line, even
3 though you don't have the same hydrogen level, I think
4 that still should be sufficient.

5 CHAIRPERSON ARMIJO: Yes.

6 MEMBER SHACK: I was just going back, too.
7 When you're actually plotting these tests of ductile
8 versus non-ductile, would it be better to actually
9 plot the strains that you've got in each of those
10 tests and then try to bracket what the uncertainty in
11 that line might be, rather than it's ductile, non-
12 ductile?

13 MR. DUNN: The strains?

14 MEMBER SHACK: Your equivalent strains,
15 you know? And then that way I would --

16 MR. DUNN: Oh, okay.

17 MEMBER SHACK: Given hydrogen level I
18 could maybe get an equivalent strain versus ECR and
19 then I could sort of bracket --

20 MR. YUEH: So I could it ask them of
21 error bar?

22 MEMBER SHACK: I could get error bars bars
23 and uncertainty in the width of that line, or you
24 know, I could determine what I wanted at any rate.

25 MR. YUEH: I don't know how useful that

NEAL R. GROSS

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

1 is.

2 MR. DUNN: Well, I don't know, but isn't
3 it there for doing load maps?

4 MR. YUEH: It's there, but it's not
5 plotted. The information is available.

6 MEMBER SHACK: I mean, eventually I would
7 think that you'd want to know what that line
8 uncertainty was.

9 MR. DUNN: You're plotting elongation
10 versus load.

11 MR. YUEH: We are plotting it, but we --
12 the data that we plot is -- the transition ECR will be
13 determined. I think what you're looking for is actual
14 strain plotted. You know, some kind of information
15 expressed on the chart, an additional, like another
16 dimension.

17 MEMBER SHACK: Well, at least I'd slice
18 the hydrogen line and then plot the ECR versus strain
19 and then determine from that where my transition ECR
20 was rather than, you know, having a point that maybe
21 -- I might get more information out of all the data
22 rather than being able to just hit bang-on a ductile-
23 brittle transition, if I had that just to --

24 MR. YUEH: Well, you -- that might -- you
25 might be able to generate something at high-hydrogen

NEAL R. GROSS

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

1 where the strain is low, but when you are at high ECR,
2 when you have very little hydrogen, I think Michelle
3 mentioned earlier, that strain could be 10 percent, 30
4 percent, 40 percent. You won't necessarily see
5 anything useful out of it.

6 MEMBER SHACK: Okay. Having never tried
7 it, you know, this is strictly off the top of the
8 head.

9 MR. DUNN: We should maybe think about it.
10 I mean, the information is obviously there at the
11 labs.

12 CHAIRPERSON ARMIJO: Okay. Let's keep
13 going.

14 MEMBER SHACK: Because when you come back
15 here to a full committee someday, the uncertainty in
16 that line is always going to come up.

17 CHAIRPERSON ARMIJO: Be ready.

18 MR. YUEH: Yes, but the conservatism
19 applied elsewhere probably overwhelms this.

20 MEMBER SHACK: Well --

21 PARTICIPANT: Not until this -- altogether
22 it doesn't.

23 MEMBER SHACK: Yes. Yes. People have
24 tried that argument before.

25 CHAIRPERSON ARMIJO: Never worked before

NEAL R. GROSS

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

1 and won't work now.

2 MR. YUEH: Well, this list is, you know,
3 high-level, you know, details of data collection and
4 test parameters. The actual list, you know, obviously
5 goes beyond this. So, the oxidation sample itself,
6 you know, we would obviously measure the hydrogen
7 concentration, set the weight gain per ASTM and also
8 check for consistency with the database. Okay. And,
9 you know, we would photograph and document any
10 abnormal oxide appearance and we would conduct a
11 cross-section evaluation to check whether there's any
12 significant temperature variation within the sample by
13 looking at the oxide, how uniform it is across the
14 circumference. So, we plan to do this for samples
15 with high ECR.

16 On the ring compression test, the only
17 modification we're making is the plus or minus one.
18 We want to do plus or minus two just to give the labs
19 more flexibility. On the ring compression test the
20 standard load displacement versus time, and then
21 permanent strain, if available. You know, we
22 discussed this earlier. It's not always available.
23 We'll photograph each sample and then measure the
24 local hydrogen level. That's, you know, where the
25 sample cracked.

1 You know, we do have plans to use a 1
2 percent plastic strain. Right now in our framework
3 the previous criteria -- I guess before the reg guide
4 was drafted, the criteria was a little bit different.
5 I think the coefficients is less severe compared to
6 now, so that's what we plan to use to determine if the
7 sample is ductile or brittle.

8 MEMBER SHACK: But it's 1 percent plastic
9 strain as interpreted in terms of the offset strain?

10 MR. YUEH: Well, in the earlier
11 guidelines 1. -- I forgot. It's 1.6 percent if we use
12 offset strain. The criteria is you must be -- the
13 measures of offset strain must be greater than 1.6
14 plus 0.05 times the ECR. I think the new criteria
15 presented today is 1.4 plus 0.1 times the ECR. So,
16 it's a bit different. It's more -- the measure is
17 higher now compared to the previous recommendation.
18 But the data will be there. If we need to re-plot it,
19 it can be done.

20 For breakaway oxidation, you know, people
21 agreed to stay within the recommended temperature
22 profile. That's included in the heat-up rate, cooling
23 rate. We would determine the breakaway oxidation at
24 800 and 1000 Celsius to within 500 seconds. So, this
25 will be the step they use to bracket.

NEAL R. GROSS

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

1 CHAIRPERSON ARMIJO: So, you'll run
2 different samples, a 500-second sample --

3 MR. YUEH: In increments.

4 CHAIRPERSON ARMIJO: -- a 1,000-second, so
5 on?

6 MR. YUEH: Yes, they will guess where it
7 is. For example, if you expect 5,000, they could
8 potentially start, you know, 500 seconds lower, work
9 their way up.

10 CHAIRPERSON ARMIJO: Yes. Yes. And then
11 the actual measurement is when you have a
12 discontinuity in the weight gain or the color of the
13 oxide, or some other parameter? How will you do that?

14 MR. YUEH: Well, right now we plan to use
15 visual indications. And if it's questionable, then we
16 would, you know, measure the hydrogen level
17 afterwards.

18 So, the data collection is similar to what
19 we had before with the oxidation test. You know, we
20 would measure the weight gain. And it takes off, that
21 will be an indication. And if the oxide is
22 continuously black, then even though the -- you know,
23 the weight gain has -- well, if it is continuously
24 black, the weight gain wouldn't have gone up. So, we
25 will call that no breakaway taking place.

NEAL R. GROSS

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

1 CHAIRPERSON ARMIJO: Are the weight gain
2 measurements -- are they pre and post-test, or are
3 they continuous weight gain?

4 MR. YUEH: It's pre and post, not
5 continuous.

6 CHAIRPERSON ARMIJO: Okay.

7 MR. YUEH: Although one of the lab can
8 measure the weight on line.

9 CHAIRPERSON ARMIJO: Okay.

10 MR. YUEH: And then the AEKI in Hungary,
11 they can measure the hydrogen. So, they can determine
12 at what time did the breakaway take place.

13 CHAIRPERSON ARMIJO: And everybody is
14 working with this master Zircaloy-4 cladding material?

15 MR. YUEH: Yes.

16 CHAIRPERSON ARMIJO: So, there's no
17 variability in the cladding material except for what
18 is created in the preparation of the samples, hydrogen
19 charging testing?

20 MR. YUEH: Yes. Okay. These are the labs
21 that have joined the round robin effort. So, we have
22 AEKI in Hungary. They use a horizontal resistance
23 furnace. I think CEA and AREVA together, I think they
24 are using direct resistance, but we had a discussion
25 on this. I don not know if they changed their mind to

NEAL R. GROSS

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

1 indirect resistance. GNF is going to be resistance.
2 KAERI, the Korean Atomic Energy Research Institute, I
3 think they have a system similar to INL. It's
4 radiant. They can -- they have instrumentation to
5 monitor the weight gain and the like. Oak Ridge is
6 going to I think use resistance furnace.
7 Surprisingly, they still don't have the equipment yet,
8 so their results probably won't come until much later.
9 Studsvik, it's the same apparatus as I think NRC-
10 sponsored. Unfortunately, the equipment has gone into
11 the cell, so they may drop out of the test. So, the
12 cost to them would be maybe order of magnitude higher
13 with the equipment in-cell. And then Westinghouse
14 uses resistance heating.

15 So, at this time --

16 CHAIRPERSON ARMIJO: Before you leave that
17 chart, I just want to ask a couple of questions.
18 Argonne used radiant heating for their furnace type,
19 or what did they --

20 MR. YUEH: Argonne? Yes, radiant.

21 CHAIRPERSON ARMIJO: Radiant? And then
22 the RCT platform, you have three of them are using a
23 flat platform where they're pressing against. What
24 are the other folks going to use?

25 MR. YUEH: I do not know what they use.

NEAL R. GROSS

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

1 CHAIRPERSON ARMIJO: Is there an
2 alternative that's being used?

3 MR. YUEH: There could be a little
4 curvature, I think.

5 CHAIRPERSON ARMIJO: I got to ask somebody
6 who knows something about mechanics.

7 MR. DUNN: I think AREVA will be using a
8 slight curvature.

9 CHAIRPERSON ARMIJO: What difference would
10 it make if it was flat or slightly curved? I guess I
11 don't understand why somebody wouldn't -- all --
12 everybody wouldn't use just a flat surface.

13 MR. DUNN: I can't recall what it is. I'm
14 sorry, I can't recall what difference it makes other
15 than the support of the materials seem -- we like it
16 better.

17
18 CHAIRPERSON ARMIJO: Okay. And then
19 finally, just for my -- who is AEKI? Sounds like they
20 have some pretty slick --

21 MR. DUNN: The Hungarian Academy of
22 Science.

23 CHAIRPERSON ARMIJO: Oh, that's why
24 they're --

25 MR. YUEH: Somehow the letters don't

NEAL R. GROSS

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

1 corresponds to the name.

2 CHAIRPERSON ARMIJO: Hungarian Academy of
3 Science? Okay. Got it.

4 MR. YUEH: And they're also known as KFKI.

5 CHAIRPERSON ARMIJO: They seem to have
6 pretty slick instrumentation online for weight gain,
7 online for hydrogen.

8 MR. YUEH: Yes, but they have to use an
9 argon carrier gas. So, it's not pure steam. There is
10 steam plus argon that passes through the furnace. And
11 on the cool side, once it exit the furnace, the water
12 is condensed.

13 CHAIRPERSON ARMIJO: And then the argon --

14 MR. YUEH: And then the argon carries the
15 hydrogen, flushes the hydrogen into the --

16 CHAIRPERSON ARMIJO: Okay.

17 MR. YUEH: We were going to start this
18 test a little bit earlier, but we had a problem
19 acquiring the test material, but it was finally
20 acquired, you know, end of last year and was shipped
21 out last year. The hydrogen-charged material was
22 shipped to a single laboratory. Now there are two of
23 them. Studsvik looks like it's going to drop out.
24 So, we have at this time six labs still in this effort
25 and we need a minimum of five to satisfy the ASTM

NEAL R. GROSS

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

1 requirement.

2 We have discussed the difficulties in
3 hitting hydrogen -- you know, targeting hydrogen
4 values. The ASTM B10.02 Committee has not said a lot
5 on this. Basically, you know, we'll have to wait and
6 see the data before we can disposition how we can do
7 the statistical evaluation. Because if you hit the
8 hydrogen level, it's a simple analysis. Now, it's not
9 on the same level. It's a little bit more difficult.

10 So, of the six labs I think five of the
11 labs have indicated the test may be finished --

12 CHAIRPERSON ARMIJO: That's good.

13 MR. YUEH: -- by the summer. Now, this is
14 still --

15 CHAIRPERSON ARMIJO: That's what we
16 expected.

17 MR. YUEH: -- not firm commitment, because
18 you know, they do it at their, you know, best-effort
19 basis.

20 CHAIRPERSON ARMIJO: Did Argonne test this
21 same material that you're going to use?

22 MR. YUEH: It's different lot of material.

23 CHAIRPERSON ARMIJO: Wouldn't it be a good
24 idea when you're finished at some point to connect the
25 national labs and the industry to get the -- since you

NEAL R. GROSS

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

1 have one?

2 MEMBER SHACK: They don't volunteer.

3 CHAIRPERSON ARMIJO: I know. Well, you
4 know? But it would seem somewhere along the line that
5 that's kind of a missing connection, that everybody's
6 in sync.

7 MR. DUNN: You know, Argonne didn't -- I
8 don't think had this material.

9 MR. YUEH: Oh, no, but the material they
10 did test.

11 MR. DUNN: Well, all of us did.
12 Westinghouse gave material, AREVA gave material.

13 MEMBER REMPE: But you have an extra set
14 of samples you sent to Studsvik and they won't be
15 using them, so couldn't they be sent to Argonne?

16 MR. YUEH: We asked if Argonne would be
17 interested in joining this round robin. They
18 declined.

19 MEMBER REMPE: Well, I'm thinking more
20 that the -- or the NRC might be interested in --

21 CHAIRPERSON ARMIJO: I think what we --
22 well, we -- you know, I can't speak for Dana, but it
23 was his -- the idea of the round robin actually
24 started with Dana. And I think it was belief that it
25 would -- that the -- you know, it would connect with

NEAL R. GROSS

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

1 what the NRC testing had been done and they would be
2 part of the program. You know, I'm kind of putting
3 words into his mouth, but that's what I expected. I
4 don't know what the rest of the members -- the
5 committee thought. So, I just think it's kind of a
6 gap if -- you know, if Argonne developed this test,
7 put out all the requirements and everything else, but
8 yet they don't test the material that's being tested
9 in the round robin, it just looks like it's flawed.

10 MR. DUNN: Well, one of the things we
11 could do I guess is we could do a comparison of the
12 materials sent out for this test to the materials sent
13 out to Argonne earlier. That's a possibility. They
14 can draw a connection that wouldn't -- I mean, because
15 it's very close. It's the same material.

16 CHAIRPERSON ARMIJO: That's your
17 expectation. It's not real clean. You need to say,
18 okay, we did the metallography, the alloy chemistry,
19 all of this stuff. Just -- anyway, if that's what
20 you're going to do, I think it's --

21 MR. YUEH: We have plenty of material, so
22 if ANL should change their mind, it's not a problem.

23 CHAIRPERSON ARMIJO: Well, let's see if
24 the ACRS wants to weigh in.

25 (No audible response.)

NEAL R. GROSS

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

1 CHAIRPERSON ARMIJO: Okay.

2 MR. YUEH: It is in my -- I think in my
3 last slide shows a -- well, we don't really have a
4 schedule, you know, completing the test. But assuming
5 the test is completed in the summer, we will first
6 distribute the data to the, you know, participants and
7 ASTM. After that, we will review the data with the
8 NRC. And after that, we will draft an ASTM test
9 procedure and that will be obviously reviewed --

10 CHAIRPERSON ARMIJO: Yes.

11 MR. YUEH: -- by both the ASTM and the
12 NRC. I think after that they have to -- ASTM have to
13 put the procedure online and it will be reviewed by
14 the industry. And only after that can the procedure
15 be implemented.

16 CHAIRPERSON ARMIJO: Right. Well, that's
17 your longer-term goal is to get that procedure, the
18 formal ASTM test procedure, or set of procedures.

19 MR. YUEH: Yes.

20 CHAIRPERSON ARMIJO: There are more than
21 one.

22 Okay. Well, I'll open it up to the
23 Committee for any questions, anybody here who wants to
24 add something. Jack?

25 MEMBER SIEBER: No questions.

NEAL R. GROSS

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

1 CHAIRPERSON ARMIJO: Bill? Charlie? Joy?
2 Mike? Said?

3 (No audible response.)

4 CHAIRPERSON ARMIJO: Well, thank you very
5 much. Thank the staff very much for their --

6 MEMBER ABDEL-KHALIK: Do you want to ask
7 for public comments?

8 CHAIRPERSON ARMIJO: Oh. Well, we were
9 told that there was none, but we do have Mike Billone;
10 that's the only person, and Ralph Meyer on the line.
11 They may have been wanting to say something. We've
12 had them on mute.

13 MR. MEYER: This is Ralph Meyer. I'm
14 still here. Can you hear me now?

15 CHAIRPERSON ARMIJO: Yes, we sure can,
16 Ralph.

17 MR. MEYER: Yes, I would like to make a
18 comment. It's broad. It applies largely to the NRC
19 proposal. I think what's been proposed adequately
20 captures the research findings and is fundamentally
21 sound, but I also think that it's a lot more
22 complicated than it has to be. There seems to be an
23 expectation that these three reg guides provide a lot
24 of performance-based provision in the rule. And in
25 fact, the hydrogen dependence of the oxidation limit

NEAL R. GROSS

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

1 is inherently performance-based. And I don't really
2 think you're getting anymore performance-based aspect
3 by the reg guides.

4 For example, in the testing that we did no
5 alloy dependence was found. And furthermore, we had
6 a mechanistic understanding which suggested you
7 shouldn't find an alloy dependence. So, tooling up to
8 do tests to find alloy-specific limits on oxidation
9 doesn't seem to be worthwhile to me.

10 The breakaway analysis, in my opinion,
11 really goes beyond our understanding of the breakaway
12 phenomenon and that a simple scoping test would be
13 sufficient to tell if we slipped into making bad
14 cladding or not.

15 The one test condition that -- where the
16 current database may not be sufficient is in the lower
17 temperature regions. And, Ken, you talked about that
18 today and showed some industry results which in fact
19 were -- showed the effect, but they weren't a whole
20 lot different in the EPRI slide 5. So, I would think
21 -- and this is an opinion, but I would think that one
22 could do exactly what EPRI had outlined in line 5, use
23 the industry data and the NRC data to get a family of
24 curves; the 1200, 725 and 1050, for example, and put
25 them in the rule. If you put them in the rule, then

NEAL R. GROSS

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

1 10 years from now when a lot of us are gone, you know,
2 it'll still be there.

3 So, I think you could do all of this with
4 a rule and one reg guide that addressed the breakaway
5 screening, the hydrogen correlation with burnup and
6 the two-sided oxidation pickup, which were the
7 important things. So, thank you for allowing me to
8 make those comments.

9 CHAIRPERSON ARMIJO: Well, Ralph, let me
10 tell you; I really appreciate those comments because
11 anything -- this is a very complicated set of reg
12 guides. The rules itself looks complicated. And as
13 you point out, maybe everything is -- we're making it
14 more complex than it needs to be. So, I really
15 appreciate that you made that point. If there's a
16 better way to do it, particularly winding up with one
17 reg guide and some ways to put some hard numbers into
18 the rule -- although I know that sounds prescriptive,
19 but maybe --

20 MEMBER SHACK: That's what we told them
21 not to do.

22 CHAIRPERSON ARMIJO: That's what we told
23 you not to do, but you know, when you think about it
24 again, it may be probably -- it could be the smarter
25 way to handle this.

NEAL R. GROSS

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

1 MR. DUNN: This is Burt Dunn, AREVA. I'm
2 sorry I'm responding, but one of the things the
3 industry did want was to be able to keep the rule up
4 to date with the science, and that's why we wanted to
5 go with numbers into reg guides. Simplify the reg
6 guides? Fine. We'll be happy with that. But putting
7 actual numbers like we did in '73 into the Code of
8 Federal Regulations, today we don't think that's wise.
9 I mean, it didn't serve us very well in trying to come
10 up with this stuff.

11 CHAIRPERSON ARMIJO: Well, it's a
12 tradeoff, Burt.

13 MR. DUNN: Yes.

14 CHAIRPERSON ARMIJO: You know, it's a
15 tradeoff of what works best and what provides the
16 assurance that we're looking for, that adequate
17 ductility. And if there's a simpler way to do it, I
18 always find it -- you know, I gravitate towards that
19 myself. But that's up to you guys and the staff, of
20 course.

21 Well, look, there's no more comments. I
22 would like to poll the Committee on the upcoming
23 presentation to the full Committee, because this is a
24 lot of stuff to swallow and I think, Chris, what do we
25 got, two hours, an hour-and-a-half?

NEAL R. GROSS

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

1 MR. BROWN: Schedule for June 8 if we want
2 to go through with the two hours.

3 CHAIRPERSON ARMIJO: Yes, well, right now
4 you're on the schedule for two hours. And if it
5 happened, I would expect that we would have no
6 comments on the reg guides. Pretty much like what was
7 announced this morning, I don't think that -- unless
8 the industry wants to comment on the draft reg guides,
9 and apparently you didn't want to do that. So, this
10 is an awful lot of material for -- and it's kind of
11 arcane stuff. So, I'd like some recommendations.

12 And the other issue is of course should
13 the full Committee, should we be recommending a letter
14 on this? Is it really ready for a letter, or just
15 strictly a briefing?

16 MEMBER CORRADINI: What would the letter
17 say if you were to write on?

18 CHAIRPERSON ARMIJO: Well, that's my
19 point. That's why I want to get --

20 MEMBER CORRADINI: I'm trying to
21 understand what -- you're kind of in midstream, aren't
22 you?

23 CHAIRPERSON ARMIJO: That's what I think,
24 but any comments? You know, if there was something
25 that the members -- and that still could come out of

NEAL R. GROSS

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

1 the full Committee, that members felt right now that
2 there's a real problem here and we want that to be
3 documented in a letter.

4 MR. BROWN: Paul just wanted to make --

5 CHAIRPERSON ARMIJO: Yes, Paul?

6 MR. CLIFFORD: Paul Clifford. I guess
7 we're seeing that, you know, towards the end of the
8 year we're going to be presenting the entire rule
9 package, okay, completely. And we could come back and
10 make a summary again of what the reg guides are. And
11 at that point we're looking for a letter for the ACRS
12 to say, yes, go forward with this rulemaking. Go out
13 for public comment with it. I'm not sure a letter --
14 I mean, you guys obviously have the ability to do what
15 you want, but I'm not sure a letter saying that it's
16 okay to seek public comment on a draft reg guide at
17 this point -- because we're not sure we're going to
18 send it out. We probably won't. So, maybe just aim
19 to write a letter at the end of the year on the
20 combined package; being the reg guide and the actual
21 rule package, as opposed to writing a letter now,
22 which -- it's just a thought.

23 CHAIRPERSON ARMIJO: Yes. Well, look, I'm
24 not anxious to write a letter unless the -- because I
25 think it's a work in progress, particularly the

NEAL R. GROSS

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

1 industry work. Then, you know, the staff's got a lot
2 of work to do. And it's really a technical briefing
3 and process briefing.

4 MEMBER SHACK: Well, I mean, big picture
5 I think they're following just sort of where we would
6 like to see it to go. I mean, at least at one time we
7 liked the performance-based rule with --

8 CHAIRPERSON ARMIJO: Well, I think we sort
9 of still do.

10 MEMBER SHACK: -- sort of, you know,
11 minimal criteria in it and, you know, put the details
12 in the regulatory guide for, you know, roughly the
13 reasons that Burt said.

14 CHAIRPERSON ARMIJO: Yes.

15 MEMBER SHACK: And that's done. You know,
16 we can properly argue over the details in the reg
17 guide and continue to argue over them for a long time.
18 But, I mean, big picture I think it's --

19 CHAIRPERSON ARMIJO: Yes.

20 MEMBER SHACK: And we seem to have
21 captured what are the important phenomenon we saw from
22 the research.

23 CHAIRPERSON ARMIJO: Well, I think as far
24 as -- Dennis, did you have anything you wanted to add?
25 Jack?

NEAL R. GROSS

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

1 MEMBER BLEY: No, you know, I appreciated
2 what we heard today, but I have no problems.

3 CHAIRPERSON ARMIJO: Yes.

4 MEMBER BLEY: I think we're on track here.

5 CHAIRPERSON ARMIJO: Well, you know, I
6 think, Paul, we can talk about the presentation,
7 trying to get it down to the two hours. I think I
8 would want to have the industry present maybe an
9 abridged version of your material. And we could limit
10 it to -- and actually Michelle's presentation was
11 pretty -- you know, moved right along. And we
12 wouldn't get into the details of the reg guides like
13 we did today, but highlight where the industry thinks
14 they have some issues, like the ID oxidation story and
15 what you're going to do to demonstrate that you've got
16 a case.

17 But so, I'm going to propose that it'll be
18 a briefing without a letter, but the full Committee
19 will decide what we actually do, as always.

20 Okay. No other -- is there any -- well,
21 I'm supposed to ask, first of all, is there anybody on
22 the bridge line, a member of the public who would like
23 to make some comments, and who is not on mute? If you
24 are, please introduce yourselves.

25 (No audible response.)

1 CHAIRPERSON ARMIJO: Okay. I don't --

2 PARTICIPANT: How about the audience?

3 MR. SCOTT: Do you want Argonne to run
4 some -- or NRC -- I'm being a little parochial because
5 I'm the manager of the Argonne Program, but if you
6 would like to see the NRC join this round robin, maybe
7 that's where your letter will help out by suggesting
8 that the ACRS believes it's -- all my friends are --

9 CHAIRPERSON ARMIJO: Well, I would like to
10 suggest that, but I don't represent the full
11 Committee. So, we'll talk about it. And a real short
12 -- maybe a real, real short letter saying, you know,
13 the round robin has a little problem might be in the
14 cards.

15 MR. CLEFTON: Mr. Chairman?

16 CHAIRPERSON ARMIJO: Very good.

17 MR. CLEFTON: Looking forward into the
18 23rd of June meeting that we have scheduled, Paul's
19 anticipating speaking details on 50.46(c). Do you
20 have expectations from the industry for comments on
21 that time, or discussions, or what type of coverage
22 would you prefer from the industry at all?

23 CHAIRPERSON ARMIJO: Well, you know, this
24 is -- these meetings are your opportunity to make your
25 points and --

NEAL R. GROSS

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

1 MR. CLEFTON: It's pre-decisional material
2 as well.

3 CHAIRPERSON ARMIJO: Yes, I know it's pre-
4 decisional and --

5 MR. CLEFTON: We don't want to --

6 CHAIRPERSON ARMIJO: -- you know, it's a
7 judgment call. I just got to leave it to you. I can
8 see your point.

9 MR. CLEFTON: We'll talk it up among
10 ourselves.

11 CHAIRPERSON ARMIJO: Yes.

12 MR. CLEFTON: We've got some points we've
13 seen. There's not that many specific changes, but
14 some directions.

15 And the other thing would be leading to
16 possible workshops, putting community resources
17 together in the room to share as we're processing the
18 rule and the three draft guides between now and
19 August, or in August, or in September, before it comes
20 to ACRS in December. Would the industry be willing to
21 contribute the resources we have --

22 CHAIRPERSON ARMIJO: Well, at some point
23 you're going to -- you know, this is going to get
24 solidified. And the more -- once it's out officially
25 for public comment and everything else, as soon as

NEAL R. GROSS

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

1 that's -- we've passed that point, then the industry
2 has to make a comment or hold your peace.

3 MR. CLEFTON: Well, we're looking at that
4 into 2012.

5 CHAIRPERSON ARMIJO: Yes.

6 MR. CLEFTON: So, we got people anxious to
7 go. We got thoroughbreds in the race.

8 CHAIRPERSON ARMIJO: Yes, champing at
9 the --

10 MR. CLEFTON: They're ready to respond
11 now, not wait for a year-plus. So, if we can help
12 contribute now and work with Paul, continue the
13 interface we've had, we'd would like to encourage
14 that.

15 CHAIRPERSON ARMIJO: Yes, well, if there's
16 issues on where this ship is going, the earlier that
17 you nudge it, the easier it is to get going in the
18 direction you want, rather than waiting for the last
19 minute and say, hey, we don't like the way this has
20 turned out.

21 MR. CLEFTON: That's right.

22 CHAIRPERSON ARMIJO: Go back. Not a good
23 idea.

24 So, okay. With that, no other comments?

25 (No audible response.)

1 CHAIRPERSON ARMIJO: With that, I'd like
2 to thank the staff and EPRI for very good
3 presentations, very helpful. And with that, we can
4 all go home ahead of schedule.

5 (Whereupon, the meeting was adjourned at
6 3:10 p.m.)

7

8

9

10

11

12

13

14

15

16

17

18

19

20

21

22

23

24

25



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 (2200°F, 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 addressed.
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 future ACRS briefings



ACRS Interactions – Future

ACRS Subcommittee:

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

Expected Outcome of Today's Briefing:

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.



U.S. NRC

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 2200° F limit specified in (d)(1)(i), then the lower temperature shall be used in place of the 2200° 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



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"



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 2200° F limit specified in (d)(1)(i), then the lower temperature shall be used in place of the 2200° 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



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

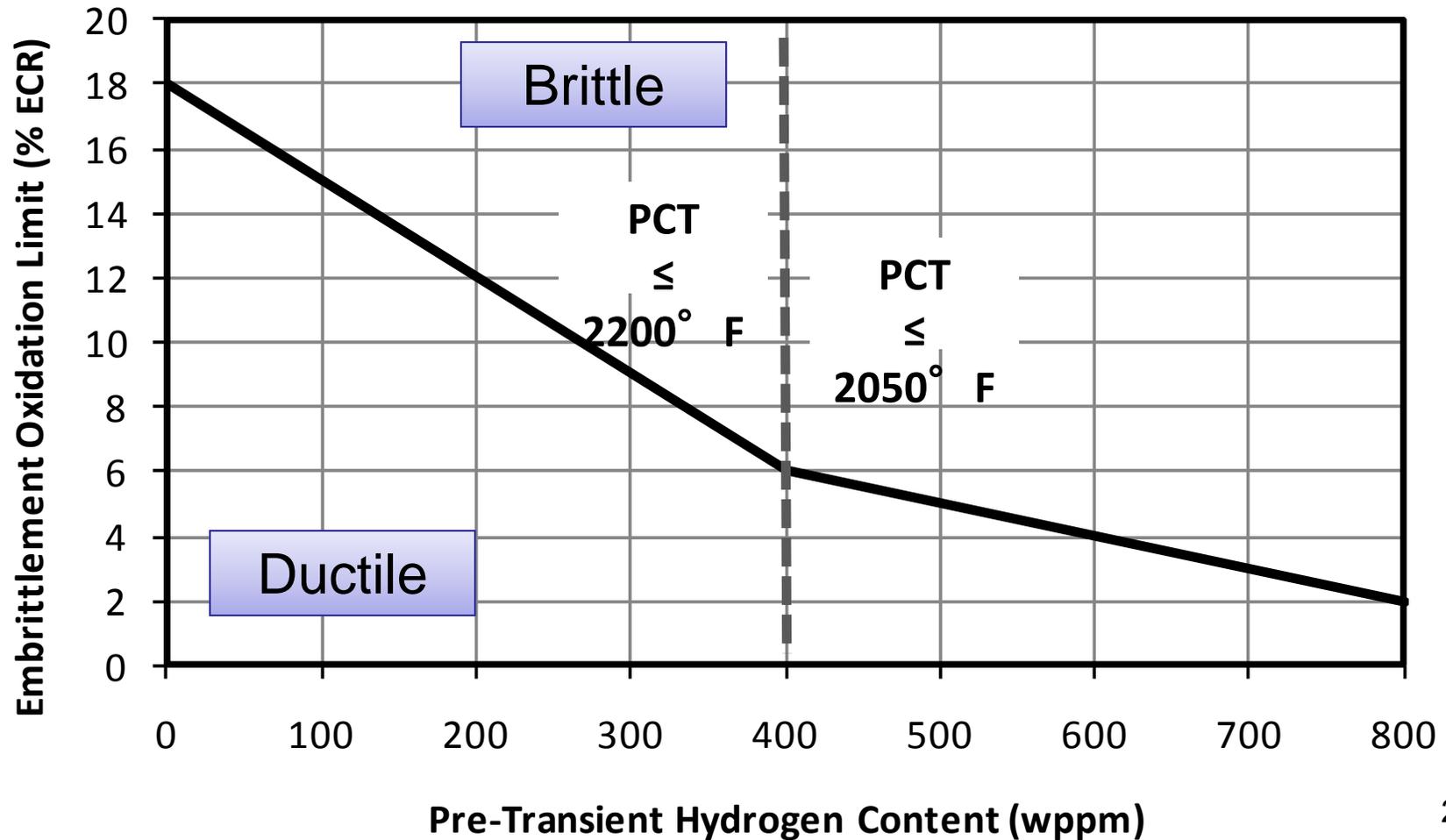
An acceptable analytical limit for time at elevated temperature for the materials tested in NRC's LOCA research program:

- (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

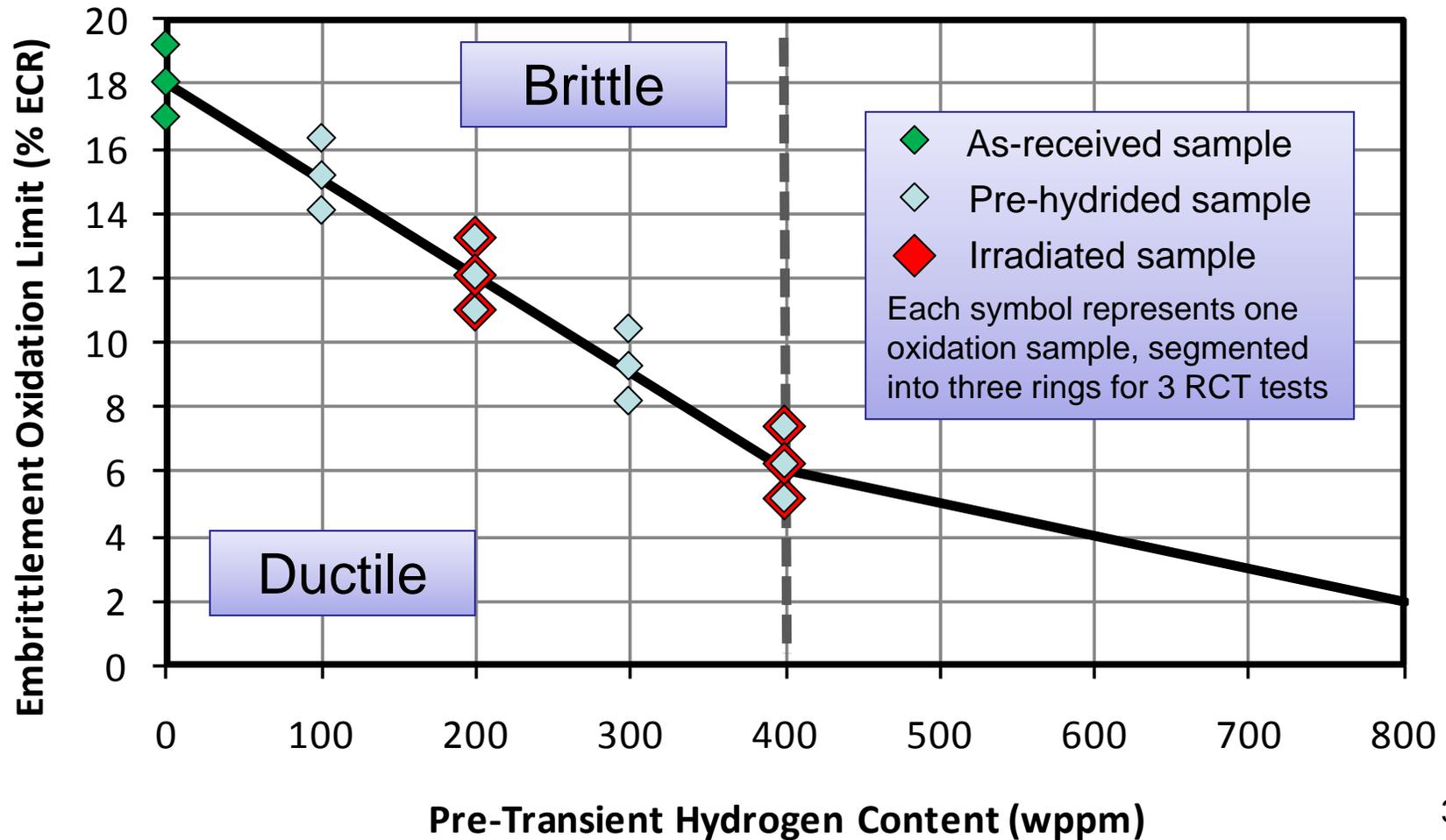
Demonstrating comparable performance for new cladding alloys:

- (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

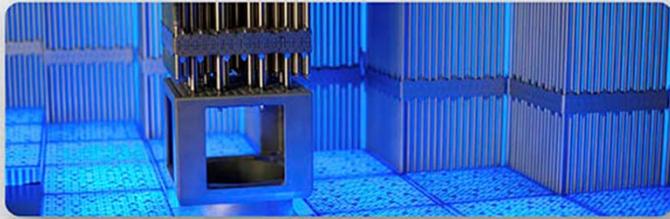
Other topics covered:

(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



EPRI

ELECTRIC POWER
RESEARCH INSTITUTE

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

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



High Temperature Oxidation Preliminary Results

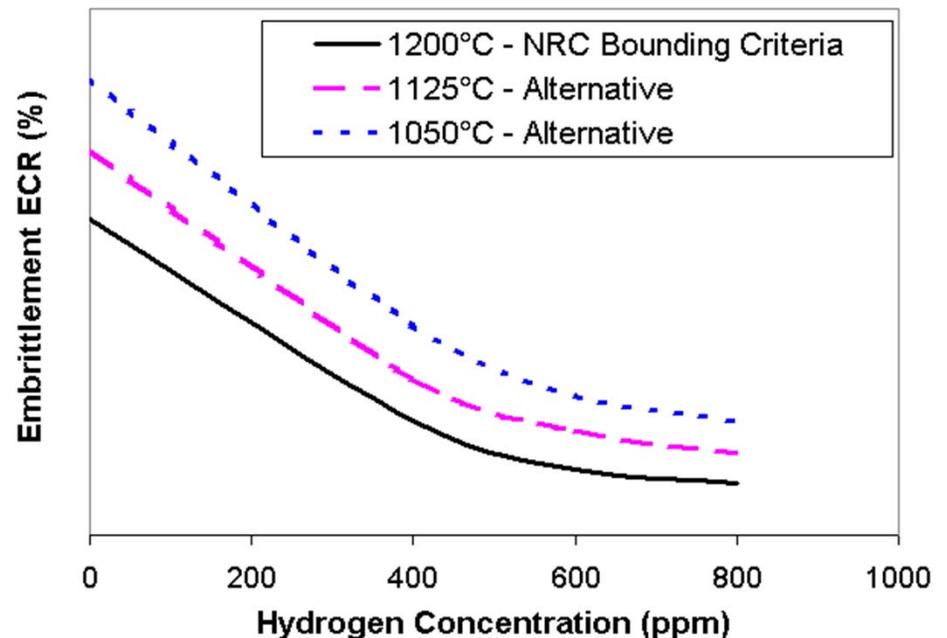
High Temperature Oxidation

- 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

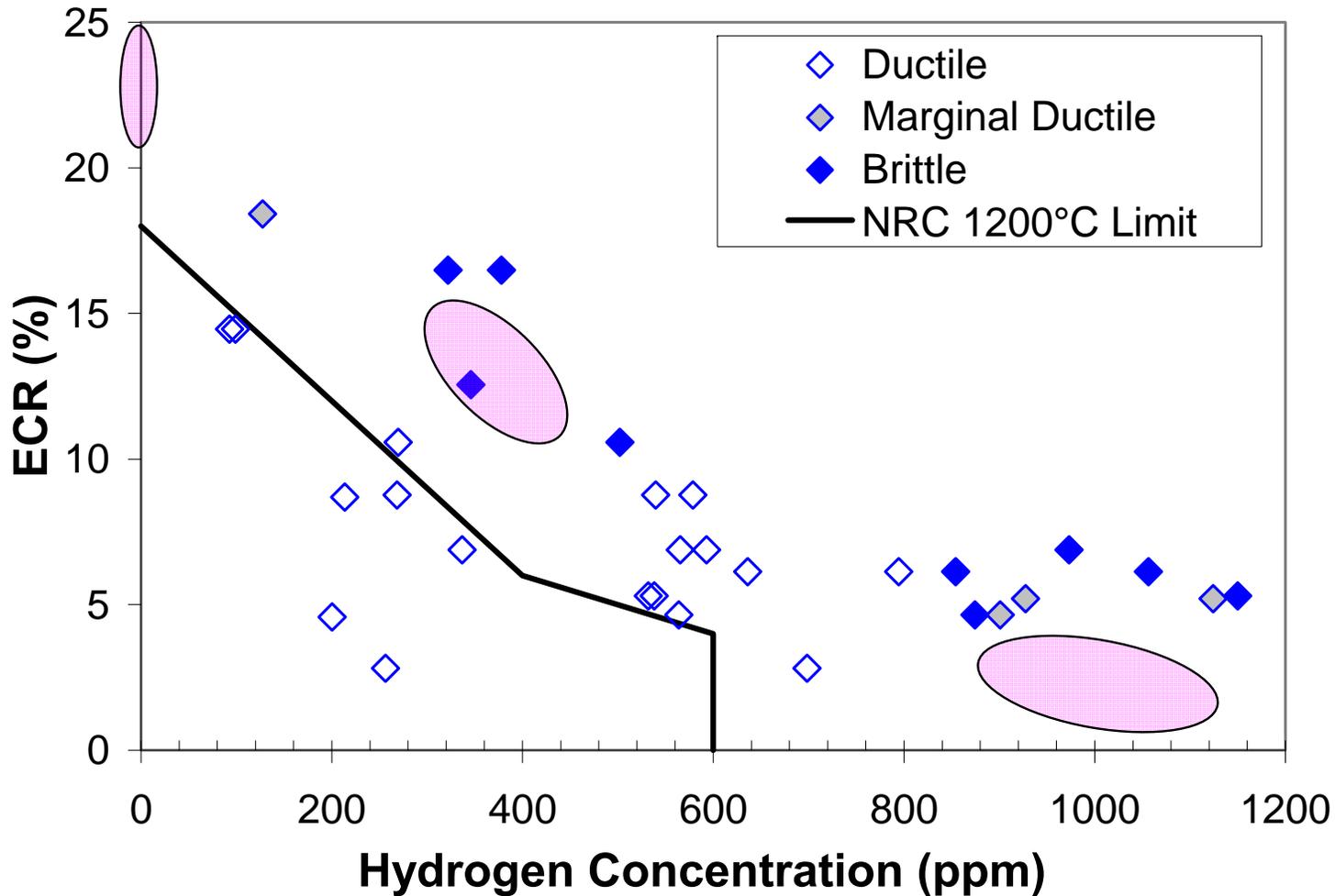


High Temperature Oxidation Test Details

- 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

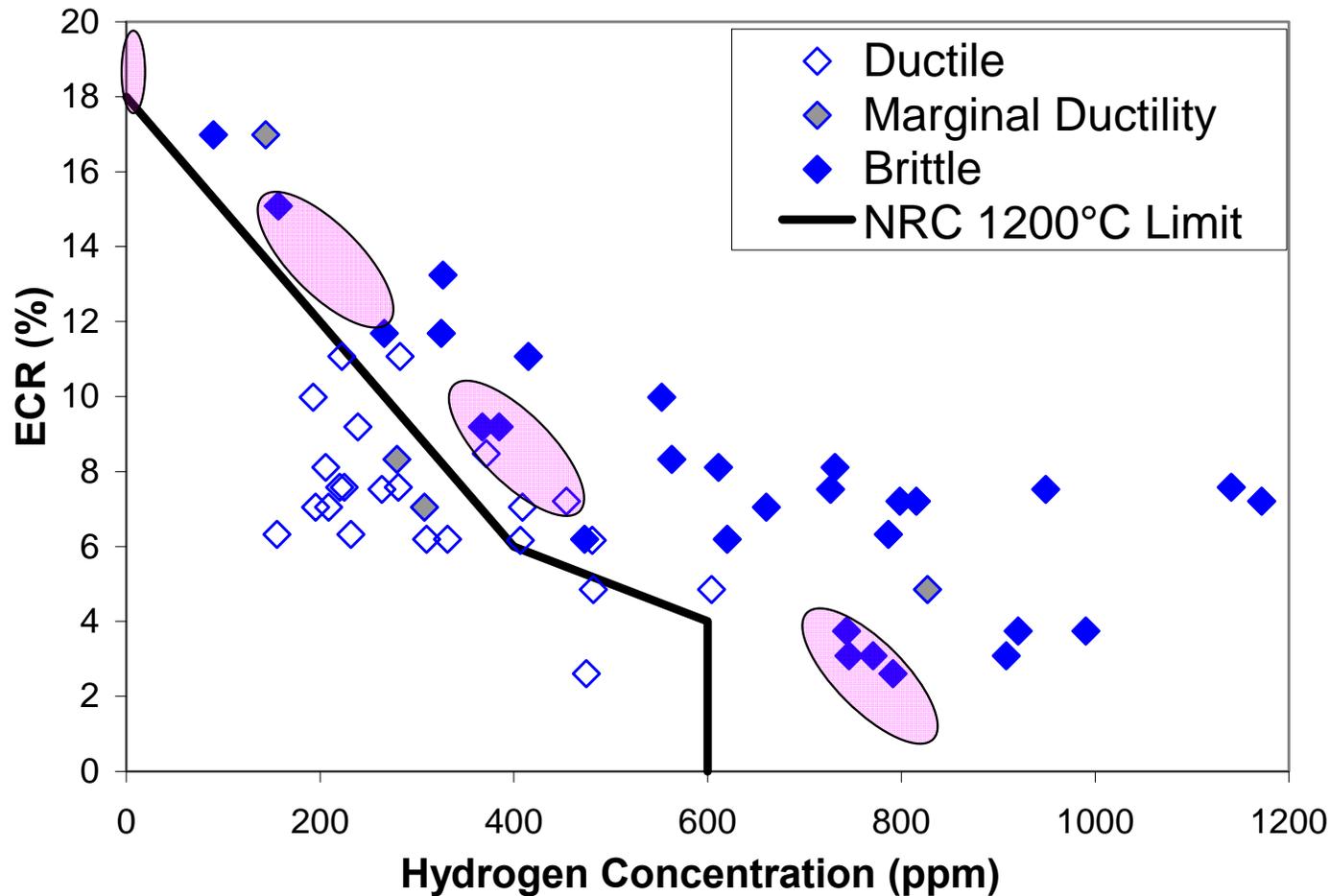
High Temperature Oxidation Preliminary 1050°C Test results

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



High Temperature Oxidation Preliminary 1125°C Test results

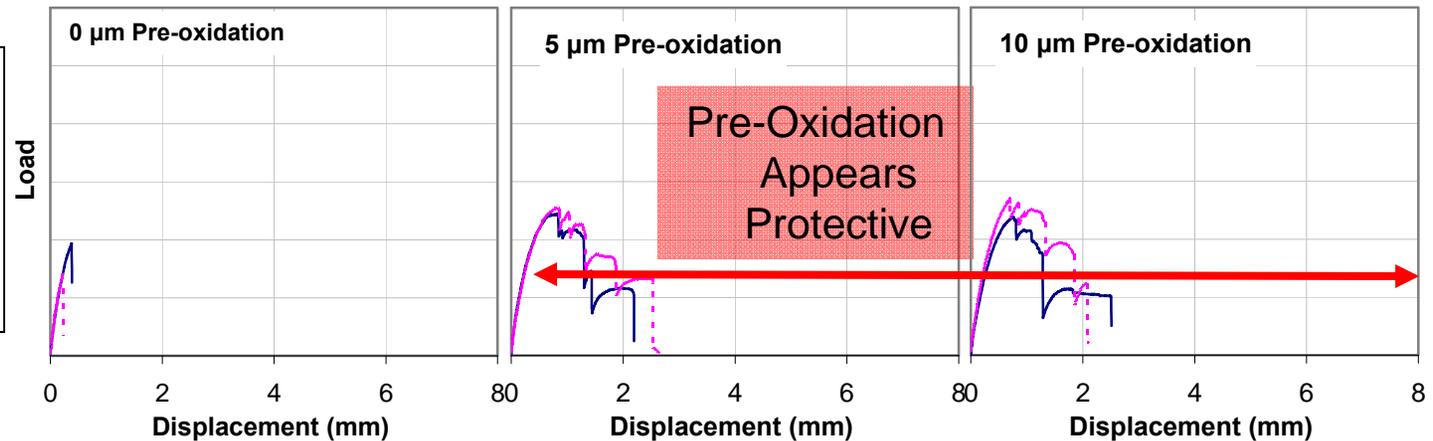
- More data to be generated (Summer 2011)



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



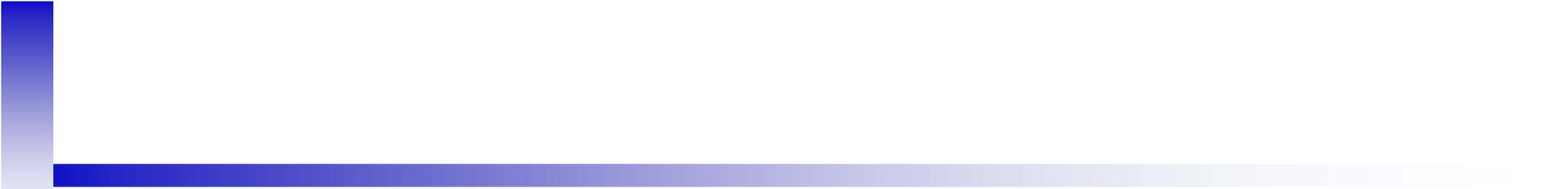
- Impact of pre-existing oxide to be evaluated
- More testing in progress

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

Recommendations

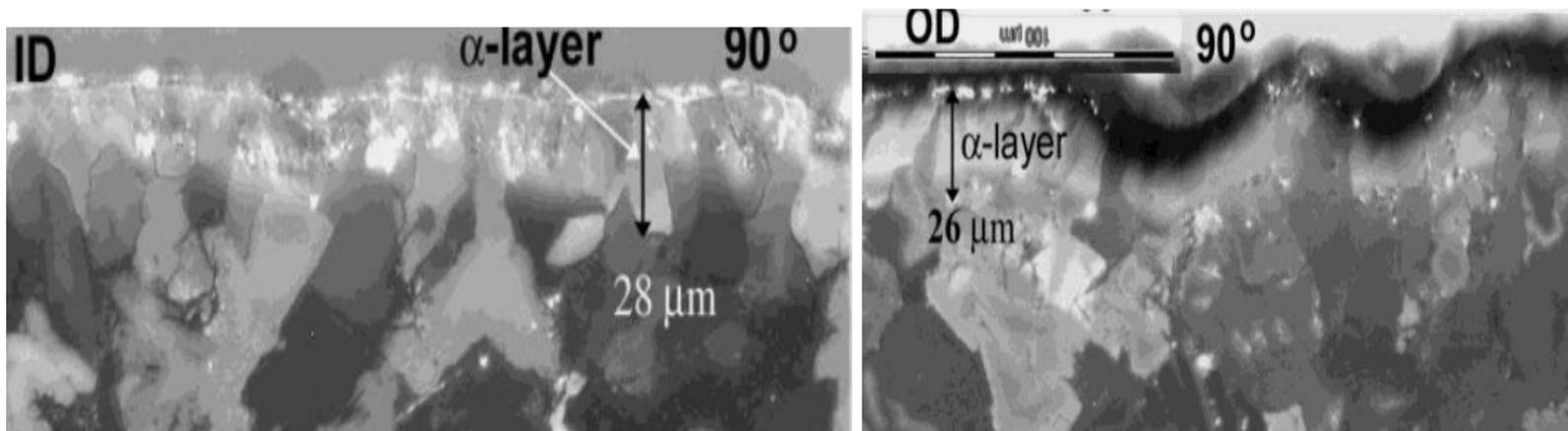
- Test data indicates alternative acceptance criteria can be justified
 - Family of embrittlement curves at different PCTs
 - Interpolation of acceptance criteria between PCTs and application of pin specific PCT
 - Use of model predictions should the phenomenon be successfully modeled



ID Oxygen Pickup

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

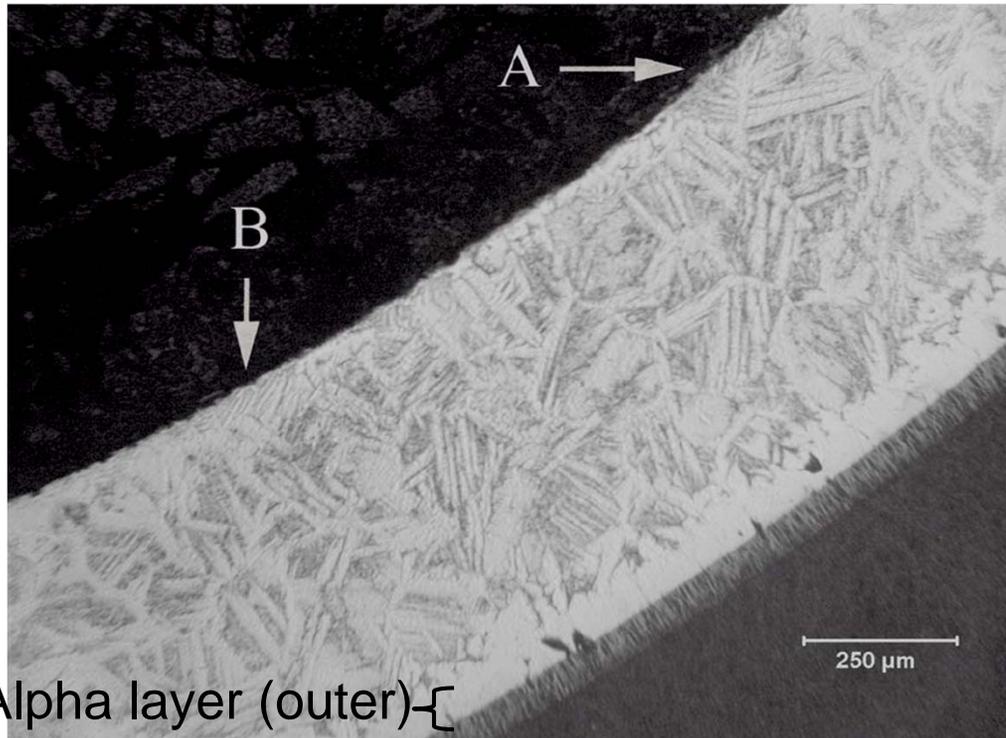
Oxygen for the alpha layer could have come from pre-transient oxide layer rather than bonded fuel

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

Experimental Evidence – Limerick Fuel

- No evidence of more alpha layer near bonded fuel



Limerick fuel at 57-60 GWd/MTu

NUREG/CR6967 Interpretation

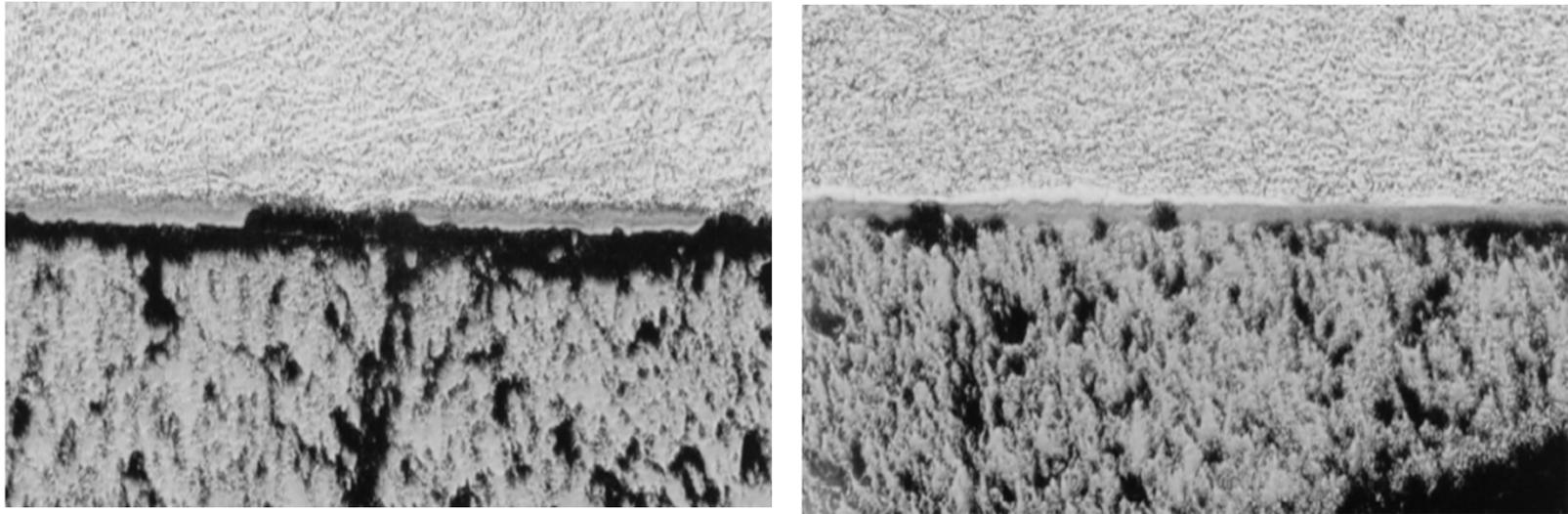
(A): This inner-surface region does not have an alpha layer even though in close proximity to fuel material. More typical of what is observed for most of the inner surface at this axial location.

(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

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

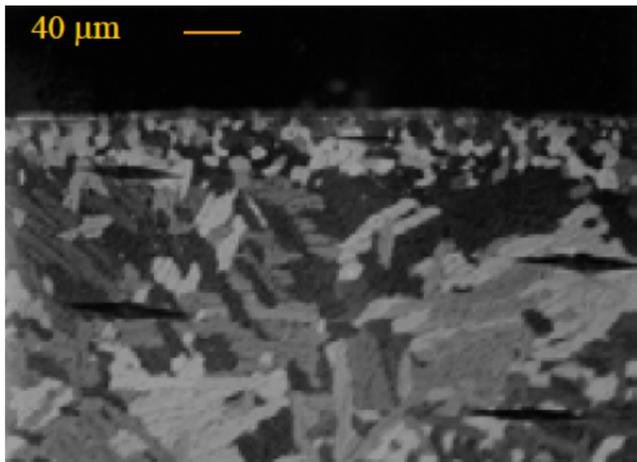
Absence of significant observed fuel-clad reaction in both Halden and ANL tests suggests oxygen transfer from bonded fuel is limited, and may be limited to the pre-transient oxide

Fuel-Clad Interaction Test

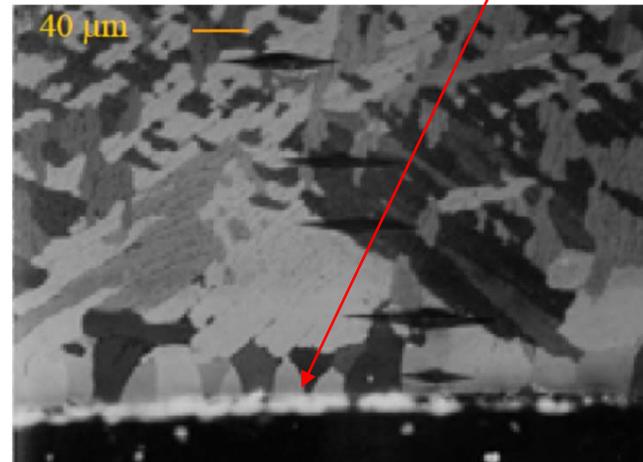
- Goals
 - Verify Hoffman's observations
 - Evaluate the extent of reaction with contact pressure and pre-oxidation
- Fuel-clad reaction test conditions
 - Short rodlets, approximately 6.5" in length, sealed with and without non-irradiated natural uranium pellets in He
 - Fresh and pre-oxidized cladding
 - 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

Fuel-Clad Interaction Test

- Halden IFA-650.5 test temperature profile approximately simulated
 - Pre-oxidized clad to $\sim 7 \mu\text{m}$ at 650°C , no fuel pellet
 - Oxygen stabilized alpha similar to Halden test observed



Outer Diameter

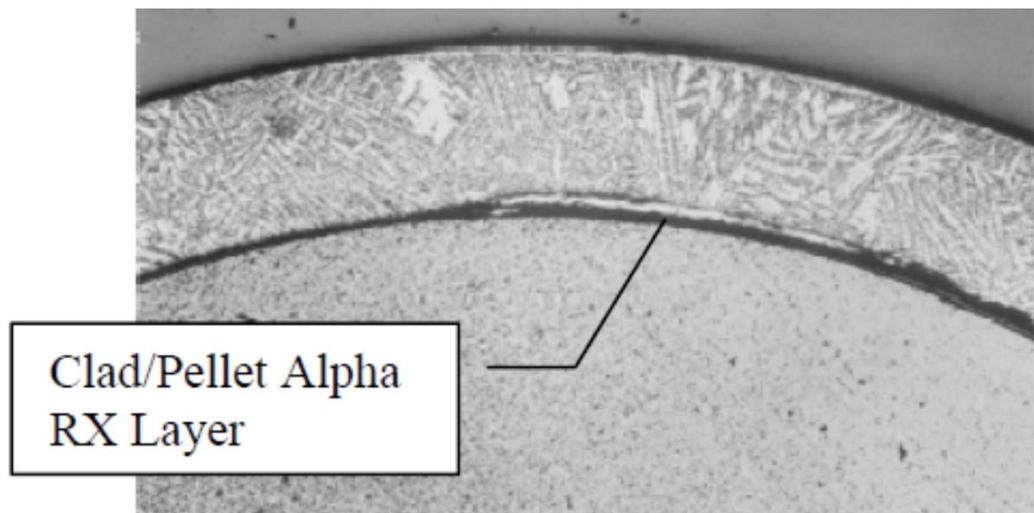


Inner Diameter

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

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



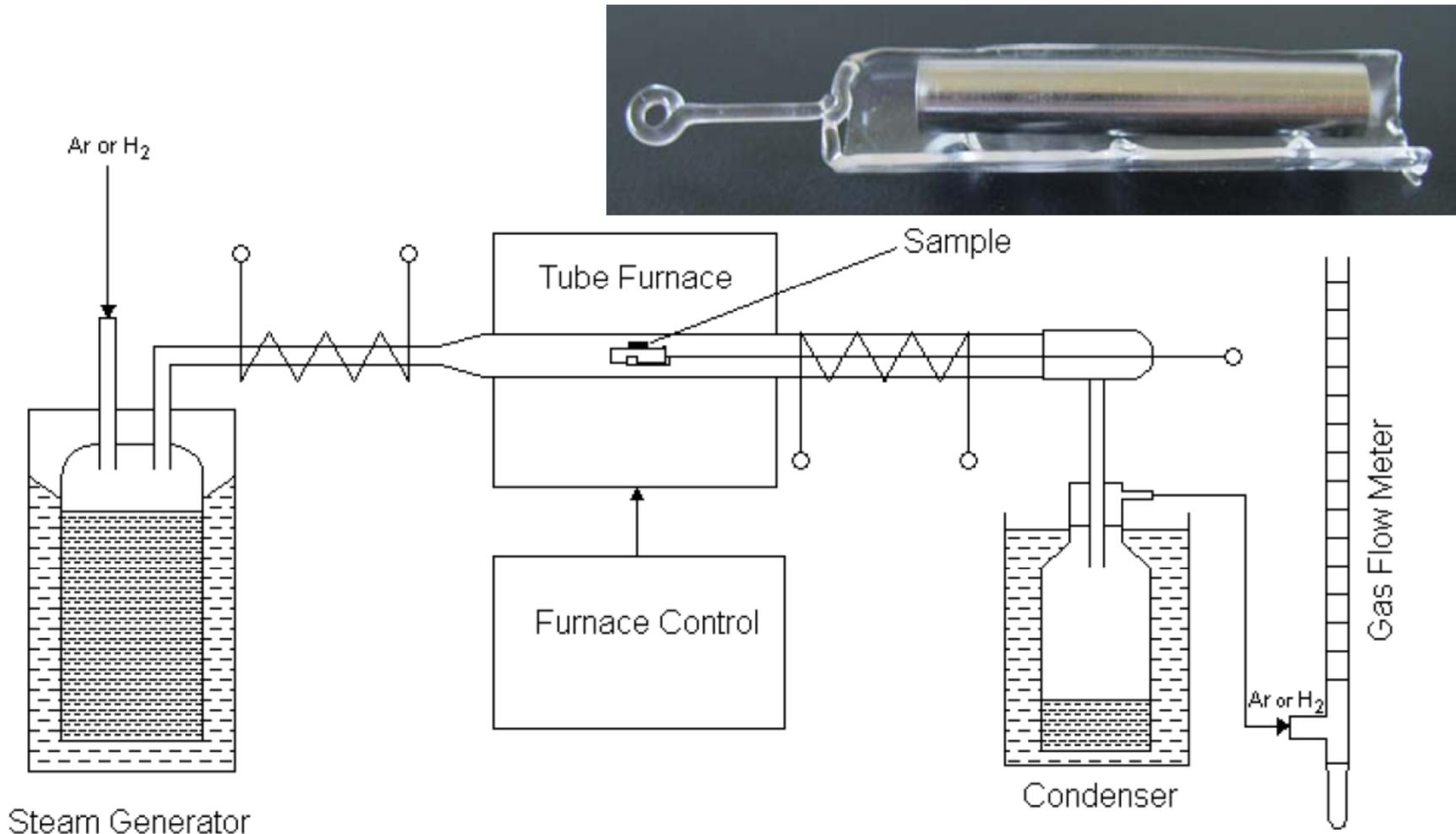
Impact of Limited ID Oxygen Source on PQD

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

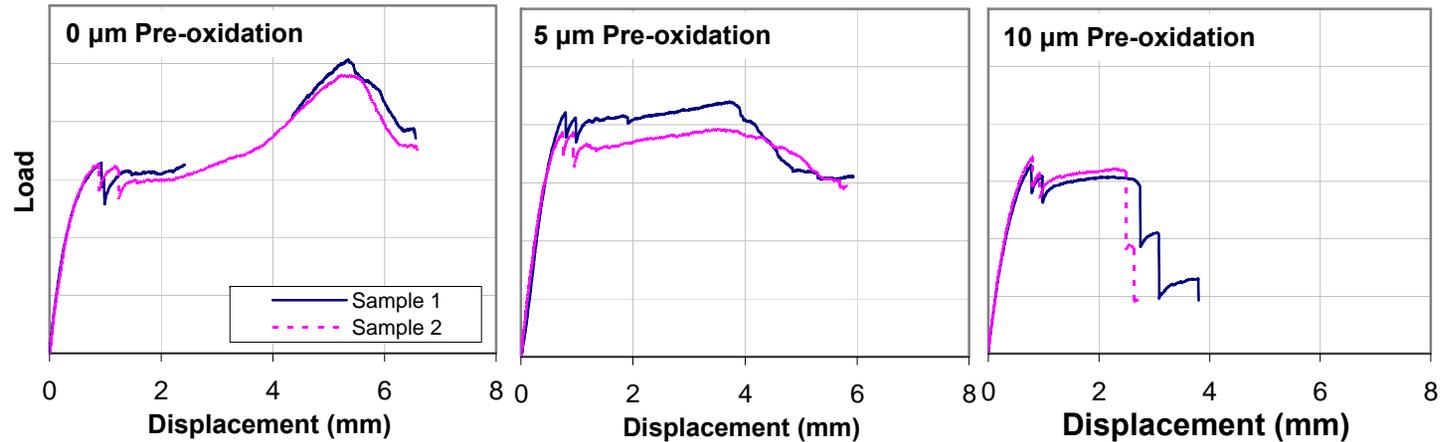
Impact of Limited Oxygen Source on PQD Test Setup

- Three zone horizontal furnace

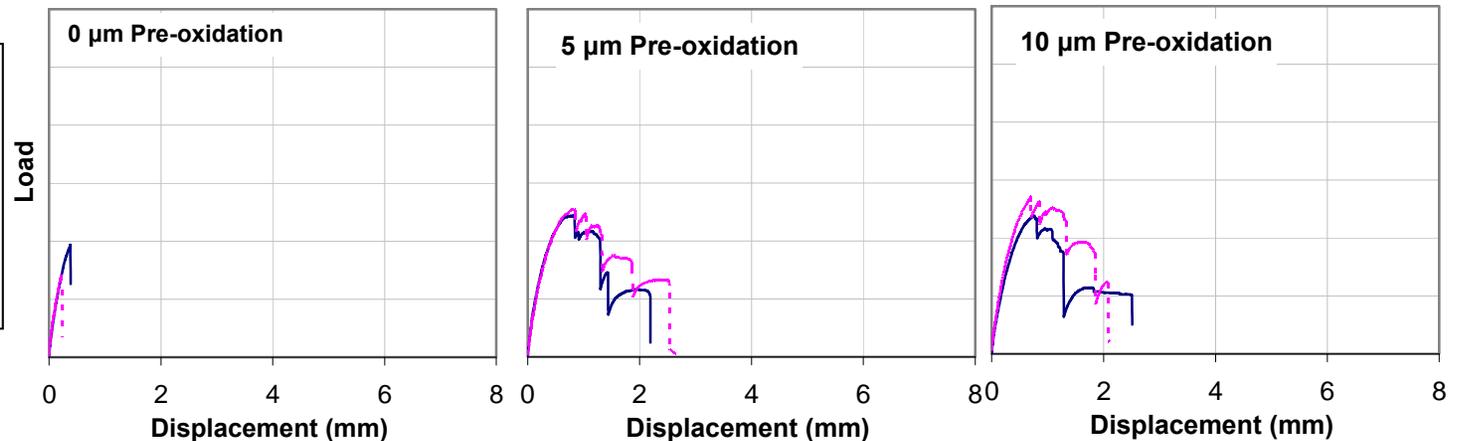


Impact of Limited Oxygen Source on PQD Results – 1200°C

- Sealed, one-sided
- 460s exposure



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



Reduced impact on PQD from limited ID oxygen source Demonstrated

Quantification of Limited Impact on PQD Test Plan

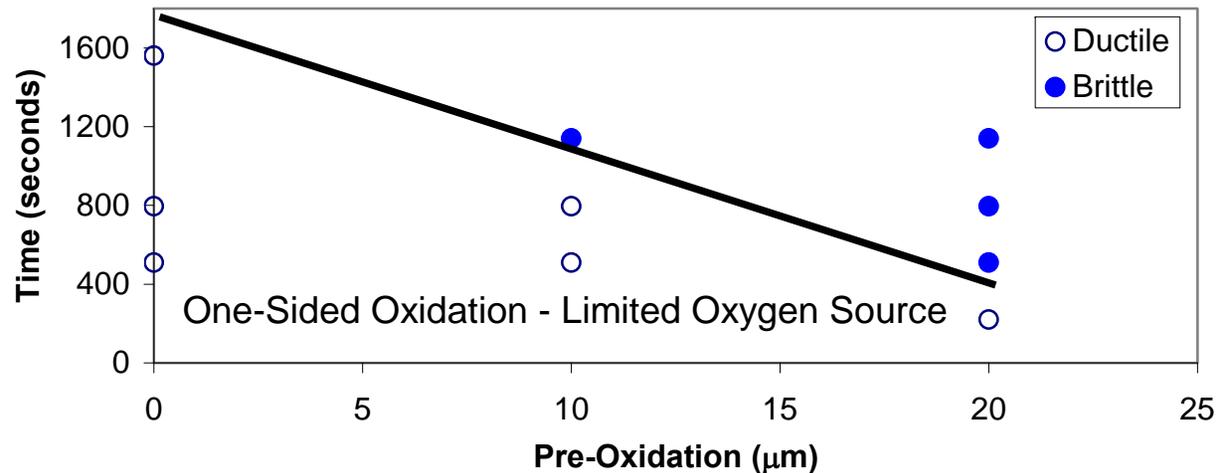
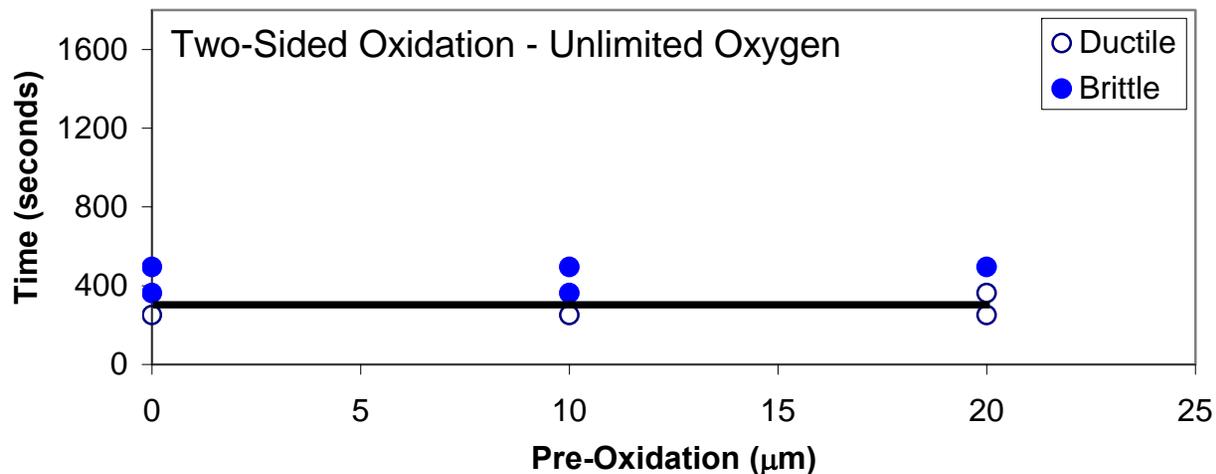
- Quantify the impact of a pre-transient oxide on PQD (Zircaloy-4)
 - Unrestricted double sided oxidation
 - Unrestricted OD/restricted ID oxidation
 - Pre-oxidized sealed capsules
 - Test parameters
 - 10 and 20 μm pre-oxidation at 800°C
 - 1200°C oxidation temperature with limited number at 1100°C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

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

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 unrestricted two-sided oxidation
 - Reduction in ductility loss is significantly less compared to unrestricted two-sided oxidation up to 20 μm of pre-oxidation
- Pre-oxidation slightly improves clad PQD performance

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



LOCA Round Robin

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

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

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

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+/-0.005 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

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

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

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

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



Together...Shaping the Future of Electricity

ROUTING AND TRANSMITTAL SLIP			4/15/2011		
TO:	NAME	ACTION REQUESTED	COMMENTS	INITIALS	DATE
	Jennifer Borges	Concur	via e-mail	JLB	4/1/11
PM	Angelisa Hicks	Concur		ALH	4/7/11
BC	Thomas Boyce	Concur/SUNSI Review		TB	4/7/11
DD	Michael Case	Concur/Sign Memo		MC	4/14/11
OFFICE	RES	<input type="checkbox"/>			
DD	N/A	Concur			
OFFICE	FSME	<input type="checkbox"/>			
LIAISON	Liaison	Distribution			
DD	Division Director	Concur			
OFFICE	NMSS	<input type="checkbox"/>			
LIAISON	Liaison	Distribution			
DD	N/A	Concur			
OFFICE	NRO	<input checked="" type="checkbox"/>			
LIAISON	Tanya Hood, DNRL	Distribution			
BC	Charles Ader, DSRA	Concur			
OFFICE	NRR	<input checked="" type="checkbox"/>			
LIAISON	Holly Cruz, DPR	Distribution			
DD	William Ruland, DSS	Concur			
OFFICE	NSIR	<input type="checkbox"/>			
LIAISON	Liaison	Distribution			
DD	Division Director	Concur			
OFFICE	OGC	<input checked="" type="checkbox"/>			
AGC	Bradley Jones, OGC	No Legal Objection (NLO)			

SUBJECT:	Request for Concurrence on Draft Regulatory Guide (DG) -1263, "Establishing Analytical Limits for Zirconium Based Alloy Cladding."		
REMARKS:	Proposed New Regulatory Guide.		
FROM:	Angelisa Hicks	Room No.:	2C27
		Phone No.:	301-251-7448

April 14, 2011

MEMORANDUM TO: William H. Ruland, Director
Division of Safety Systems
Office of Nuclear Reactor Regulation

Charles E. Ader, Director
Division of Safety Systems and Risk Assessment
Office of New Reactors

Bradley W. Jones, Assistant General Counsel
for Reactors and Materials Rulemaking
Office of the General Counsel

FROM: Michael J. Case, Director */RA/*
Division of Engineering
Office of Nuclear Regulatory Research

SUBJECT: REQUEST FOR CONCURRENCE ON DRAFT REGULATORY GUIDE,
DG-1263, "ESTABLISHING ANALYTICAL LIMITS FOR ZIRCONIUM
BASED ALLOY CLADDING."

I am forwarding for your concurrence Draft Guide (DG) DG-1263, "Establishing Analytical Limits for Zirconium Based Alloy Cladding." The enclosed DG-1263 is a proposed new regulatory guide. This draft has been developed by the Office of Nuclear Regulatory Research (RES) with close cooperation and coordination with the following organizations and individuals:

- Office of New Reactors: Paul Clifford
- Office of Nuclear Reactor Regulation: Ralph Landry

The agency will publish a notice in the *Federal Register* concerning the issuance and availability of DG-1263. The public comment period for this guide will be 60 days from the date of issuance. If there are only editorial changes following internal concurrence and resolution of public comments, your concurrence will not be needed for publication of the final regulatory guide.

CONTACT: Michelle Flanagan, RES/DE
(301) 251-7547

Angelisa Hicks, RES/DE
(301) 251-7448

W. Ruland, et al.

- 2 -

Please contact either Michelle Flanagan or Angelisa Hicks as early as possible during the concurrence review period to resolve any questions or issues in a timely manner.

Enclosures:

1. DG-1263
2. Regulatory Analysis

W. Ruland, et al.

- 2 -

Please contact either Michelle Flanagan or Angelisa Hicks as early as possible during the concurrence review period to resolve any questions or issues in a timely manner.

Enclosures:

1. DG-1263
2. Regulatory Analysis

DISTRIBUTION: DE r/f

ADAMS Accession No. ML110871360

OFFICE	RES/DE	RES/DE	RES/DE	SUNSI Review	RES/DE	NRO
NAME	J. Borges via email	A. Hicks	T. Boyce	T. Boyce	M. Case	C. Ader
DATE	4/1/11	4/7/11	4/7/11	4/7/11	4/14/11	/ /11
OFFICE	NRR	OGC	QTE			
NAME	W. Ruland	B. Jones	Via e-mail			
DATE	/ /11	/ /11	2/14/11			

OFFICIAL RECORD COPY



DRAFT REGULATORY GUIDE

Contact: M. Flanagan
(301) 251-7547

DRAFT REGULATORY GUIDE DG-1263

(Proposed New Regulatory Guide 1.224)

ESTABLISHING ANALYTICAL LIMITS FOR ZIRCONIUM-BASED ALLOY CLADDING

A. INTRODUCTION

Title 10, Section 50.46(c), of the *Code of Federal Regulations* (10 CFR 50.46(c)) (Ref. 1), calls for the establishment of analytical limits on peak cladding temperature and time at elevated temperature that correspond to the measured ductile-to-brittle transition for the zirconium-alloy cladding material. This guide defines an acceptable analytical limit on peak cladding temperature and time at elevated temperature for the zirconium-alloy cladding materials tested in the U.S. Nuclear Regulatory Commission's (NRC's) loss-of-coolant accident (LOCA) research program. This analytical limit is based on the data obtained in the NRC's LOCA research program.

For zirconium-alloy cladding materials not tested in the NRC's LOCA research program, a demonstration of comparable performance with the database established in the NRC's LOCA research program would be necessary in order to establish the analytical limit provided in this guide as the limit for that alloy. Draft Regulatory Guide (DG)-1262, "Testing for Postquench Ductility" (Ref. 2), provides an experimental technique acceptable to the NRC for measuring the ductile-to-brittle transition for zirconium-alloy cladding material through ring compression tests (RCT). This guide describes a method to demonstrate comparable performance with the established database in order to establish the analytical limit provided in this guide for a particular cladding alloy not tested in the NRC's LOCA research program.

The database established in the NRC's LOCA research program and the resulting analytical limit described in this regulatory guide are intended to provide a best-estimate limit for the ductile-to-brittle transition for zirconium alloys. The analytical limit described in this guide is applicable to Zircaloy-2 (Zry-2), Zircaloy-4 (Zry-4), ZIRLO™, and M5. In some instances, a zirconium-alloy cladding material may experience the transition from ductile to brittle behavior at a higher level of oxidation than the established database. This regulatory guide also describes a methodology to establish a zirconium-alloy-specific limit other than the limit provided in this guide.

This regulatory guide is being issued in draft form to involve the public in the early stages of the development of a regulatory position in this area. It has not received final staff review or approval and does not represent an official NRC final staff position. Public comments are being solicited on this draft guide (including any implementation schedule) and its associated regulatory analysis or value/impact statement. Comments should be accompanied by appropriate supporting data. Written comments may be submitted to the Rules, Announcements, and Directives Branch, Office of Administration, U.S. Nuclear Regulatory Commission, Washington, DC 20555-0001; submitted through the NRC's interactive rulemaking Web page at <http://www.nrc.gov>; or faxed to (301) 492-3446. Copies of comments received may be examined at the NRC's Public Document Room, 11555 Rockville Pike, Rockville, MD. Comments will be most helpful if received by **[insert date - 60 days from issuance]**.

Electronic copies of this draft regulatory guide are available through the NRC's interactive rulemaking Web page (see above); the NRC's public Web site under Draft Regulatory Guides in the Regulatory Guides document collection of the NRC's Electronic Reading Room at <http://www.nrc.gov/reading-rm/doc-collections/>; and the NRC's Agencywide Documents Access and Management System (ADAMS) at <http://www.nrc.gov/reading-rm/adams.html>, under Accession No. ML110871607. The regulatory analysis may be found in ADAMS under Accession No. ML110910441.

The database established in the NRC’s LOCA research program and the resulting analytical limit described in this regulatory guide are intended to bound emergency core cooling system (ECCS) performance. In the test program, experiments were conducted at maximum oxidation temperatures. Some ECCSs may perform such that the maximum oxidation temperature is significantly below 1,204 degrees Celsius (°C) (2,200 degrees Fahrenheit (°F)). Oxidation at lower temperatures has been shown to increase the allowable calculated oxidation before embrittlement. Therefore, conducting tests at lower peak temperatures may provide additional margin for some zirconium-alloy cladding materials. This regulatory guide describes a methodology to establish analytical limits at peak oxidation temperatures less than 1,204 °C (2,200 °F).

In 10 CFR 50.46(c), the NRC calls for measurement of the onset of breakaway oxidation for a zirconium-alloy cladding material based on an acceptable experimental technique, evaluation of the measurement relative to ECCS performance, and annual retesting and reporting of values measured (Ref. 1). DG-1261, “Conducting Periodic Testing for Breakaway Oxidation Behavior” (Ref. 3), provides an experimental technique acceptable to the NRC for measuring the onset of breakaway oxidation for zirconium-alloy cladding materials. DG-1261 also describes an acceptable method of meeting the annual retesting and reporting requirements in 10 CFR 50.46(c). This guide describes a methodology for establishing a specified and acceptable limit for the total accumulated time that the cladding may remain above a temperature at which the zirconium alloy has been shown to be susceptible to breakaway oxidation.

The NRC issues regulatory guides to describe to the public methods that the staff considers acceptable for use in implementing specific parts of the agency’s regulations, to explain techniques that the staff uses in evaluating specific problems or postulated accidents, and to provide guidance to applicants. Regulatory guides are not substitutes for regulations and compliance with them is not required.

This regulatory guide contains information collection requirements covered by 10 CFR Part 50 that the Office of Management and Budget (OMB) approved under OMB control number 3150-0011. The NRC may neither conduct nor sponsor, and a person is not required to respond to, an information collection request or requirement unless the requesting document displays a currently valid OMB control number. The NRC has determined that this regulatory guide is not a major rule as designated by the Congressional Review Act and has verified this determination with OMB.

	<u>Page</u>
A. INTRODUCTION	1
B. DISCUSSION	4
Background	4
Summary of the NRC’s LOCA Research Program	4
Existing Embrittlement Database	4
An Acceptable Analytical Limit on Peak Cladding Temperature and Time at Elevated Temperature	6
Methodology for Demonstrating Consistency with the Existing Database for New Cladding Alloys	6
Methodology for Establishing a Zirconium-Alloy-Specific Limit	8
Methodology for Establishing Analytical Limits at Peak Oxidation Temperatures Less than 1,204 °C (2,200 °F)	9
Methodology for Establishing Analytical Limits for Breakaway Oxidation	11
Applying Analytical Limits	12
Qualification of Hydrogen Pickup Models	12
Accounting for Uncertainty and Variability in Hydrogen Content	12

Postquench Ductility Analytical Limits	13
Application in the Rupture Region	13
Accounting for Double-Sided Oxidation Due to the Fuel-Cladding Bond Layer	13
Breakaway Oxidation Analytical Limits	14
C. REGULATORY POSITION.....	15
D. IMPLEMENTATION	18
GLOSSARY	19
REFERENCES	20
APPENDIX A: Relationship between Offset Strain and Permanent Strain.....	A-1
APPENDIX B: Overview of Acceptable Test Matrices	B-1

B. DISCUSSION

Background

In 1996, the NRC initiated a fuel-cladding research program intended to investigate the behavior of high-exposure fuel cladding under accident conditions. This program included an extensive LOCA research and testing program at Argonne National Laboratory (ANL), as well as jointly funded programs at the Kurchatov Institute (Ref. 4) and the Halden Reactor Project (Ref. 5), to develop the body of technical information needed to evaluate LOCA regulations for high-exposure fuel. The research findings were summarized in Research Information Letter 0801, “Technical Basis for Revision of Embrittlement Criteria in 10 CFR 50.46,” dated May 30, 2008 (Ref. 6). Most of the detailed experimental results from the program at ANL appear in NUREG/CR-6967, “Cladding Embrittlement during Postulated Loss-of-Coolant Accidents,” issued July 2008 (Ref. 7).

The research results revealed that hydrogen, which is absorbed into the cladding during the burnup-related corrosion process under normal operation, has a significant influence on embrittlement during a hypothetical LOCA. When that cladding is exposed to high-temperature LOCA conditions, the elevated hydrogen levels increase the solubility of oxygen in the beta phase and the rate of diffusion of oxygen into the beta phase. Thus, for cladding exposed to high-temperature LOCA conditions, embrittlement can occur for times corresponding to less than 17% oxidation in corroded cladding with significant hydrogen pickup. The research results also revealed that an embrittlement mechanism referred to as “breakaway oxidation” may occur during prolonged exposure to elevated cladding temperature during a LOCA.

Summary of the NRC’s LOCA Research Program

Existing Embrittlement Database

The majority of the cladding embrittlement experimental results from the NRC’s LOCA research program are summarized in NUREG/CR-6967 (Ref. 7). Since the publication of NUREG/CR-6967 in 2008, additional testing was conducted, focusing on cladding materials with hydrogen contents in the 200- to 350-weight parts per million (wppm) range (Refs. 8–9, 11). Additional oxidation and postquench ductility (PQD) tests were conducted with cladding samples sectioned from high-burnup ZIRLO™ fuel rods. The two defueled segments used to prepare samples had 25–30 micrometers corrosion-layer thickness and 300–340 wppm of hydrogen in the cladding metal before oxidation (Ref. 8). Also, the ductility data for an oxidation sample with ≈600-wppm hydrogen was reassessed (Ref. 9). In addition, since the publication of NUREG-6967, oxidation and PQD tests were conducted with prehydrided cladding samples containing 200–300 wppm of hydrogen (Ref. 9).

The tests that were conducted after the publication of NUREG/CR-6967 were combined with the data reported in NUREG/CR-6967 to generate a more robust and informed description of cladding embrittlement as a function of hydrogen content.

Before combining the new data with the data reported in NUREG/CR-6967, two refinements were made in data assessment. The first refinement was to establish and verify the following ductility criteria: average permanent strain $\geq 1.0\%$ or, if permanent strain cannot be measured, the average ring compression test (RCT) offset strain $\geq 1.41\% + 0.1082$ Cathcart-Pawel equivalent cladding reacted (CP-ECR) (Ref. 10). Rounded to the nearest tenth of a percent, this correlation represents the one-sigma upper bound of offset strain values from 65 RCT data sets with 1.0 to 2.3% permanent strain. (DG-1262 and Appendix A to this regulatory guide provide discussion and details about a ductility criterion based

on RCT offset strain.) The second refinement was to develop and use a new methodology to determine the pretest hydrogen content in the cladding metal for corroded cladding (Ref. 8).

Ductility and hydrogen data presented in NUREG/CR-6967 were reassessed to determine embrittlement oxidation levels versus hydrogen content for prehydrided and high-burnup cladding. When the tests that were conducted after the publication of NUREG/CR-6967 were combined with the data reported in NUREG/CR-6967, and the refinements in hydrogen content and the relationship between offset and permanent strain were made, the resulting behavior description of cladding embrittlement as a function of hydrogen content could be depicted as shown in Figure 1.

For modern as-fabricated cladding (Zry-2, Zry-4, ZIRLO™, and M5), embrittlement thresholds cluster at 19–20% CP-ECR, as compared to 16% CP-ECR for older Zry-4 cladding. However, this improvement is negated with hydrogen pickup as low as 100 wppm. A bilinear function for CP-ECR versus hydrogen content was used to fit the embrittlement data for prehydrided and high-burnup cladding. The embrittlement rate is steep for cladding with ≤ 400 -wppm hydrogen. For higher hydrogen content, the embrittlement rate is more gradual because embrittlement occurs during the heating ramp at $\leq 1,180$ °C ($\leq 2,156$ °F). High-burnup ZIRLO™ with 600-wppm hydrogen is highly ductile at 4% CP-ECR, but the peak oxidation temperature was only 1,130 °C (2,066 °F). Embrittlement is highly sensitive to both hydrogen content and peak oxidation temperature.

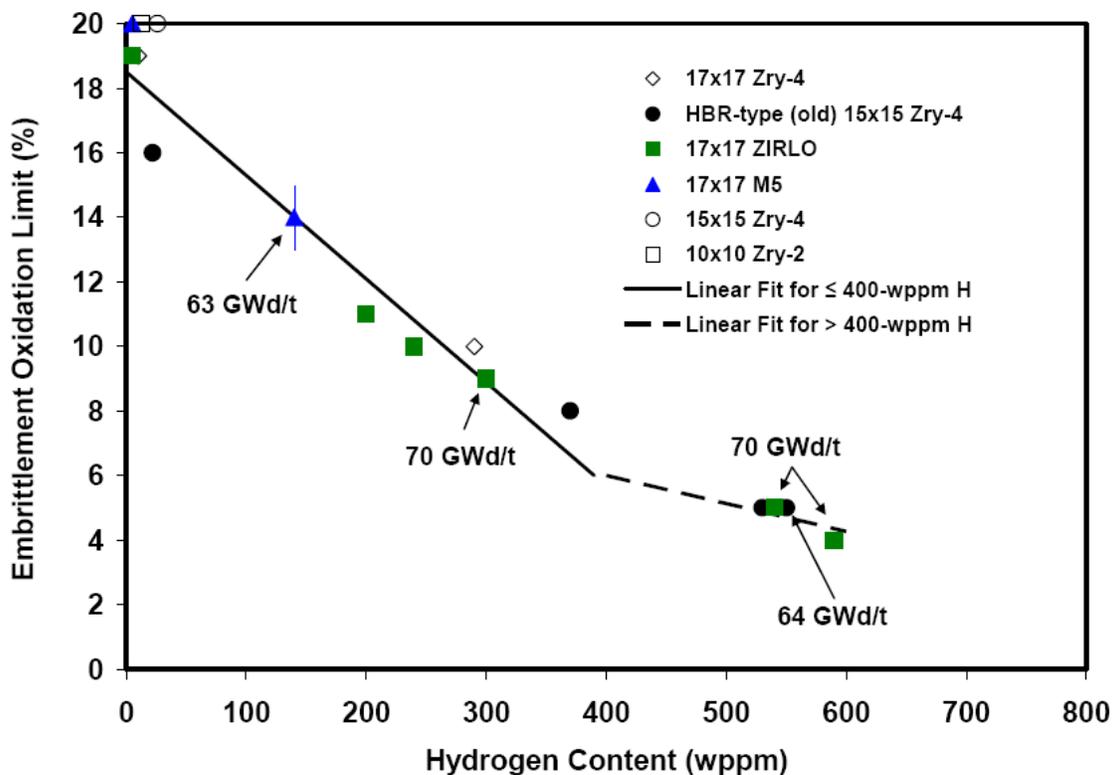


Figure 1. Ductile-to-brittle transition oxidation level (CP-ECR) as a function of pretest hydrogen content in cladding metal for as-fabricated, prehydrided, and high-burnup cladding materials. Samples were oxidized at $\leq 1,200$ °C ± 10 °C and quenched at 800 °C. For high-burnup cladding with about 550-wppm hydrogen, embrittlement occurred during the heating ramp at 1,160–1,180 °C peak oxidation temperatures (Ref. 8).

An Acceptable Analytical Limit on Peak Cladding Temperature and Time at Elevated Temperature

In 10 CFR 50.46(c), the NRC calls for the establishing of analytical limits on peak cladding temperature and time at elevated temperature, which correspond to the measured ductile-to-brittle transition for the zirconium-alloy cladding material (Ref. 1). The ductile-to-brittle threshold defined in Figure 2 is an acceptable analytical limit on time at elevated temperature as calculated in local oxidation calculations using the Cathcart-Pawel (CP) correlation (Ref. 11). This analytical limit is acceptable for the zirconium-alloy cladding materials tested in the NRC's LOCA research program, which were Zry-2, Zry-4, ZIRLO™, and M5. This analytical limit is based on the data obtained in the NRC's LOCA research program. Since PQD tests above 400-wppm hydrogen were conducted at a peak oxidation temperature below 1,204 °C (2,200 °F), a separate PCT analytical limit must be defined that is consistent with test temperature. A limit on peak cladding temperature of 1,204 °C (2,200 °F) below 400-wppm cladding hydrogen content and 1,121 °C (2,050 °F) at or above 400-wppm cladding hydrogen content is acceptable.

Demonstrating that ECCS performance is such that local oxidation and peak cladding temperature are calculated below the analytical limits defined in Figure 2 is acceptable to demonstrate compliance with 10 CFR 50.46(c).

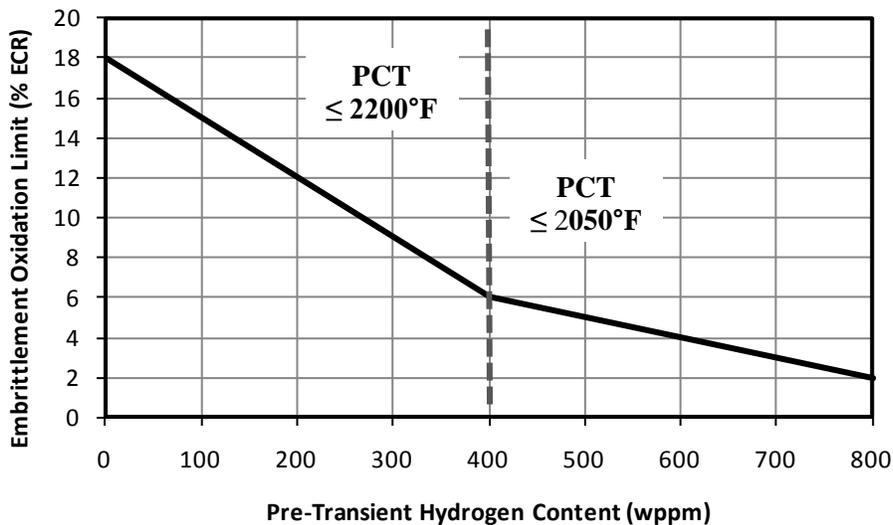


Figure 2. An acceptable analytical limit on peak cladding temperature and time at elevated temperature (as calculated in local oxidation calculations using the CP correlation (Ref. 11))

Methodology for Demonstrating Consistency with the Existing Database for New Cladding Alloys

For zirconium-alloy cladding materials not tested in the NRC's LOCA research program, a demonstration of comparable performance with the established database is necessary. The objective of PQD testing to demonstrate consistency with the analytical limit provided in Figure 2 of this regulatory guide is to confirm that the transition to brittle behavior does not take place at a lower equivalent cladding reacted (ECR) than the provided limit. A range of material conditions can serve to provide a characterization of PQD behavior through the spectrum of conditions expected during operation and during a transient. Repeat testing can be used to address expected variability in oxidation behavior. The methodology outlined in this regulatory guide includes testing of as-received, prehydrided, and irradiated

material. The methodology outlined in this regulatory guide uses the experimental procedure in DG-1262 to generate RCT data to demonstrate consistency with the analytical limit in Figure 2 of this regulatory guide.

As-received cladding material may be used to characterize an alloy's oxidation embrittlement behavior in the as-received condition. The analytical limit provided in Figure 2 of this regulatory guide can be used to reduce the extent of testing by focusing on specific oxidation levels. One approach would be to conduct oxidation and quench testing at the transition ECR defined in Figure 2, an ECR 1% above, and an ECR 1% below this limit. Following the guidance of DG-1262, each oxidation and quench sample would be segmented into three RCT samples. The average of these three RCT samples would be compared to the ductility criterion defined in terms of $\geq 1.0\%$ permanent strain or an offset strain ductility criterion presented in Appendix A to this regulatory guide. This would generate nine RCT results for as-received cladding material.

Prehydrided cladding material may be used to characterize the effect of hydrogen on an alloy's oxidation embrittlement behavior. The entire range of a cladding material's anticipated hydrogen level should be characterized. To characterize the range of a cladding material's anticipated hydrogen content, an acceptable approach would be to determine the ductile-to-brittle transition for prehydrided material in increments not more than every 100 wppm of hydrogen. The analytical limit provided in Figure 2 of this regulatory guide can be used to reduce the extent of testing by focusing on specific oxidation levels at each hydrogen level. One approach would be to conduct oxidation and quench testing at the transition ECR defined in Figure 2 for a given hydrogen content, an ECR 1% above, and an ECR 1% below this limit. Following the guidance of DG-1262, each oxidation and quench sample would be segmented into three RCT samples. The average of these three RCT samples would be compared to the ductility criterion defined in terms of $\geq 1.0\%$ permanent strain or an offset strain ductility criterion presented in Appendix A. This would generate nine RCT results at each hydrogen level.

Irradiated cladding material can be used to demonstrate that a cladding alloy's embrittlement behavior is accurately characterized by using prehydrided material. To demonstrate this, an acceptable approach would be to determine the ductile-to-brittle transition for irradiated material with hydrogen contents within 50 wppm of the anticipated maximum hydrogen content and within 50 wppm of half of the anticipated maximum hydrogen content. The analytical limit provided in Figure 2 of this regulatory guide can be used to reduce the extent of testing by focusing on specific oxidation levels relevant for the hydrogen content of the irradiated material. One approach would be to conduct oxidation and quench testing at the transition ECR defined in Figure 2 for the irradiated material's hydrogen content, an ECR 1% above, and an ECR 1% below this limit. Following the guidance of DG-1262, each oxidation and quench sample would be segmented into three RCT samples. The average of these three RCT samples would be compared to the ductility criterion defined in terms of $\geq 1.0\%$ permanent strain or an offset strain ductility criterion presented in Appendix A. This would generate nine RCT results at each hydrogen level, and a total of 18 RCT results for irradiated material.

Appendix B to this regulatory guide presents a high-level overview of an acceptable test matrix. The test matrix overview is intended to provide a clear picture of the range of material and test conditions that could be used to demonstrate comparable embrittlement behavior with the analytical limit in Figure 2. It is intended to complement the test matrix guidance in DG-1262.

To demonstrate comparable performance with the existing database and adopt the analytical limits provided in this guide for a new fuel design, the applicant would submit experimental results as part of the documentation supporting the NRC staff's review and approval of the new fuel design (i.e., license amendment request or vendor topical report). The applicant would provide details of the experimental technique (unless the experiments were conducted in accordance with DG-1262) and the

results of experiments conducted with as-fabricated, prehydrided, and irradiated cladding material. Provided that the experimental results for the new fuel design measured the transition from ductile to brittle behavior to be no lower than the analytical limit defined in Figure 2,¹ an acceptable method to demonstrate that licensees meet the requirements of 10 CFR 50.46(c) is demonstrating that ECCS performance is such that local oxidation is calculated below the analytical limit defined in Figure 2.

Methodology for Establishing a Zirconium-Alloy-Specific Limit

The existing database and resulting analytical limit described in this regulatory guide are intended to provide a best-estimate limit for the ductile-to-brittle transition for zirconium alloys. The analytical limit described in this guide is applicable to Zry-4, Zry-2, ZIRLO™, and M5. In some instances, a zirconium-alloy cladding material may experience the transition from ductile to brittle behavior at a higher level of oxidation than the established database.

The objective of PQD testing to establish an alloy-specific limit is to characterize a cladding alloy's embrittlement behavior through the entire spectrum of conditions expected during operation. A diverse matrix of material conditions can provide a complete characterization, and repeat testing can be used to address expected variability in oxidation behavior. The methodology outlined in this regulatory guide includes testing of as-received, prehydrided, and irradiated material. The methodology uses the experimental procedure in DG-1262 to generate RCT data to establish a zirconium-alloy-specific limit.

As-received cladding material may be used to characterize an alloy's oxidation embrittlement behavior in the as-received condition. The methodology outlined in this regulatory guide for establishing a zirconium-alloy-specific limit other than the analytical limit provided in Figure 2 includes more repeat testing than was outlined for demonstrating consistency with the established database. One approach would be to conduct oxidation and quench testing at a wide range of ECRs to scope out a zirconium-alloy cladding material's oxidation behavior in the as-received condition. Testing would then focus on the ECR range between ductile and brittle results and include three repeat oxidation and quench tests at two ECR levels (a total of six oxidation and quench tests). Following the guidance of DG-1262, each oxidation and quench sample would be segmented into three RCT samples. The average of these three RCT samples would be compared to the ductility criterion defined in terms of $\geq 1.0\%$ permanent strain or the offset strain ductility criterion presented in Appendix A.

Prehydrided cladding material may be used to characterize the effect of hydrogen on an alloy's oxidation embrittlement behavior. The entire range of a cladding material's anticipated hydrogen level should be characterized. To characterize the range of a cladding material's anticipated hydrogen content, an acceptable approach would be to determine the ductile-to-brittle transition for prehydrided material in increments not more than every 100 wppm of hydrogen. The methodology outlined in this regulatory guide for establishing a zirconium-alloy-specific limit other than the analytical limit provided in Figure 2 includes more repeat testing at each hydrogen level than was outlined for demonstrating consistency with the established database. One approach would be to conduct oxidation and quench testing at the transition ECR defined in Figure 2 and, based on the result of this test, proceed to an ECR 2% above or an ECR 2% below this limit (2% above if the initial test was ductile, 2% below if the initial test was brittle). Testing would then focus on the ECR range between ductile and brittle results and include three repeat oxidation and quench tests at the transition ECR level. Following the guidance of DG-1262, each oxidation and quench sample would be segmented into three RCT samples. The average of these three RCT samples would be compared to the ductility criterion defined in terms of $\geq 1.0\%$ permanent strain or the offset strain ductility criterion presented in Appendix A.

¹ For accurate comparison to the research data, local oxidation calculations must be performed using the CP correlation.

Irradiated cladding material can be used to demonstrate that a cladding alloy's embrittlement behavior is accurately characterized by using prehydrided material. To demonstrate this, an acceptable approach would be to determine the ductile-to-brittle transition for irradiated material with hydrogen contents within 50 wppm of the anticipated maximum hydrogen content and within 50 wppm of half of the anticipated maximum hydrogen content. The methodology outlined in this regulatory guide for establishing a zirconium-alloy-specific limit other than the analytical limit provided in Figure 2 includes more repeat testing for irradiated material than was outlined for demonstrating consistency with the established database. One approach would be to conduct oxidation and quench testing at the transition ECR defined by the as-received and prehydrided testing described above. Testing would then focus on the ECR range between ductile and brittle results and include three repeat oxidation and quench tests at the transition ECR level. Following the guidance of DG-1262, each oxidation and quench sample would be segmented into three RCT samples. The average of these three RCT samples would be compared to the ductility criterion defined in terms of $\geq 1.0\%$ permanent strain or an offset strain ductility criterion presented in Appendix A.

Appendix B to this regulatory guide provides a high-level overview of an acceptable test matrix. The test matrix overview is intended to provide a clear picture of the range of material and test conditions that could be used to establish an alloy-specific limit other than the analytical limit in Figure 2. It is intended to complement the test matrix guidance in DG-1262.

To establish a zirconium-alloy-specific limit for a new or existing fuel design, the applicant would provide experimental results as part of the documentation supporting the NRC staff's review and approval of the new or existing fuel design (i.e., license amendment request or vendor topical report). The applicant would provide details of the experimental technique (unless the experiments were conducted in accordance with DG-1262) and the results of experiments conducted with as-fabricated, prehydrided, and irradiated material, as well as a specified analytical limit on peak cladding temperature and time at elevated temperature that corresponds to the measured ductile-to-brittle transition for the zirconium-alloy cladding material.

Upon review and approval of the fuel design, an acceptable method to demonstrate that licensees meet the requirements of 10 CFR 50.46(c) is demonstrating that ECCS performance is such that local oxidation is calculated below the specified analytical limit provided.

Methodology for Establishing Analytical Limits at Peak Oxidation Temperatures Less than 1,204 °C (2,200 °F)

The existing database and resulting analytical limit described in this regulatory guide is intended to bound ECCS performance. In the test program, experiments were conducted at maximum oxidation temperatures $\leq 1,200\text{ °C} \pm 10\text{ °C}$ and quenched at 800 °C .² Some ECCS may perform such that the maximum oxidation temperature is significantly below $1,204\text{ °C}$ ($2,200\text{ °F}$). Oxidation at lower temperatures has been shown to increase the allowable calculated oxidation before embrittlement. Therefore, conducting tests at lower peak temperatures may provide additional margin for some zirconium-alloy cladding materials.

² These test conditions were selected with the objective of bounding the performance of ECCSs. They are considered relevant and bounding for current light-water reactor ECCSs. However, it may be necessary to evaluate and possibly modify the conditions accordingly for ECCSs of advanced reactor designs. In addition, postquench ductility measurements were made at 135 °C . During the 1973 hearing, investigators suggested considering a test temperature no higher than the saturation temperature during reflood (i.e., $\approx 135\text{ °C}$). This test condition is considered relevant for current light-water reactor ECCSs. However, it may be necessary to evaluate and possibly modify the conditions accordingly for ECCSs of advanced reactor designs.

The objective of PQD testing to establish a limit at a peak cladding temperature lower than 1,204 °C (2,200 °F) is to characterize a cladding alloy's embrittlement behavior through the entire spectrum of conditions expected during operation. A diverse matrix of material conditions can serve to provide a complete characterization, and repeat testing can be used to address expected variability in oxidation behavior. The methodology outlined in this regulatory guide includes testing of as-received, prehydrided, and irradiated material. The methodology outlined in this regulatory guide uses the experimental procedure in DG-1262 to generate RCT data to establish a limit at a peak cladding temperature lower than 1,204 °C (2,200 °F).

As-received cladding material may be used to characterize an alloy's oxidation embrittlement behavior in the as-received condition. The methodology outlined in this regulatory guide for establishing an analytical limit at a peak oxidation temperature less than 1,204 °C (2,200 °F) includes more repeat testing for irradiated material than was outlined for demonstrating consistency with the established database. One approach would be to conduct oxidation and quench testing at a wide range of ECRs to scope out a zirconium-alloy cladding material's oxidation behavior in the as-received condition. Testing would then focus on the ECR range between ductile and brittle results and include three repeat oxidation and quench tests at two ECR levels (a total of six oxidation and quench tests). Following the guidance of DG-1262, each oxidation and quench sample would be segmented into three RCT samples. The average of these three RCT samples would be compared to the ductility criterion defined in terms of $\geq 1.0\%$ permanent strain or the offset strain ductility criterion presented in Appendix A.

Prehydrided cladding material may be used to characterize the effect of hydrogen on an alloy's oxidation embrittlement behavior. The entire range of a cladding material's anticipated hydrogen level should be characterized. To characterize the range of a cladding material's anticipated hydrogen content, an acceptable approach would be to determine the ductile-to-brittle transition for prehydrided material in increments not more than every 100 wppm of hydrogen. One approach would be to conduct oxidation and quench testing at the transition ECR defined in Figure 2, and, based on the result of this test, proceed to an ECR 2% above or an ECR 2% below this limit (2% above if the initial test was ductile, 2% below if the initial test was brittle). Testing would then focus on the ECR range between ductile and brittle results and include three repeat oxidation and quench tests at the transition ECR level. Following the guidance of DG-1262, each oxidation and quench sample would be segmented into three RCT samples. The average of these three RCT samples would be compared to the ductility criterion defined in terms of $\geq 1.0\%$ permanent strain or the offset strain ductility criterion presented in Appendix A.

Irradiated cladding material can be used to demonstrate that a cladding alloy's embrittlement behavior is accurately characterized by using prehydrided material. To demonstrate this, an acceptable approach would be to determine the ductile-to-brittle transition for irradiated material with hydrogen contents within 50 wppm of the anticipated maximum hydrogen content and within 50 wppm of half of the anticipated maximum hydrogen content. The methodology outlined in this regulatory guide for establishing an analytical limit at a peak oxidation temperature less than 2,200 °F includes more repeat testing for irradiated material than was outlined for demonstrating consistency with the established database. One approach would be to conduct oxidation and quench testing at the transition ECR defined by the as-received and prehydrided testing conducted as described above. Testing would then focus on the ECR range between ductile and brittle results and include three repeat oxidation and quench tests at the transition ECR level. Following the guidance of DG-1262, each oxidation and quench sample would be segmented into three RCT samples. The average of these three RCT samples would be compared to the ductility criterion defined in terms of $\geq 1.0\%$ permanent strain or the offset strain ductility criterion presented in Appendix A.

Appendix B to this guide presents a high-level overview of an acceptable test matrix. The test matrix overview is intended to provide a clear picture of the range of material and test conditions that

could be used to establish a limit at a peak cladding temperature lower than 1,204 °C (2,200 °F). It is intended to complement the test matrix guidance in DG-1262.

To establish analytical limits at peak oxidation temperatures less than 1,204 °C (2,200 °F), the applicant would provide experimental results as part of the documentation supporting the NRC staff's review and approval of the new fuel design or existing fuel design (i.e., license amendment request or vendor topical report). The applicant would provide details of the experimental technique (unless the experiments were conducted in accordance with DG-1262) and the results of experiments conducted with as-fabricated, prehydrided, and irradiated material, as well as a specified analytical limit on peak cladding temperature and time at elevated temperature that corresponds to the measured ductile-to-brittle transition for the zirconium-alloy cladding material.

For a given zirconium alloy, an applicant would be able to define analytical limits on time at elevated temperature (CP-ECR as a function of cladding hydrogen) corresponding to different peak cladding temperature analytical limits. This approach may provide margin for high-burnup, high-corrosion, low-power fuel rods that experience a relatively benign temperature transient.

Upon review and approval of the fuel design, an acceptable method to demonstrate that licensees meet the requirements of 10 CFR 50.46(c) is demonstrating that ECCS performance is such that local oxidation is calculated below the specified analytical limit provided.

Methodology for Establishing Analytical Limits for Breakaway Oxidation

The purpose of the requirements in 10 CFR 50.46, "Acceptance Criteria for Emergency Core Cooling Systems for Light-Water Nuclear Power Reactors," is to ensure core coolability during and following a LOCA. If breakaway oxidation occurs, the embrittlement process is accelerated. Therefore, the PQD analytical limits established in accordance with 10 CFR 50.46 are no longer effective to preclude embrittlement, and core coolability may not be maintained even if the analytical limits on peak cladding temperature and local oxidation (surrogate for time at temperature) are not exceeded.

In 10 CFR 50.46(c), the NRC calls for measurement of the onset of breakaway oxidation for a zirconium cladding alloy based on an acceptable experimental technique, evaluation of the measurement relative to ECCS performance, and reporting of values measured (Ref. 1).

Based on data reported by Leistikow and Schanz (Ref. 12), zirconium alloys have been shown to be susceptible to the breakaway oxidation phenomenon at temperatures as low as 650 °C. At 650 °C, it took more than 4 hours (beyond LOCA-relevant times) for Zry-4 to accumulate 200-wppm hydrogen, while at 800 °C, the time to accumulate 200-wppm hydrogen was only 1 hour (within LOCA-relevant times). Thus, time spent in steam at ≤ 650 °C was benign with regard to breakaway oxidation and hydrogen accumulation because of the very low oxidation rate. Because NUREG/IA-0211, "Experimental Study of Embrittlement of Zr-1%Nb VVER Cladding under LOCA-Relevant Conditions," issued March 2005 (Ref. 4), did not present hydrogen-accumulation data for temperatures between 650 °C and 800 °C, there is no basis for *not* including time spent at temperatures > 650 °C in establishing the analytical limit for transient time.

To establish a zirconium-alloy-specific limit for a new or existing fuel design, the applicant would provide experimental results for testing for breakaway oxidation behavior as part of the documentation supporting the NRC staff's review and approval of the new or existing fuel design (i.e., license amendment request or vendor topical report). DG-1261 provides an experimental technique to measure the onset of breakaway oxidation in order to establish a specified and acceptable limit on the total accumulated time that a cladding may remain at high temperature. The applicant would provide

details of the experimental technique (unless the experiments were conducted in accordance with DG-1261) and the results of experiments conducted. Applicants would establish the 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 (i.e., license amendment request or vendor topical report).

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. This approach may reduce the likelihood of reassessing small-break LOCA cladding temperature histories in the event of a minor change in measured time to breakaway oxidation. For example, the minimum time to breakaway oxidation may be demonstrated to occur at 975 °C at a time of 4,000 seconds. An applicant may elect to establish an analytical limit of 3,000 seconds for the total accumulated time that the cladding may remain above 650 °C.

Upon review and approval of the fuel design, an acceptable method to demonstrate that licensees meet the requirements of 10 CFR 50.46(c) is 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.

Applying Analytical Limits

Qualification of Hydrogen Pickup Models

An alloy-specific cladding hydrogen uptake model will be required if a licensee chooses to use the hydrogen-dependent embrittlement threshold provided in this regulatory guide. To establish an alloy-specific cladding hydrogen uptake model for a new or existing fuel design, the applicant would provide postirradiation examination hydrogen measurement data and a hydrogen uptake model as part of the documentation supporting the NRC staff's review and approval of the new or existing fuel design (i.e., license amendment request or vendor topical report). The documentation should include a cladding-specific plot of predicted versus measured cladding hydrogen content. The postirradiation examination data supporting the hydrogen uptake model should include values for multiple burnup levels, encompass all applicable operating conditions and reactor coolant chemistry, and should quantify axial, radial, and circumferential variability. (See the next section for further details.)

Accounting for Uncertainty and Variability in Hydrogen Content

Variation of hydrogen content across the radius of the cladding (hydride rim effect) and over short axial distances (pellet-pellet interface effect) has been observed by many investigators. Studies using prehydrided Zry-4 with dense hydride rims have demonstrated that the homogenization of hydrogen across the radius of the cladding is very rapid at >900 °C due to the affinity of the beta phase for hydrogen, as well as the high solubility of hydrogen in this phase. In the NRC's LOCA research program, significant circumferential variation (± 100 –140 wppm) in hydrogen content was measured (by the LECO inert gas fusion thermal conductivity method) and observed (by optical microscopy) for high-burnup cladding alloys. For oxidation test times at 1,200 °C up to the embrittlement CP-ECR level, no significant diffusion of hydrogen in the circumferential direction was observed. Hydrogen-concentration variations of 450 to 750 wppm measured for cladding quarter segments before LOCA testing remained after LOCA testing.

The uncertainty in the model can be characterized and quantified by supporting the model with postirradiation examination that include values for multiple burnup levels, encompasses all applicable

operating conditions and reactor coolant chemistry, and quantifies axial, radial, and circumferential variability.

To apply the analytical limit in Figure 2 to an individual fuel rod (or fuel rod grouping), the allowable CP-ECR should be based on predicted peak circumferential average hydrogen content for the individual rod (or fuel rod grouping).

Postquench Ductility Analytical Limits

Based on the approved ECCS evaluation models and methods, the applicant should identify the limiting combination of break size, break location, and initial conditions and assumptions that maximize predicted peak cladding temperature and local oxidation (surrogate for time at temperature). Combinations of initial conditions and uncertainties will vary between Appendix K, "ECCS Evaluation Models," to 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities," and best-estimate methods. Separate cases may be necessary to identify the limiting scenario for peak cladding temperature relative to local oxidation and vice versa. The applicant should demonstrate that predicted peak cladding temperature remains below the lesser of the regulatory limit of 2,200 °F and the maximum oxidation PQD temperature. The applicant will also need to demonstrate that the maximum predicted local oxidation remains below the established PQD analytical limits.

Because of the strong function of allowable local oxidation with cladding hydrogen content (see Figure 1), the applicant may elect to subdivide the fuel rods within the core based on cladding hydrogen content, burnup, fuel rod power, or a combination. For example, peak cladding temperature and local oxidation calculations would be performed on three representative sets of fuel rods (e.g., 0–30 gigawatt-days per metric ton of uranium (GWd/MTU), 30–45 GWd/MTU, and 45–62 GWd/MTU) using bounding power histories for each fuel rod grouping. The predicted peak cladding temperature and local oxidation would then be compared to the analytical limits for that range of burnup/hydrogen.

Application in the Rupture Region

During a postulated LOCA, fuel rods may be predicted to balloon and rupture as a result of elevated cladding temperature and differential pressure (between rod internal pressure and system pressure, which is decreasing because of a break in pressure boundary). The regions of the fuel rod near the ballooned and ruptured location will thus be exposed to oxidation from the inside surface of the cladding. Combined with oxygen diffusion from the cladding outside diameter (OD), oxygen diffusion from the cladding inside diameter (ID) would further limit time at elevated temperature to reach the analytical limit in Figure 2. In addition, these regions will experience wall thinning, which impacts the calculation of ECR because the value is taken to be a percentage of the preoxidation cladding thickness.

To apply the analytical limit in Figure 2 (or an alternative specified and acceptable analytical limit) in regions of the fuel rod where the calculated conditions of transient pressure and temperature lead to a prediction of cladding swelling, one approach would be to 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, and to calculate two-sided oxidation using the CP correlation.

Accounting for Double-Sided Oxidation Due to the Fuel-Cladding Bond Layer

The NRC's LOCA research program identified that, for high-burnup fuel, oxygen can diffuse into the cladding metal during a LOCA from the ID as well as from the OD, even when no steam oxidation is occurring on the ID (Refs. 5 and 6). The ID oxygen diffusion phenomenon was discovered in the United States in 1977, confirmed by tests in Germany in 1979, and is seen in the present results.

Combined with oxygen diffusion from the cladding OD, oxygen diffusion from the cladding ID would further limit time at elevated temperature to nil ductility. To account for the observation that oxygen can diffuse into the cladding metal during a LOCA from the ID, one acceptable approach would be to calculate two-sided local oxidation for fuel rods with a local (nodal) exposure beyond 30 GWd/MTU. It should be noted that there would be no metal-water-reaction heat associated with this process on the ID, in contrast to the situation in a rupture node. A threshold for the onset of this inside surface oxidation source other than 30 GWd/MTU 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 (i.e., license amendment request or vendor topical report). A threshold other than 30 GWd/MTU could be supported by metallographic images of bonding layers as a function of burnup.

Breakaway Oxidation Analytical Limits

Based on the approved ECCS evaluation models and methods, the applicant should identify the limiting combination of break size, break location, and initial conditions and assumptions that maximize 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. The applicant should demonstrate that this time interval remains below the established alloy-specific breakaway oxidation analytical limit.

The applicant may credit operator actions to limit the duration at elevated temperatures provided these actions are consistent with existing emergency operating procedures and the timing of such actions is validated by operator training on the plant simulator.

C. REGULATORY POSITION

Regulatory Positions 1 through 4 provide acceptable methods for establishing an analytical limit on peak cladding temperature and time at elevated temperature for zirconium-alloy cladding materials. Applicants should use one of the four methods provided. Regulatory Position 5 provides an acceptable method for establishing an analytical limit for breakaway oxidation.

1. Apply the specified and acceptable limit defined in Figure 2 of this regulatory guide for cladding materials tested in the NRC's LOCA research program.
2. Demonstrate comparable behavior of cladding alloys not tested in the NRC's LOCA research program, with the database established in the NRC's LOCA research program, in order to apply the limit defined in Figure 2 of this regulatory guide.
 - a. Conduct oxidation and quench testing on (1) as-fabricated material, (2) prehydrided material for the entire range of a cladding material's anticipated hydrogen level (testing pre-hydrided material in increments not more than every 100 wppm hydrogen), and (3) irradiated material for the entire range of a cladding material's anticipated hydrogen level (testing irradiated material with hydrogen contents within 50 wppm of the anticipated maximum hydrogen content and within 50 wppm of half of the anticipated maximum hydrogen content) at the transition ECR defined in Figure 2 for the each sample's hydrogen level, an ECR 1% above and an ECR 1% below this limit.
 - b. Determine the ECR at which the material transitions from ductile-to-brittle behavior using the results of ring compression testing conducted using the experimental procedure and the guidance provided in DG-1262 for each material condition called for in Regulatory Position 2.a³. Compare to the limit defined in Figure 2 of this guide.
 - c. If the experimental results for the new fuel design measured the transition from ductile to brittle behavior to be no lower than the analytical limit defined in Figure 2, the analytical limit defined in Figure 2 may be established for the cladding alloy not tested in NRC's LOCA research program.
 - d. Provide details of experimental techniques, unless conducted using the guidance in DG-1262, as part of the documentation supporting the staff's review and approval of the new or existing fuel design (i.e., license amendment request or vendor topical report).
 - e. Provide results of experiments conducted with as-fabricated, irradiated material and identify the specific analytical limit on peak cladding temperature and time at elevated temperature as part of the documentation supporting the staff's review and approval of the new or existing fuel design (i.e., license amendment request or vendor topical report). The limit should correspond the ductile-to-brittle transition for the zirconium-alloy cladding material and the oxidation temperature of the oxidation and quench experiments.

³ "each material condition" refers to the range of as-fabricated, prehydrided and irradiated material called for within the discussion section of this regulatory guide. For a zirconium alloy with an anticipated, end of life hydrogen content, the range of material conditions called for within the discussion section of this regulatory guide would include (1) as-fabricated, (2) pre-hydrided material at 100 wppm H, (3) pre-hydrided material at 200 wppm H, (4) pre-hydrided material at 300 wppm H, (5) pre-hydrided material at 400 wppm H, (6) irradiated material with a hydrogen content of 200 ± 50 wppm H, and (7) irradiated material with a hydrogen content of 400 ± 50 wppm H. See also Appendix B of this guide for a high-level overview of an acceptable test matrix.

3. Establish a zirconium alloy specific analytical limit on peak cladding temperature and time at elevated temperature at a peak cladding oxidation temperature of 2200°F.
 - a. Conduct oxidation and quench testing on (1) as-fabricated material, (2) prehydrided material for the entire range of a cladding material's anticipated hydrogen level (testing pre-hydrided material in increments not more than every 100 wppm hydrogen), and (3) irradiated material for the entire range of a cladding material's anticipated hydrogen level (testing irradiated material with hydrogen contents within 50 wppm of the anticipated maximum hydrogen content and within 50 wppm of half of the anticipated maximum hydrogen content) at four oxidation levels for each material condition³, in increments not greater than 2% ECR.
 - b. With the results of four oxidation levels, for each material condition called for in (a) above, determine the ECR range in which the transition from ductile-to-brittle behavior occurs and conduct three repeat oxidation and quench tests at each ECR level within this range using the guidance provided in DG-1262.
 - c. Determine the ECR at which the material transitions from ductile to brittle behavior, using the results of ring compression testing conducted using the experimental procedure and the guidance provided in DG-1262 for each material condition called for in Regulatory Position 3.a.
 - d. Provide details of experimental techniques, unless conducted using the guidance in DG-1262, as part of the documentation supporting the NRC staff's review and approval of the new or existing fuel design (i.e., license amendment request or vendor topical report).
 - e. Provide the results of experiments conducted with as-fabricated, irradiated material and identify the specific analytical limit on peak cladding temperature and time at elevated temperature as part of the documentation supporting the NRC staff's review and approval of the new or existing fuel design (i.e., license amendment request or vendor topical report). The limit should correspond the ductile-to-brittle transition for the zirconium-alloy cladding material and the oxidation temperature of the oxidation and quench experiments.
4. Establish an analytical limit on peak cladding temperature and time at elevated temperature at a peak oxidation temperature less than 2,200 °F.
 - a. Conduct oxidation and quench testing on (1) as-fabricated material, (2) prehydrided material for the entire range of a cladding material's anticipated hydrogen level (testing prehydrided material in increments not more than every 100 wppm of hydrogen), and (3) irradiated material for the entire range of a cladding material's anticipated hydrogen level (testing irradiated material with hydrogen contents within 50 wppm of the anticipated maximum hydrogen content and within 50 wppm of half of the anticipated maximum hydrogen content) at four oxidation levels for each material condition³, in increments not greater than 2% ECR.
 - b. With the results of four oxidation levels for each material condition called for in Regulatory Position 4.a, determine the ECR range in which the transition from ductile to brittle behavior occurs and conduct three repeat oxidation and quench tests at each ECR level within this range using the guidance provided in DG-1262.

- c. Determine the ECR at which the material transitions from ductile-to-brittle behavior, using the results of ring compression testing conducted using the experimental procedure and the guidance provided in DG-1262 for each material condition called for in Regulatory Position 4.a.
 - d. Provide details of experimental techniques, unless conducted using the guidance in DG-1262, as part of the documentation supporting the NRC staff's review and approval of the new or existing fuel design (i.e., license amendment request or vendor topical report).
 - e. Provide the results of experiments conducted with as-fabricated, irradiated material and identify the specific analytical limit on peak cladding temperature and time at elevated temperature as part of the documentation supporting the NRC staff's review and approval of the new or existing fuel design (i.e., license amendment request or vendor topical report). The limit should correspond the ductile-to-brittle transition for the zirconium-alloy cladding material and the oxidation temperature of the oxidation and quench experiments.
5. Establish an analytical limit for breakaway oxidation.
- a. Follow the procedures in DG-1261 to establish the shortest time observed to lead to breakaway oxidation for a zirconium cladding alloy.
 - b. Provide the results of the testing as part of the documentation supporting the NRC staff's review and approval of the new or existing fuel design (i.e., license amendment request or vendor topical report).
 - c. Establish an analytical limit for the total accumulated time the cladding may remain above 650°C, which is less than or equal to the shortest time observed to lead to breakaway oxidation.
 - d. Provide the analytical limit for breakaway oxidation as part of the documentation supporting the NRC staff's review and approval of the new or existing fuel design (i.e., license amendment request or vendor topical report).

D. IMPLEMENTATION

The purpose of this section is to provide information to applicants and licensees regarding the NRC's plans for using this regulatory guide.

This regulatory guide provides the NRC's first guidance on a new rule. When there is an issuance of a new rule, the agency backfitting considerations have been taken into account in the related rulemaking. The position of this guide is one methodology to meet the requirements of the rule. While an applicant or licensee is not required to use the methodology set forth in this guidance, they are required to comply with the rule. Should the applicant or licensee elect to use a different methodology, the NRC staff may require a demonstration of how the proposed methodology complies with rule. This regulatory guidance complies with backfit requirements set forth in 10 CFR 50.109.

GLOSSARY

breakaway oxidation—For the purposes of this regulatory guide, the fuel-cladding oxidation phenomenon in which weight gain rate deviates from normal kinetics. This change occurs with a rapid increase of hydrogen pickup during prolonged exposure to a high-temperature steam environment, which promotes loss of cladding ductility.

corrosion—For the purposes of this regulatory guide, the formation of a zirconium oxide layer resulting from the reaction of zirconium with coolant water during normal operation.

loss-of-coolant accident (LOCA)—A hypothetical accident that would result from the loss of reactor coolant at a rate in excess of the capability of the reactor coolant makeup system, from breaks in pipes in the reactor coolant pressure boundary up to and including a break equivalent in size to the double-ended rupture of the largest pipe in the reactor coolant system.

offset strain—For the purposes of this regulatory guide, the value determined from a load-displacement curve by the following procedure: (1) linearize the initial loading curve, (2) use the slope of the initial loading curve to mathematically unload the sample at the peak load before a significant load drop (≈ 30 – 50%) indicating a through-wall crack along the length of the sample, and (3) determine the offset displacement (distance along the displacement axis between loading and unloading lines). This offset displacement is normalized to the outer diameter of the preoxidized cladding to determine a relative plastic strain.

oxidation—For the purposes of this regulatory guide, the formation of a zirconium oxide layer resulting from the reaction of zirconium with high-temperature steam during LOCA conditions.

permanent strain—For the purposes of this regulatory guide, the difference between the posttest outer diameter (after the sample is unloaded) and the pretest outer diameter of a cladding ring, normalized to the initial diameter of the cladding ring.

REFERENCES¹

1. 7X FR XXXXX, "Proposed Rule FRN," *Federal Register*, Volume 7X, Number XXX, p. XXXX, Washington, DC, June 31, 2011 (*insert FRN of proposed rule reference when available*).
2. DG-1262, "Testing for Postquench Ductility," U.S. Nuclear Regulatory Commission, Washington, DC.
3. DG-1261, "Conducting Periodic Testing for Breakaway Oxidation Behavior," U.S. Nuclear Regulatory Commission, Washington, DC.
4. NUREG/IA-0211, "Experimental Study of Embrittlement of Zr-1%Nb VVER Cladding under LOCA-Relevant Conditions," U.S. Nuclear Regulatory Commission, Washington, DC, March 2005. (ADAMS Accession No. ML051100343)
5. IFE/KR/E-2008/004, "LOCA Testing of High Burnup PWR Fuel in the HBWR. Additional PIE on the Cladding of the Segment 650-5," Institute for Energy Technology, Kjeller, Norway, April 2008. (ADAMS Accession No. ML081750715)
6. Research Information Letter 0801, "Technical Basis for Revision of Embrittlement Criteria in 10 CFR 50.46," U.S. Nuclear Regulatory Commission, Washington, DC, May 30, 2008. (ADAMS Accession No. ML081350225)
7. NUREG/CR-6967, "Cladding Embrittlement during Postulated Loss-of-Coolant Accidents," U.S. Nuclear Regulatory Commission, Washington, DC, July 2008. (ADAMS Accession No. ML082130389)
8. Yan, Y., T.A. Burtseva, and M.C. Billone, "Post-Quench Ductility Results for North Anna High-Burnup 17×17 ZIRLO™ Cladding with Intermediate Hydrogen Content," ANL letter report to NRC, April 17, 2009. (ADAMS Accession No. ML091200702)
9. May 15th email correspondence
10. ORNL/NUREG-17, "Zirconium Metal-Water Oxidation Kinetics IV. Reaction Rate Studies," U.S. Nuclear Regulatory Commission, Washington, DC, August 1977.
11. Billone, M.C., T.A. Burtseva, and Y. Yan, "Cladding Tests for Conditions, Monthly Letter Status Report," ANL letter report to the NRC, October 22, 2009, ANL Response to ANPR
12. Leistikow, S., and G. Schanz, "Oxidation Kinetics and Related Phenomena of Zircaloy-4 Fuel Cladding Exposed to High Temperature Steam and Hydrogen-Steam Mixtures under PWR Accident Conditions," *Nuclear Engineering and Design*, 103: 65–84.

¹ Publicly available NRC published documents are available electronically through the Electronic Reading Room on the NRC's public Web site at: <http://www.nrc.gov/reading-rm/doc-collections/>. The documents can also be viewed on-line or printed for a fee in the NRC's Public Document Room (PDR) at 11555 Rockville Pike, Rockville, MD; the mailing address is USNRC PDR, Washington, DC 20555; telephone 301-415-4737 or (800) 397-4209; fax (301) 415-3548; and e-mail pdr.resource@nrc.gov.

APPENDIX A

RELATIONSHIP BETWEEN OFFSET STRAIN AND PERMANENT STRAIN

For as-fabricated cladding compressed at room temperature (RT) or 135 degrees Celsius (°C) and at 0.033 millimeter per second (mm/s) to a total displacement of 2 millimeters (mm), the difference between offset displacement and permanent displacement is ≤ 0.2 mm, which corresponds to a strain difference of $\approx 2\%$. As the applied displacement is decreased, the plastic deformation decreases and the deviation between offset and permanent strain also decreases. This was demonstrated by conducting a set of ring compression tests designed to result in low permanent strains of 1.0 to 2.3%. Table A-1 shows the results of these tests.

Table A-1. Results of Ring Compression Tests Conducted with As-Fabricated Cladding Samples at RT and 2 mm/minute Displacement Rate. Total Applied Displacements Were Chosen to Give Low Permanent Strains (d_p/D_o) in the Range of 1.0 to 2.3% and Corresponding Low Offset Strains

Material (D_o , mm)	Sample ID IPS or AG No.	Offset Displacement δ_d , mm	Permanent Displacement d_p , mm	Permanent Strain d_p/D_o , %	Strain Difference $(\delta_d - d_p)/D_o$, %
15×15 Zry-4 (10.91 mm)	101B7	0.24	0.21	1.9	0.3
	101B8	0.20	0.17	1.6	0.3
	101B9	0.20	0.18	1.6	0.2
	101B10	0.16	0.14	1.3	0.2
17×17 ZIRLO™ (9.48 mm)	109D7	0.25	0.22	2.3	0.3
	109D8	0.17	0.16	1.7	0.1
	109D9	0.14	0.12	1.3	0.2
	109D10	0.14	0.12	1.3	0.2
17×17 M5 (9.48 mm)	636B2	0.18	0.19	2.0	0.0
	636B3	0.14	0.14	1.5	0.0
	636B4	0.15	0.15	1.6	0.0

For as-fabricated and prehydrided cladding oxidized at $\leq 1,200$ °C, the difference between offset and permanent displacement depends on both the oxidation level and the magnitude of the permanent displacement. For material with high ductility, the difference in displacements can be as high as 0.5 mm. For material with essentially no ductility, both offset and the permanent displacement values are in the "noise of uncertainty" and their difference can be as low as 0.01 mm.

However, what is relevant to the determination of the ductile-to-brittle transition oxidation level is the error in offset strain as determined by the difference between offset (δ_p/D_o in %) and permanent (d_p/D_o in %) strains for permanent strains in the range of 1.0 to 2.3%. Figure A-1 summarizes the data reported in Refs. 1 and 15, in Figures 1 and 2 of this procedure, and in Table A-1. The data are plotted as a function of Cathcart-Pawel equivalent cladding reacted (CP-ECR). Low values of permanent strain at low CP-ECR levels (e.g., 5–10%) are from prehydrided Zircaloy-4 (Zry-4), high-burnup Zry-4, and ZIRLO™ samples. Low values of permanent strain at intermediate CP-ECR levels (10–18%) are from high-burnup ZIRLO™ and M5 samples. Low values of permanent strain at high CP-ECR values (15–20%) are from as-fabricated cladding materials. The best linear fit to the data is given by:

$$\delta_p/D_o - d_p/D_o = 0.25 + 0.0863 \text{ CP-ECR} \quad (\text{A1})$$

The one-sigma upper bound to the data is given by:

$$\delta_p/D_o - d_p/D_o = 0.41 + 0.1082 \text{ CP-ECR} \quad (\text{A2})$$

Because of the large data scatter in Figure A-1, the one-sigma upper bound is used to establish the offset-strain ductility criterion. It is derived by setting the permanent strain (d_p/D_o) in Equation (A2) to 1.0%:

$$\delta_p/D_o \geq 1.41 + 0.1082 \text{ CP-ECR} \quad (\text{A3})$$

For multiple offset-strain data points at the same CP-ECR level, the average value for the data set, rounded to the nearest tenth of a percent, should be used for δ_p/D_o in Equation (A3). Similarly, the limit calculated from the right-hand side of Equation (A3) should also be rounded to the nearest tenth of a percent.

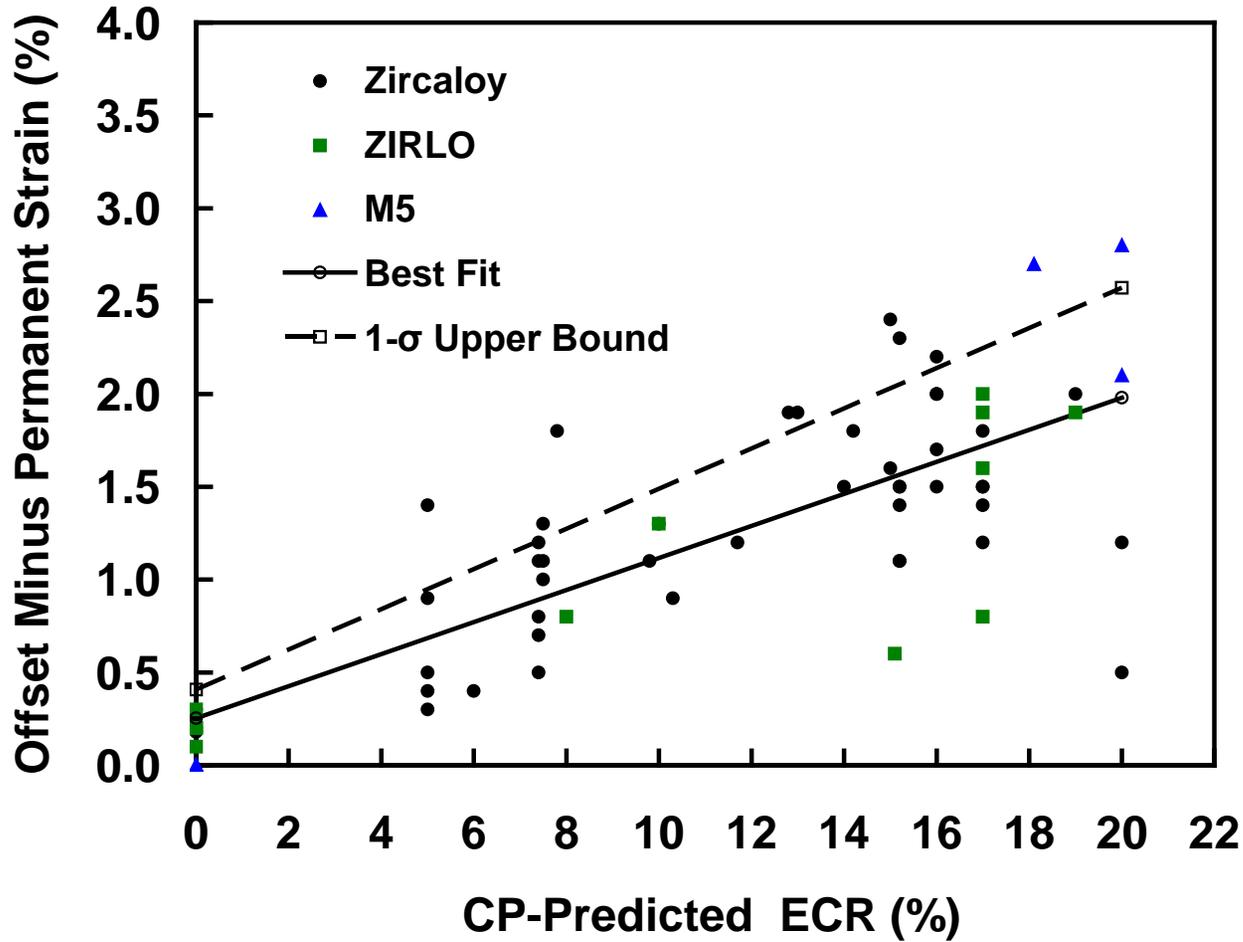


Figure A-1. Difference in offset strain and permanent strain as a function of calculated oxidation level (CP-ECR) for permanent strains near the embrittlement threshold (1.0% to 2.3%) for as-fabricated, prehydrided, and high-burnup cladding alloys oxidized at 1,200 °C and ring-compressed at RT and 135 °C and at 0.033 mm/s.

APPENDIX B

OVERVIEW OF ACCEPTABLE TEST MATRICES

Draft Regulatory Guide (DG)-1262, “Testing for Postquench Ductility,” provides a detailed test procedure that is acceptable for generating postquench ductility data through ring compression tests. This appendix is intended to provide a simple, straightforward overview of acceptable test matrices. The test matrix overviews provided in this appendix are consistent with the guidance in DG-1262.

This appendix will provide two examples. The first series of test matrices could be used to generate ring compression test data to establish an alloy-specific limit or to establish a limit at a peak cladding temperature lower than 2,200 degrees Fahrenheit (°F). The second series of test matrices could be used to generate ring compression test data to demonstrate consistency with the analytical limit provided in Figure 2 of this regulatory guide.

B-1. Overview of Sample Test Matrix To Generate Ring Compression Test Data To Establish an Alloy-Specific Limit or To Establish a Limit at a Peak Cladding Temperature Lower than 2,200 °F

The objective of postquench ductility testing to establish an alloy-specific limit or to establish a limit at a peak cladding temperature lower than 2,200 °F is to characterize a cladding alloy’s embrittlement behavior through the entire spectrum of conditions expected during operation. A diverse matrix of material conditions can provide a complete characterization, and repeat testing can be used to address expected variability in oxidation behavior. The test matrix to generate ring compression test data to establish an alloy-specific limit or to establish a limit at a peak cladding temperature lower than 2,200 °F provided here includes testing of as-received, prehydrided, and irradiated material.

As-received cladding material may be used to conduct scoping tests to identify the oxidation equivalent cladding reacted (ECR) where transition behavior likely occurs. Table B-1 provides a sample test matrix for this scoping test.

Table B-1. Sample Test Matrix for Scoping Tests for As-Received Cladding Material

From the scoping test, a brittle result and a ductile result will likely be identified. For example, the average of three samples at 17% ECR may be determined to be ductile using the ductility criterion $\geq 1.0\%$ permanent strain or the offset strain criterion defined in Appendix A to this regulatory guide, while the average of three samples at 20% ECR may be determined to be brittle. Following the evaluation of results from the scoping tests, the next set of tests with as-received cladding material should be conducted within the range where the brittle and ductile results were observed, to identify the ECR at which the transition occurs. For example, if the average of three samples at 17% ECR was determined to be ductile, while the average of three samples at 20% ECR was determined to be brittle, the next set of tests should be conducted at 18% and 19% ECR. In the transition region, repeat tests provide improved characterization because of variability in oxidation behavior. Therefore, a sample test matrix for testing in this region includes multiple oxidation and quench tests at each oxidation level, as shown in Table B-2. The transition from ductile to brittle behavior should be identified to occur at the highest Cathcart-Pawel equivalent cladding reacted (CP-ECR) at which the permanent strain is $\geq 1.0\%$.

Table B-2. Sample Test Matrix for Testing As-Received Cladding Material in the Identified Transition Region

Prehydrided cladding material may be used to characterize the effect of hydrogen on an alloy's oxidation embrittlement behavior. The entire range of a cladding material's anticipated hydrogen level should be characterized. To characterize the range of a cladding material's anticipated hydrogen content, an acceptable approach would be to determine the ductile-to-brittle transition for prehydrided material in increments not more than every 100 weight parts per million (wppm) of hydrogen. The test matrix below illustrates 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. The embrittlement threshold provided in Figure 2 as a function of hydrogen content may be used as a guide in selecting the range of oxidation levels to be included in the test matrix. Table B-3 provides the embrittlement threshold in Figure 2 in tabular form for clarity. Table B-4 provides a sample test matrix for scoping the behavior of prehydrided material.

Table B-3. Tabulated Values for the Embrittlement Threshold in DG-1263

Hydrogen Content (wppm)	Embrittlement ECR
0	18%
100	15.5%
200	12%
300	9%
400	6%
500	5%
600	4%
700	3%
800	2%

Table B-4. Sample Test Matrix for Scoping Tests for Prehydrided Cladding Material

The objective of the scoping tests for prehydrided material is to identify an ECR level at which ductile behavior is observed, and an ECR level at which brittle behavior is observed, and thus identify the range in which the ductile-to-brittle behavior is observed. Once this range of ECR levels is identified, the test matrix continues with testing at an ECR level between the ECR level at which ductile behavior is observed and the ECR level at which brittle behavior is observed. Table B-5 provides a test matrix that can be used at each hydrogen level to characterize embrittlement behavior at the ECR level at which the ductile-to-brittle transition is expected to occur.

Table B-5. Sample Test Matrix for Testing Prehydrided Cladding Material in the Identified Transition Region

Irradiated cladding material can be used to demonstrate that a cladding alloy's embrittlement behavior is accurately characterized by using prehydrided material. To demonstrate this, an acceptable approach would be to determine the ductile-to-brittle transition for irradiated material with hydrogen contents within 50 wppm of the anticipated maximum hydrogen content and within 100 wppm of half of the anticipated maximum hydrogen content. The test matrix below illustrates 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. Table B-6 provides a sample test matrix for demonstrating that a cladding alloy's embrittlement behavior is accurately characterized by using prehydrided material.

Table B-6. Sample Test Matrix for Testing Irradiated Cladding Material

B-2. Overview of Sample Test Matrix To Generate Ring Compression Test Data To Demonstrate Consistency with the Analytical Limit Provided in DG-1263

The objective of postquench ductility testing to demonstrate consistency with the analytical limit provided in Figure 2 of this regulatory guide is to confirm that the transition to brittle behavior does not take place at a lower ECR than the provided limit. Because of this, the matrix of material conditions and oxidation levels can be significantly reduced from the matrix outlined in the previous section. A range of material conditions can serve to provide a characterization through the spectrum of conditions expected during operation, and repeat testing can be used to address expected variability in oxidation behavior. The test matrix provided here to generate ring compression test data to demonstrate consistency with the analytical limit provided in Figure 2 of this regulatory guide includes testing of as-received, prehydrided, and irradiated material. The transition from ductile to brittle behavior should be identified to occur at the highest CP-ECR at which the permanent strain is $\geq 1.0\%$. Consistency with the analytical limit provided in Figure 2 of this regulatory guide would be considered demonstrated when the transition from ductile to brittle behavior is not lower than the provided limit.

Prehydrided cladding material may be used to characterize the effect of hydrogen on an alloy's oxidation embrittlement behavior. The entire range of a cladding material's anticipated hydrogen level should be characterized. To characterize the range of a cladding material's anticipated hydrogen content, an acceptable approach would be to determine the ductile-to-brittle transition for prehydrided material in increments

not more than every 100 wppm of hydrogen. The test matrix in Table B-7 illustrates 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. The analytical limit provided in Figure 2 of this regulatory guide as a function of hydrogen content may be used as a guide in selecting the range of oxidation levels to be included in the test matrix. Table 3 of this regulatory guide provides the embrittlement threshold in Figure 2 in tabular form for clarity.

Irradiated cladding material can be used to demonstrate that a cladding alloy's embrittlement behavior is accurately characterized by using prehydrided material. To demonstrate this, an acceptable approach would be to determine the ductile-to-brittle transition for irradiated material with hydrogen contents within 50 wppm of the anticipated maximum hydrogen content and within 100 wppm of half of the anticipated maximum hydrogen content. Table B-7 illustrates 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.

Table B-7 provides a complete test matrix, including as-received, prehydrided, and irradiated material, acceptable to the NRC for using in postquench ductility testing to demonstrate consistency with the analytical limit provided in Figure 2 of this regulatory guide.

Table B-7. Sample Test Matrix for Testing As-Received, Prehydrided, and Irradiated Cladding Material To Demonstrate Consistency with the Analytical Limit Provided in Figure 2 of DG-1263

REGULATORY ANALYSIS

Draft Regulatory Guide, DG-1263, “Establishing Analytical Limits for Zirconium-Based Alloy Cladding” (Proposed New Regulatory Guide 1.224)

Statement of the Problem

In 1996, the U.S. Nuclear Regulatory Commission (NRC) initiated a fuel-cladding research program¹ intended to investigate the behavior of high-exposure fuel cladding under accident conditions. The research program identified new cladding embrittlement mechanisms and expanded NRC’s knowledge of previously identified mechanisms. The research results revealed that hydrogen, which is absorbed into the cladding during the burnup-related corrosion process under normal operation, has a significant influence on embrittlement during a hypothetical loss-of-coolant accident (LOCA). The research results also revealed that an embrittlement mechanism referred to as “breakaway oxidation” may occur during prolonged exposure to elevated cladding temperature during a LOCA.

NRC initiated rulemaking activities (Ref. 1) to revise Emergency Core Cooling System (ECCS) acceptance criteria to reflect recent research findings on these new cladding embrittlement mechanisms. The revisions to the ECCS acceptance criteria were developed to enhance performance-based features of 10 CFR 50.46. Therefore, 10 CFR 50.46(c) calls for the establishment of (1) analytical limits on peak cladding temperature and time at elevated temperature to address the effects of hydrogen on embrittlement during a LOCA and (2) analytical limits on prolonged exposure to elevated cladding temperature to prevent “breakaway oxidation.” With this approach, the limits imposed on each zirconium-based alloy are consistent with the alloy’s particular behavior because they are based on measurements for that zirconium-based alloy.

This regulatory guidance makes it possible to revise 10 CFR 50.46(c) in a performance-based manner 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. Draft Regulatory Guide (DG)-1261, “Conducting Periodic Testing for Breakaway Oxidation Behavior” (Ref. 2), provides an experimental technique acceptable to NRC for measuring the onset of breakaway oxidation for zirconium-alloy cladding materials. This guide describes a methodology for using experimental results to establish a specified and acceptable limit for the total accumulated time that the cladding may remain above a temperature at which the zirconium alloy has been shown to be susceptible to breakaway oxidation. DG-1262, “Testing for Postquench Ductility” (Ref. 3), provides an experimental technique acceptable to NRC for measuring the ductile-to-brittle transition for zirconium-alloy cladding material through ring compression tests. This guide (1) defines an acceptable analytical limit on peak cladding temperature and time at elevated temperature for the zirconium-alloy cladding materials tested in NRC’s LOCA research program, (2) describes a method to use experimental results to demonstrate comparable performance with the established database to establish the analytical limit provided in this guide for a particular cladding alloy not tested in NRC’s LOCA research program, (3) describes a method to use experimental results to establish a zirconium-alloy-specific limit other than the

¹ The research program included an extensive loss-of-coolant accident (LOCA) research and testing program at Argonne National Laboratory (ANL), as well as jointly funded programs at the Kurchatov Institute (Ref. 4) and the Halden Reactor (Ref. 5) project, to develop the body of technical information needed to evaluate LOCA regulations for high-exposure fuel. The research findings have been summarized in Research Information Letter (RIL) 0801, “Technical Basis for Revision of Embrittlement Criteria in 10 CFR 50.46,” dated May 30, 2008 (Ref. 6) and the detailed experimental results from the program at ANL are contained in NUREG/CR-6967, “Cladding Embrittlement During Postulated Loss-of-Coolant Accidents” (Ref. 7).

limit provided in this guide, and (4) describes a method to use experimental results to establish analytical limits at peak oxidation temperatures less than 1,204 °C (2,200 °F).

Development of this regulatory guidance provides a method acceptable to NRC to implement the performance-based rule language in 10 CFR 50.46(c).

Objective

The objective of this regulatory action is to enable performance-based rule language in 10 CFR 50.46(c) 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.

Alternative Approaches

The NRC staff considered the following alternative approaches:

Alternative 1: Do Not Create Draft Regulatory Guide-1263

Under this alternative, NRC would not create DG-1263. If NRC does not take action, no changes would occur in costs or benefit to the public, licensees, or NRC. However, the “no-action” alternative would not provide a clear, acceptable approach for implementing the performance-based regulatory requirements proposed for 50.46(c). NRC would have to review the methodology used to establish regulatory limits related to cladding embrittlement and the breakaway behavior of zirconium-based alloys during LOCA conditions on a case-by-case basis.

The impact associated with not creating the regulatory guide is that NRC and its licensees and applicants may interpret differently the extent of experiential support and methodology for using experimental data to support regulatory limits related to cladding embrittlement and breakaway oxidation behavior of zirconium-based alloys during LOCA conditions. In addition, the NRC resources required to review the methodology used to establish regulatory limits related to cladding embrittlement and the breakaway oxidation behavior of zirconium-based alloys during LOCA conditions would be significant.

Alternative 2: Create Draft Regulatory Guide-1263

Under this alternative, NRC would create DG-1263. Creating DG-1263 will (1) provide a clear, acceptable methodology for supporting and establishing the performance-based regulatory limits called for in 50.46(c); (2) simplify the staff’s review process; and (3) reduce regulatory uncertainty and thereby help to minimize the costs associated with the implementation of the regulatory requirements proposed for 50.46(c). A benefit of this action is that it would enhance reactor safety by ensuring that clear guidance is available for establishing regulatory limits related to cladding embrittlement and the breakaway oxidation behavior of zirconium-based alloys during LOCA conditions.

The impact to NRC would be the costs associated with preparing and creating the regulatory guide. The impact to the public would be the voluntary costs associated with reviewing and providing comments to NRC during the public comment period. The value to NRC and its applicants would be the benefits associated with enhanced efficiency and effectiveness in using a common methodology for supporting and establishing the performance-based regulatory limits related to cladding embrittlement and the breakaway oxidation behavior of zirconium-based alloys during LOCA conditions.

Conclusions

Based on this regulatory analysis, the NRC staff recommends creating DG-1263. The staff concludes that the proposed action will enhance reactor safety ensuring clear guidance is available for supporting and establishing the performance-based regulatory limits related to cladding embrittlement and the breakaway behavior of zirconium-based alloys during LOCA conditions. The creation of this guide also could reduce regulatory uncertainties and thereby minimize costs for the industry.

REFERENCES²

1. 7X FR XXXXX, "Proposed Rule FRN," *Federal Register*, Volume 7X, Number XXX, p. XXXX, Washington, DC, June 31, 2011. (*insert FRN of proposed rule reference when available*)
2. DG-1261, "Conducting Periodic Testing for Breakaway Oxidation Behavior," U.S. Nuclear Regulatory Commission, Washington, DC.
3. DG-1262, "Testing for Postquench Ductility," U.S. Nuclear Regulatory Commission, Washington, DC.
4. NUREG/IA 0211, "Experimental Study of Embrittlement of Zr 1%Nb VVER Cladding under LOCA-Relevant Conditions," U.S. Nuclear Regulatory Commission, Washington, DC, March 2005. (ADAMS Accession No. ML051100343)
5. IFE/KR/E 2008/004, "LOCA Testing of High Burnup PWR Fuel in the HBWR. Additional PIE on the Cladding of the Segment 650 5," Institute for Energy Technology, Kjeller, Norway, April 2008. (ADAMS Accession No. ML081750715)
6. Research Information Letter 0801, "Technical Basis for Revision of Embrittlement Criteria in 10 CFR 50.46," U.S. Nuclear Regulatory Commission, Washington, DC, May 30, 2008. (ADAMS Accession No. ML081350225)
7. NUREG/CR 6967, "Cladding Embrittlement during Postulated Loss-of-Coolant Accidents," U.S. Nuclear Regulatory Commission, Washington, DC, July 2008. (ADAMS Accession No. ML082130389)

²

Publicly available NRC published documents are available electronically through the Electronic Reading Room on the NRC's public Web site at: <http://www.nrc.gov/reading-rm/doc-collections/>. The documents can also be viewed on-line or printed for a fee in the NRC's Public Document Room (PDR) at 11555 Rockville Pike, Rockville, MD; the mailing address is USNRC PDR, Washington, DC 20555; telephone 301-415-4737 or 800-397-4209; fax 301-415-3548; and e-mail pdresource@nrc.gov.

NOTE: The availability of this draft rule language, as it exists in this document, is intended to inform stakeholders of the current status of the NRC's activities to revise the requirements for emergency core cooling systems to support an upcoming meeting with the Advisory Committee on Reactor Safeguards. The NRC staff is considering restructuring the current Section 50.46 regulation to distinguish ECCS performance requirements (i.e., criteria governing acceptable capability of ECCS to perform its cooling function during and after a design basis LOCA) from fuel/cladding performance requirements (i.e., criteria intended to ensure that the fuel and cladding do not result in prevention of successful cooling during and after a design basis LOCA, and any other effects with adverse impacts on the capability or other safety systems). Additionally, the NRC staff may add new paragraphs to address long standing issues and concerns with the current regulation. As such, this draft rule language may be incomplete or in error in one or more respects, and will be subject to further revisions during the rulemaking process. The NRC is not requesting formal public comments on this draft rule language. The NRC may post updated materials, including updated draft rule language, to this page. Interested stakeholders should periodically check this page for updates and added materials.

Draft Rule Language for 10 CFR 50.46c

§ 50.46c Requirements for emergency core cooling systems for light-water nuclear power reactors.

(a) *Applicability.* The requirements of this section apply to each holder of an operating license for any light water nuclear power reactor (LWR), regardless of fuel design or cladding material, except for a licensee who has submitted the certifications required under 10 CFR 50.82(a)(1) to the NRC.

(b) *Definitions.* As used in this section:

(1) *Loss-of-coolant accident (LOCA)* means a hypothetical accident that would result from the loss of reactor coolant, at a rate in excess of the capability of the reactor coolant makeup system, from breaks in pipes in the reactor coolant pressure boundary up to and including a break equivalent in size to the double-ended rupture of the largest pipe in the reactor coolant system.

(2) *Evaluation model* means the calculational framework for evaluating the behavior of the reactor system during a postulated loss-of-coolant accident (LOCA). It includes one or more computer programs and all other information necessary for application of the calculational framework to a specific LOCA, such as mathematical models used, assumptions included in the programs, procedure for treating the program input and output information, specification of those portions of analysis not included in computer programs, values of parameters, and all other information necessary to specify the calculational procedure.

(3) *Breakaway oxidation* means, for the purposes of this section, the fuel cladding oxidation phenomenon in which weight gain rate deviates from normal kinetics. This change occurs with a rapid increase of hydrogen pickup during prolonged exposure to a high temperature steam environment, which promotes loss of cladding ductility

(c) *General performance requirements for any fuel design or cladding material.* Each LWR must be provided with an emergency core cooling system (ECCS) designed so that, when fueled with an acceptable fuel design, the following performance requirements are satisfied in the event of a postulated loss-of-coolant accident (LOCA):

- (1) Core geometry remains amenable to cooling;
- (2) Generation of combustible gas is limited to the maximum extent practicable;
- (3) Core temperature is maintained at a value sufficient to ensure compliance with criteria in paragraphs (c)(1) and (c)(2) of this section;

NOTE: The availability of this draft rule language, as it exists in this document, is intended to inform stakeholders of the current status of the NRC's activities to revise the requirements for emergency core cooling systems to support an upcoming meeting with the Advisory Committee on Reactor Safeguards. The NRC staff is considering restructuring the current Section 50.46 regulation to distinguish ECCS performance requirements (i.e., criteria governing acceptable capability of ECCS to perform its cooling function during and after a design basis LOCA) from fuel/cladding performance requirements (i.e., criteria intended to ensure that the fuel and cladding do not result in prevention of successful cooling during and after a design basis LOCA, and any other effects with adverse impacts on the capability or other safety systems). Additionally, the NRC staff may add new paragraphs to address long standing issues and concerns with the current regulation. As such, this draft rule language may be incomplete or in error in one or more respects, and will be subject to further revisions during the rulemaking process. The NRC is not requesting formal public comments on this draft rule language. The NRC may post updated materials, including updated draft rule language, to this page. Interested stakeholders should periodically check this page for updates and added materials.

(4) Decay heat is removed for the extended period of time required by the long-lived radioactivity remaining in the core.

(5) ECCS cooling performance must be calculated in accordance with an acceptable evaluation model and must be calculated for a number of postulated loss-of-coolant accidents of different sizes, locations, and other properties sufficient to provide assurance that the most severe postulated loss-of-coolant accidents are calculated. The evaluation model must include sufficient supporting justification to show that the analytical technique realistically describes the behavior of the reactor system during a loss-of-coolant accident. Comparisons to applicable experimental data must be made and uncertainties in the analysis method and inputs must be identified and assessed so that the uncertainty in the calculated results can be estimated. This uncertainty must be accounted for, so that when the calculated ECCS cooling performance is compared to the applicable specified and acceptable analytical limits there is a high level of probability that the limits would not be exceeded. Appendix K, Part II Required Documentation, sets forth the documentation requirements for each evaluation model.

(d) *Specific requirements for fuel designs consisting of uranium oxide or mixed uranium-plutonium oxide pellets within zirconium-alloy cladding material.* Each LWR must be provided with an ECCS designed so that, when fueled with an acceptable fuel design consisting of uranium oxide or mixed uranium-plutonium oxide pellets within cylindrical zirconium-alloy cladding, the following performance requirements are satisfied in the event of a postulated LOCA:

(1) *Coolable geometry.* Calculated changes in core geometry shall be such that the core remains amenable to cooling.

(i) *Peak cladding temperature.* Except as provided in paragraph (d)(1)(ii) of this section, the calculated maximum fuel element cladding temperature shall not exceed 2200° F.

(ii) *Cladding embrittlement.* 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 2200° F limit specified in (d)(1)(i), then the lower temperature shall be used in place of the 2200° F limit.

iii) *Zirconium fuel cladding oxidation limits.* 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

NOTE: The availability of this draft rule language, as it exists in this document, is intended to inform stakeholders of the current status of the NRC's activities to revise the requirements for emergency core cooling systems to support an upcoming meeting with the Advisory Committee on Reactor Safeguards. The NRC staff is considering restructuring the current Section 50.46 regulation to distinguish ECCS performance requirements (i.e., criteria governing acceptable capability of ECCS to perform its cooling function during and after a design basis LOCA) from fuel/cladding performance requirements (i.e., criteria intended to ensure that the fuel and cladding do not result in prevention of successful cooling during and after a design basis LOCA, and any other effects with adverse impacts on the capability or other safety systems). Additionally, the NRC staff may add new paragraphs to address long standing issues and concerns with the current regulation. As such, this draft rule language may be incomplete or in error in one or more respects, and will be subject to further revisions during the rulemaking process. The NRC is not requesting formal public comments on this draft rule language. The NRC may post updated materials, including updated draft rule language, to this page. Interested stakeholders should periodically check this page for updates and added materials.

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.

(2) *Maximum hydrogen generation.* The calculated total amount of hydrogen generated from the chemical reaction of the cladding with water or steam shall not exceed 0.01 times the hypothetical amount that would be generated if all of the metal in the cladding cylinders surrounding the fuel, excluding the cladding surrounding the plenum volume, were to react.

(3) *Long-term cooling.* After any calculated successful initial operation of the ECCS, the calculated core temperature shall be maintained at an acceptably low value and decay heat shall be removed for the extended period of time required by the long-lived radioactivity remaining in the core.

(4) *Evaluation model.* ECCS cooling performance must be calculated in accordance with an acceptable evaluation model and must be calculated for a number of postulated loss-of-coolant accidents of different sizes, locations, and other properties sufficient to provide assurance that the most severe postulated loss-of-coolant accidents are calculated. Except as provided in paragraph (d)(4)(i) of this section, the evaluation model must include sufficient supporting justification to show that the analytical technique realistically describes the behavior of the reactor system during a loss-of-coolant accident. Comparisons to applicable experimental data must be made and uncertainties in the analysis method and inputs must be identified and assessed so that the uncertainty in the calculated results can be estimated. This uncertainty must be accounted for, so that when the calculated ECCS cooling performance is compared to the analytical limits established in accordance with paragraph (d)(1), (2), and (3) of this section, there is a high level of probability that the limits would not be exceeded. Appendix K, Part II Required Documentation, sets forth the documentation requirements for each evaluation model.

(i) Alternatively, an ECCS evaluation model may be developed in conformance with the required and acceptable features of appendix K ECCS Evaluation Models.

(ii) Oxygen diffusion from the cladding inside surfaces will reduce the allowable time at elevated temperature to embrittlement. If an oxygen source is present on the inside surfaces of the cladding at the onset of the LOCA, the effects of oxygen diffusion from the cladding inside surfaces shall be considered in the evaluation model.

- (e) [Reserved]
- (f) [Reserved]
- (g) [Reserved]
- (h) [Reserved]
- (i) [Reserved]

NOTE: The availability of this draft rule language, as it exists in this document, is intended to inform stakeholders of the current status of the NRC's activities to revise the requirements for emergency core cooling systems to support an upcoming meeting with the Advisory Committee on Reactor Safeguards. The NRC staff is considering restructuring the current Section 50.46 regulation to distinguish ECCS performance requirements (i.e., criteria governing acceptable capability of ECCS to perform its cooling function during and after a design basis LOCA) from fuel/cladding performance requirements (i.e., criteria intended to ensure that the fuel and cladding do not result in prevention of successful cooling during and after a design basis LOCA, and any other effects with adverse impacts on the capability or other safety systems). Additionally, the NRC staff may add new paragraphs to address long standing issues and concerns with the current regulation. As such, this draft rule language may be incomplete or in error in one or more respects, and will be subject to further revisions during the rulemaking process. The NRC is not requesting formal public comments on this draft rule language. The NRC may post updated materials, including updated draft rule language, to this page. Interested stakeholders should periodically check this page for updates and added materials.

(j) [Reserved]

(k) *Reporting.*

(1) Each applicant for or holder of an operating license or construction permit issued under this part, applicant for a standard design certification under part 52 of this chapter (including an applicant after the Commission has adopted a final design certification regulation), or an applicant for or holder of a standard design approval, a combined license or a manufacturing license issued under part 52 of this chapter, shall estimate the effect of any change to or error in an acceptable evaluation model or in the application of such a model to determine if the change or error is significant. For this purpose, a significant change or error is one which results in a calculated peak fuel cladding temperature different by more than 50 °F from the temperature calculated for the limiting transient using the last acceptable model, or is a cumulation of changes and errors such that the sum of the absolute magnitudes of the respective temperature changes is greater than 50 °F.

(2) For each change to or error discovered in an acceptable evaluation model or in the application of such a model that affects the temperature calculation, the applicant or holder of a construction permit, operating license, combined license, or manufacturing license shall report the nature of the change or error and its estimated effect on the limiting ECCS analysis to the Commission at least annually as specified in § 50.4 or § 52.3 of this chapter, as applicable. If the change or error is significant, the applicant or licensee shall provide this report within 30 days and include with the report a proposed schedule for providing a reanalysis or taking other action as may be needed to show compliance with § 50.46 requirements. This schedule may be developed using an integrated scheduling system previously approved for the facility by the NRC. For those facilities not using an NRC approved integrated scheduling system, a schedule will be established by the NRC staff within 60 days of receipt of the proposed schedule. Any change or error correction that results in a calculated ECCS performance that does not conform **to the analytical limits established in accordance with this section, as applicable**, is a reportable event as described in §§ 50.55(e), 50.72, and 50.73. The affected applicant or licensee shall propose immediate steps to demonstrate compliance or bring plant design or operation into compliance with § 50.46 requirements.

(3) For each change to or error discovered in an acceptable evaluation model or in the application of such a model that affects the temperature calculation, the applicant or holder of a standard design approval or the applicant for a standard design certification (including an applicant after the Commission has adopted a final design certification rule) shall report the nature of the change or error and its estimated effect on the limiting ECCS analysis to the Commission and to any applicant or licensee referencing the design approval or design certification at least annually as specified in § 52.3 of this chapter. If the change or error is significant, the applicant or holder of the design approval or the applicant for the design certification shall provide this report within 30 days and include with the report a proposed schedule for providing a reanalysis or taking other action as may be needed to show

NOTE: The availability of this draft rule language, as it exists in this document, is intended to inform stakeholders of the current status of the NRC's activities to revise the requirements for emergency core cooling systems to support an upcoming meeting with the Advisory Committee on Reactor Safeguards. The NRC staff is considering restructuring the current Section 50.46 regulation to distinguish ECCS performance requirements (i.e., criteria governing acceptable capability of ECCS to perform its cooling function during and after a design basis LOCA) from fuel/cladding performance requirements (i.e., criteria intended to ensure that the fuel and cladding do not result in prevention of successful cooling during and after a design basis LOCA, and any other effects with adverse impacts on the capability or other safety systems). Additionally, the NRC staff may add new paragraphs to address long standing issues and concerns with the current regulation. As such, this draft rule language may be incomplete or in error in one or more respects, and will be subject to further revisions during the rulemaking process. The NRC is not requesting formal public comments on this draft rule language. The NRC may post updated materials, including updated draft rule language, to this page. Interested stakeholders should periodically check this page for updates and added materials.

compliance with § 50.46 requirements. The affected applicant or holder shall propose immediate steps to demonstrate compliance or bring plant design into compliance with § 50.46 requirements.

(l) Authority to impose restrictions on operation. The Director of the Office of Nuclear Reactor Regulation (for licenses issued under 10 CFR 50) or the Director of the Office of New Reactors (for licenses issued under 10 CFR 52) may impose restrictions on reactor operation if it is found that the evaluations of ECCS cooling performance submitted are not consistent with the requirements of this section.

(m) Relationship to other NRC regulations. The requirements of this section are in addition to any other requirements applicable to ECCS set forth in this part. The analytical limits established in accordance with this section, with cooling performance calculated in accordance with an acceptable evaluation model, are in implementation of the general requirements with respect to ECCS cooling performance design set forth in this part, including in particular Criterion 35 of appendix A of this part.

(n) Implementation.

- (1) Construction permits issued under Part 50 after [EFFECTIVE DATE OF RULE] must comply with the requirements of this section.
- (2) Operating licenses issued under Part 50 which are based upon construction permits in effect as of [EFFECTIVE DATE OF RULE] (including deferred and reinstated construction permits) must comply with the requirements of § 50.46c by no later than the applicable data set forth in Table 1. Until such compliance is achieved, the requirements of this section continue to apply.
- (3) Operating licenses issued under Part 50 after [EFFECTIVE DATE OF RULE] must comply with the requirements of this section.
- (4) Operating licenses issued under Part 50 as of [EFFECTIVE DATE OF RULE] must comply with the requirements § 50.46c by no later than the applicable date set forth in Table 1. Until such compliance is achieved, the requirements of this section continue to apply.
- (5) Standard design certifications under part 52 of this chapter, whose applications (including applications for amendment) are pending as of or docketed after [EFFECTIVE DATE OF RULE], and new branches of these certifications whose applications are pending as of or docketed after [EFFECTIVE DATE OF RULE] must be amended to reflect compliance with this section no later than 36 months after [EFFECTIVE DATE OF RULE]. For purposes of this paragraph, a "branch" represents an alternative to the

NOTE: The availability of this draft rule language, as it exists in this document, is intended to inform stakeholders of the current status of the NRC's activities to revise the requirements for emergency core cooling systems to support an upcoming meeting with the Advisory Committee on Reactor Safeguards. The NRC staff is considering restructuring the current Section 50.46 regulation to distinguish ECCS performance requirements (i.e., criteria governing acceptable capability of ECCS to perform its cooling function during and after a design basis LOCA) from fuel/cladding performance requirements (i.e., criteria intended to ensure that the fuel and cladding do not result in prevention of successful cooling during and after a design basis LOCA, and any other effects with adverse impacts on the capability or other safety systems). Additionally, the NRC staff may add new paragraphs to address long standing issues and concerns with the current regulation. As such, this draft rule language may be incomplete or in error in one or more respects, and will be subject to further revisions during the rulemaking process. The NRC is not requesting formal public comments on this draft rule language. The NRC may post updated materials, including updated draft rule language, to this page. Interested stakeholders should periodically check this page for updates and added materials.

certified design as approved in the original design certification rulemaking. Such amendments are not subject to either the issue finality provisions under 10 CFR 52.103(g) or the backfitting requirements under 10 CFR 50.109.

- (6) Standard design certifications under part 52 of this chapter, or branches of standard design certifications in effect on [EFFECTIVE DATE OF RULE] but not referenced in an application for combined license or in a combined license, must be amended to reflect compliance with this section 36 months after the design certification rule is referenced in a combined license application or upon renewal, whichever is later. Such amendments are not subject to either the issue finality provisions under 10 CFR 52.103(g) or the backfitting requirements under 10 CFR 50.109.
- (7) Combined licenses under part 52 of this chapter must comply with this section no later than completion of the first refueling outage after initial fuel load. Until such compliance is achieved, the requirements in § 50.46 continue to apply.
- (8) Standard design approvals under part 52 of this chapter issued before [EFFECTIVE DATE OF RULE] must comply with this section before the design approval may be referenced in a construction permit, operating license, design certification, combined license or manufacturing license issued by the NRC.
- (9) Applications for standard design approvals under part 52 of this chapter issued after [EFFECTIVE DATE OF RULE] must comply with this section.
- (10) Applications for manufacturing licenses under part 52 of this chapter submitted after [EFFECTIVE DATE OF RULE] must comply with this section.

NOTE: The availability of this draft rule language, as it exists in this document, is intended to inform stakeholders of the current status of the NRC’s activities to revise the requirements for emergency core cooling systems to support an upcoming meeting with the Advisory Committee on Reactor Safeguards. The NRC staff is considering restructuring the current Section 50.46 regulation to distinguish ECCS performance requirements (i.e., criteria governing acceptable capability of ECCS to perform its cooling function during and after a design basis LOCA) from fuel/cladding performance requirements (i.e., criteria intended to ensure that the fuel and cladding do not result in prevention of successful cooling during and after a design basis LOCA, and any other effects with adverse impacts on the capability or other safety systems). Additionally, the NRC staff may add new paragraphs to address long standing issues and concerns with the current regulation. As such, this draft rule language may be incomplete or in error in one or more respects, and will be subject to further revisions during the rulemaking process. The NRC is not requesting formal public comments on this draft rule language. The NRC may post updated materials, including updated draft rule language, to this page. Interested stakeholders should periodically check this page for updates and added materials.

Table 1: Implementation dates for Nuclear Power Plants with operating licenses as of [EFFECTIVE DATE OF RULE] or operating licenses which are based upon construction permits in effect as of [EFFECTIVE DATE OF RULE] (including deferred and reinstated construction permits).

Calculated Local Oxidation (ECR ¹) Reported in UFSAR	Latest Date for Demonstrating Compliance
$ECR \geq 10.0$	No later than 36 months from effective date of rule
$10.0 > ECR > 5.0$	No later than 48 months from effective date of rule
$ECR \leq 5.0$	No later than 60 months from effective date of rule

¹ Equivalent cladding reacted

NOTE: The availability of this draft rule language, as it exists in this document, is intended to inform stakeholders of the current status of the NRC's activities to revise the requirements for emergency core cooling systems to support an upcoming meeting with the Advisory Committee on Reactor Safeguards. The NRC staff is considering restructuring the current Section 50.46 regulation to distinguish ECCS performance requirements (i.e., criteria governing acceptable capability of ECCS to perform its cooling function during and after a design basis LOCA) from fuel/cladding performance requirements (i.e., criteria intended to ensure that the fuel and cladding do not result in prevention of successful cooling during and after a design basis LOCA, and any other effects with adverse impacts on the capability or other safety systems). Additionally, the NRC staff may add new paragraphs to address long standing issues and concerns with the current regulation. As such, this draft rule language may be incomplete or in error in one or more respects, and will be subject to further revisions during the rulemaking process. The NRC is not requesting formal public comments on this draft rule language. The NRC may post updated materials, including updated draft rule language, to this page. Interested stakeholders should periodically check this page for updates and added materials.

In Appendix K to 10 CFR Part 50: (I)(B)

(B). Swelling and Rupture of the Cladding and Fuel Rod Thermal Parameters

Each evaluation model shall include a provision for predicting cladding swelling and rupture from consideration of the axial temperature distribution of the cladding and from the difference in pressure between the inside and outside of the cladding, both as functions of time. To be acceptable the swelling and rupture calculations shall be based on applicable data in such a way that the degree of swelling and incidence of rupture are not underestimated. The degree of swelling and rupture shall be taken into account in calculations of gap conductance, cladding oxidation and embrittlement, and hydrogen generation.

The calculations of fuel and cladding temperatures as a function of time shall use values for gap conductance and other thermal parameters as functions of temperature and other applicable time-dependent variables. The gap conductance shall be varied in accordance with changes in gap dimensions and any other applicable variables. The thermal effects of crud and oxide layers that accumulate on the fuel cladding during plant operation must be evaluated.

In Appendix K to 10 CFR Part 50: (II)(5)

5. General Standards for Acceptability—Elements of evaluation models reviewed will include technical adequacy of the calculation methods, including: For models covered by §50.46c(d)(4)(i) compliance with required features of section I of this Appendix K; and, for models covered by § 50.46c(d)(4), assurance of a high level of probability that the performance criteria of § 50.46c(b) would not be exceeded.

ROUTING AND TRANSMITTAL SLIP			4/15/2011		
TO:	NAME	ACTION REQUESTED	COMMENTS	INITIALS	DATE
	Jennifer Borges	Concur	via e-mail	JLB	4/1/11
PM	Angelisa Hicks	Concur		ALH	4/7/11
BC	Thomas Boyce	Concur/SUNSI Review		TB	4/7/11
DD	Michael Case	Concur/Sign Memo		MC	4/14/11
OFFICE	RES	<input type="checkbox"/>			
DD	N/A	Concur			
OFFICE	FSME	<input type="checkbox"/>			
LIAISON	Liaison	Distribution			
DD	Division Director	Concur			
OFFICE	NMSS	<input type="checkbox"/>			
LIAISON	Liaison	Distribution			
DD	N/A	Concur			
OFFICE	NRO	<input checked="" type="checkbox"/>			
LIAISON	Tanya Hood, DNRL	Distribution			
BC	Charles Ader, DSRA	Concur			
OFFICE	NRR	<input checked="" type="checkbox"/>			
LIAISON	Holly Cruz, DPR	Distribution			
DD	William Ruland, DSS	Concur			
OFFICE	NSIR	<input type="checkbox"/>			
LIAISON	Liaison	Distribution			
DD	Division Director	Concur			
OFFICE	OGC	<input checked="" type="checkbox"/>			
AGC	Bradley Jones, OGC	No Legal Objection (NLO)			

SUBJECT:	Request for Concurrence on Draft Regulatory Guide (DG) -1261, "Conducting Periodic Testing for Breakaway Oxidation Behavior."		
REMARKS:	Proposed New Regulatory Guide.		
FROM:	Angelisa Hicks	Room No.:	2C27
		Phone No.:	301-251-7448

April 14, 2011

MEMORANDUM TO: William H. Ruland, Director
Division of Safety Systems
Office of Nuclear Reactor Regulation

Charles E. Ader, Director
Division of Safety Systems and Risk Assessment
Office of New Reactors

Bradley W. Jones, Assistant General Counsel
for Reactors and Materials Rulemaking
Office of the General Counsel

FROM: Michael J. Case, Director */RA/*
Division of Engineering
Office of Nuclear Regulatory Research

SUBJECT: REQUEST FOR CONCURRENCE ON DRAFT REGULATORY GUIDE,
DG-1261, "CONDUCTING PERIODIC TESTING FOR BREAKAWAY
OXIDATION BEHAVIOR"

I am forwarding for your concurrence Draft Guide (DG) DG-1261, "Conducting Periodic Testing for Breakaway Oxidation Behavior." The enclosed DG-1261 is a proposed new regulatory guide. This draft has been developed by the Office of Nuclear Regulatory Research (RES) with close cooperation and coordination with the following organizations and individuals:

- Office of New Reactors: Paul Clifford
- Office of Nuclear Reactor Regulation: Ralph Landry

The agency will publish a notice in the *Federal Register* concerning the issuance and availability of DG-1261. The public comment period for this guide will be 60 days from the date of issuance. If there are only editorial changes following internal concurrence and resolution of public comments, your concurrence will not be needed for publication of the final regulatory guide.

CONTACT: Michelle Flanagan, RES/DE
(301) 251-7547

Angelisa Hicks, RES/DE
(301) 251-7448

W. Ruland, et al.

- 2 -

Please contact either Michelle Flanagan or Angelisa Hicks as early as possible during the concurrence review period to resolve any questions or issues in a timely manner.

Enclosures:

1. DG-1261
2. Regulatory Analysis

Please contact either Michelle Flanagan or Angelisa Hicks as early as possible during the concurrence review period to resolve any questions or issues in a timely manner.

Enclosures:

1. DG-1261
2. Regulatory Analysis

DISTRIBUTION: DE r/f

ADAMS Accession No. ML110840080

OFFICE	RES/DE	RES/DE	RES/DE	SUNSI Review	RES/DE	NRO
NAME	J. Borges via email	A. Hicks	T. Boyce	T. Boyce	M. Case	C. Ader
DATE	4/1/11	4/7/11	4/7/11	4/7/11	4/14/11	/ /11
OFFICE	NRR	OGC	QTE			
NAME	W. Ruland	B. Jones	Via e-mail			
DATE	/ /11	/ /11	2/14/11			

OFFICIAL RECORD COPY



DRAFT REGULATORY GUIDE

Contact: M. Flanagan
(301) 251-7547

DRAFT REGULATORY GUIDE DG-1261

(Proposed New Regulatory Guide 1.222)

CONDUCTING PERIODIC TESTING FOR BREAKAWAY OXIDATION BEHAVIOR

A. INTRODUCTION

This guide describes a method that the U.S. Nuclear Regulatory Commission (NRC) considers acceptable to implement the requirements in Title 10, Section 50.46(c), of the *Code of Federal Regulations* (10 CFR 50.46(c)) (Ref. 1), for an embrittlement mechanism, referred to as a “breakaway oxidation,” that may occur during prolonged exposure to elevated cladding temperature during a loss-of-coolant accident (LOCA).

In 10 CFR 50.46(c), the NRC calls for measurement of the onset of breakaway oxidation for a zirconium cladding alloy based on an acceptable experimental technique, evaluation of the measurement relative to emergency core cooling system performance, and periodic testing and reporting of the values measured. This regulatory guide describes an experimental technique acceptable to the NRC staff to measure the onset of breakaway oxidation in order to support a specified and acceptable limit on the total accumulated time that a cladding may remain at high temperature, as required by 10 CFR 50.46(c). This regulatory guide also describes a method acceptable to the NRC to implement the periodic testing and reporting requirements in 10 CFR 50.46(c).

The NRC issues regulatory guides to describe to the public methods that the staff considers acceptable for use in implementing specific parts of the agency’s regulations, to explain techniques that the staff uses in evaluating specific problems or postulated accidents, and to provide guidance to applicants. Regulatory guides are not substitutes for regulations and compliance with them is not required.

This regulatory guide contains information collection requirements covered by 10 CFR Part 50 that the Office of Management and Budget (OMB) approved under OMB control number 3150-0011. The NRC may neither conduct nor sponsor, and a person is not required to respond to, an information collection request or requirement unless the requesting document displays a currently valid OMB control

This regulatory guide is being issued in draft form to involve the public in the early stages of the development of a regulatory position in this area. It has not received final staff review or approval and does not represent an official NRC final staff position. Public comments are being solicited on this draft guide (including any implementation schedule) and its associated regulatory analysis or value/impact statement. Comments should be accompanied by appropriate supporting data. Written comments may be submitted to the Rules, Announcements, and Directives Branch, Office of Administration, U.S. Nuclear Regulatory Commission, Washington, DC 20555-0001; submitted through the NRC’s interactive rulemaking Web page at <http://www.nrc.gov>; or faxed to (301) 492-3446. Copies of comments received may be examined at the NRC’s Public Document Room, 11555 Rockville Pike, Rockville, MD. Comments will be most helpful if received by **[insert date - 60 days from issuance]**.

Electronic copies of this draft regulatory guide are available through the NRC’s interactive rulemaking Web page (see above); the NRC’s public Web site under Draft Regulatory Guides in the Regulatory Guides document collection of the NRC’s Electronic Reading Room at <http://www.nrc.gov/reading-rm/doc-collections/>; and the NRC’s Agencywide Documents Access and Management System (ADAMS) at <http://www.nrc.gov/reading-rm/adams.html>, under Accession No. ML110840089. The regulatory analysis may be found in ADAMS under Accession No. ML110910408.

number. The NRC has determined that this regulatory guide is not a major rule as designated by the Congressional Review Act and has verified this determination with OMB.

	<u>Page</u>
A. INTRODUCTION	1
B. DISCUSSION	3
Background.....	3
Description of Breakaway Oxidation Phenomenon.....	3
Breakaway Oxidation Testing.....	4
Establishing the Onset of Breakaway Oxidation	5
Periodic Testing	5
Reporting Results of Periodic Testing	5
C. REGULATORY POSITION.....	6
D. IMPLEMENTATION	7
GLOSSARY	8
REFERENCES	9
APPENDIX A: Procedure for Conducting Breakaway Oxidation Tests with Zirconium-Based Cladding Alloys	A-1
APPENDIX B: Rationale for the 200-wppm Hydrogen Pickup Criterion for Breakaway Oxidation	B-1
APPENDIX C: Negative Effects of Etching with Hydrofluoric-Containing Acid as Part of Sample Cleaning	C-1
APPENDIX D: Correlation between Cladding Outer-Surface Appearance and Hydrogen Pickup	D-1
APPENDIX E: Overview and Logic Diagram to Illustrate Sample Test Matrices	E-1

B. DISCUSSION

Background

In 1996, the NRC initiated a fuel-cladding research program intended to investigate the behavior of high-exposure fuel cladding under accident conditions. This research program included an extensive LOCA research and testing program at Argonne National Laboratory (ANL), as well as jointly funded programs at the Kurchatov Institute (Ref. 2) and the Halden Reactor Project (Ref. 3), to develop the body of technical information needed to evaluate LOCA regulations for high-exposure fuel. The agency has summarized the research findings in Research Information Letter 0801, "Technical Basis for Revision of Embrittlement Criteria in 10 CFR 50.46," dated May 30, 2008 (Ref. 4). The detailed experimental results from the program at ANL appear in NUREG/CR-6967, "Cladding Embrittlement during Postulated Loss-of-Coolant Accidents," issued July 2008 (Ref. 5).

The research program identified new cladding embrittlement mechanisms and expanded the NRC's knowledge of previously identified mechanisms. One of the embrittlement mechanisms investigated in NRC's LOCA research program is called "breakaway oxidation," which is described below.

Description of Breakaway Oxidation Phenomenon

Zirconium dioxide can exist in several crystallographic forms (allotropes). The normal tetragonal oxide that develops under LOCA conditions is dense, adherent, and protective with respect to hydrogen pickup. However, conditions might occur during a small-break LOCA (such as extended time-at-temperature around 1,000 degrees Celsius ($^{\circ}\text{C}$) (1,832 degrees Fahrenheit ($^{\circ}\text{F}$))) that promote a transformation to the monoclinic phase. The monoclinic phase is the oxide phase that is grown during normal operation and is neither fully dense nor protective. The tetragonal-to-monoclinic transformation is an instability that initiates at local regions of the metal-oxide interface and grows rapidly throughout the oxide layer. Because this transformation results in an increase in oxidation rate, it is referred to as breakaway oxidation.

Along with this increase in oxidation rate caused by cracks in the monoclinic oxide, there is significant hydrogen pickup. Hydrogen that enters in this manner during a postulated LOCA promotes rapid embrittlement of the cladding. If breakaway oxidation occurs, the embrittlement process is accelerated and the oxidation limits or time-at-temperature criteria are no longer effective to preclude embrittlement.

Figure 1 illustrates the damaging effects of breakaway oxidation. This sample of the Russian alloy E110 (an older version no longer representative of commercial cladding) was exposed to high-temperature steam oxidation for a hold time of 1,350 seconds at 1,000 $^{\circ}\text{C}$ (1,832 $^{\circ}\text{F}$). Breakaway oxidation, delamination, and spallation are evident. Hydrogen pickup was approximately 4,200 weight parts per million (wppm).

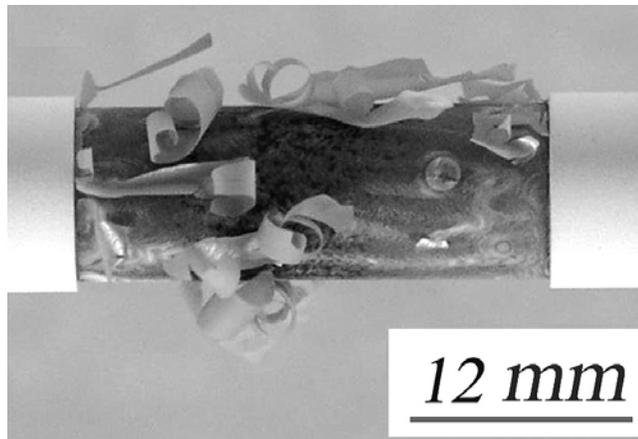


Figure 1. E110 cladding test specimen

Source: NUREG/CR-6967

Although all zirconium alloys will eventually experience breakaway oxide phase transformation when exposed to long durations of high-temperature steam oxidation, alloying composition and manufacturing process parameters (e.g., surface roughness) influence the timing of this phenomenon. As shown in Table 1, several domestic cladding alloys tested as part of the NRC’s LOCA research program proved to be less susceptible to early breakaway oxidation.

Table 1. Breakaway Test Results

Alloy	Measured Minimum Breakaway Time	Temperature at which Minimum Breakaway Time Was Measured
Zircaloy-2	>5,000 seconds	1,000 °C
Zircaloy-4	5,000 seconds	986 °C
ZIRLO™	3,000 seconds	970 °C
M5	>5,000 seconds	1,000 °C

Breakaway Oxidation Testing

The purpose of the requirements in 10 CFR 50.46(c) is to ensure core coolability during and following a LOCA. If breakaway oxidation occurs, the embrittlement process is accelerated. Therefore, the postquench ductility analytical limits established in accordance with 10 CFR 50.46(c) are no longer effective to preclude embrittlement, and core coolability may not be maintained even if the analytical limits on peak cladding temperature and local oxidation (surrogate for time-at-elevated-temperature) are not exceeded. Specifically, 10 CFR 50.46(c) calls for (1) measurement of the onset of breakaway oxidation for a zirconium cladding alloy based on an acceptable experimental technique and (2) evaluation of the measurement relative to emergency core cooling system performance.

The NRC’s LOCA research program revealed that different zirconium-based alloys have varying susceptibility to breakaway oxidation that is dependent on factors such as alloy content, manufacturing process, and surface preparation, among others (Refs. 2, 5–6). Therefore, 10 CFR 50.46(c) includes a periodic testing and reporting requirement to confirm that slight composition changes or manufacturing changes have not inadvertently altered the cladding’s susceptibility to breakaway oxidation.

Establishing the Onset of Breakaway Oxidation

The experimental procedure provided in Appendix A to this regulatory guide defines a procedure acceptable to the NRC staff to measure the onset of breakaway oxidation. This experimental procedure may be used to characterize the onset of breakaway oxidation as a function of temperature for a zirconium cladding alloy. For zirconium cladding alloys, the experimental results of breakaway testing would be provided as part of the documentation supporting the staff's review and approval of the new fuel design (i.e., a license amendment request or vendor topical report). The applicant would provide details of the experimental technique (unless the experiments were conducted in accordance with Appendix A to this regulatory guide) and the results of experiments conducted as a function of temperature.¹

Periodic Testing

To confirm that slight composition changes or manufacturing changes have not inadvertently altered the cladding's susceptibility to breakaway oxidation, 10 CFR 50.46(c) calls for periodic measurement of the onset of breakaway oxidation. To meet this requirement, it is acceptable to use the experimental procedure provided in Appendix A to this regulatory guide to measure the onset of breakaway oxidation and to reduce the test matrix that is described in Section A-10.

Specifically, it is acceptable to measure the onset of breakaway oxidation annually for only the temperature at which the minimum time to breakaway oxidation was measured and to demonstrate that breakaway oxidation is not experienced within the time of the established analytical limit. An observation of a lustrous black oxide or a measurement of less than 200-wppm hydrogen pickup (see Appendix B for further discussion) after this test would be sufficient to demonstrate that breakaway oxidation had not occurred during the test. In this case, a total of five repeat tests at the temperature at which the minimum time to breakaway oxidation was measured and the time of the cladding alloy's established analytical limit is acceptable to address variability and demonstrate continued acceptable performance.

For test times below the established time for breakaway oxidation, all five samples must exhibit lustrous black oxides on the cladding outer surface or hydrogen contents less than 200 wppm to conclude that changes in processing parameters or time-dependent variables (e.g., new versus used polishing belt or wheel) did not cause a change in breakaway oxidation time.

Reporting Results of Periodic Testing

In 10 CFR 50.46(c), the NRC requires, in part, that the values measured in periodic breakaway testing be reported to the NRC. The 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.

¹ Section A-10, "Test Temperatures," in the procedure detailed in Appendix A specifies that the test matrix should include measurements at 1,050, 1,030, 1,015, 1,000, 985, 970, 950, and 800 °C and defines the extent of replicate testing for the purpose of characterizing variability.

C. REGULATORY POSITION

1. Establish the susceptibility to breakaway oxidation for a zirconium cladding alloy.
 - a. Define the minimum time to the onset of breakaway oxidation following the experimental procedure provided in Appendix A to this regulatory guide.
 - b. Provide the results of breakaway testing as part of the documentation supporting the staff's review and approval of a fuel design (i.e., a license amendment request or vendor topical report).
2. Conduct periodic testing to confirm that slight composition changes or manufacturing changes have not inadvertently altered the cladding's susceptibility to breakaway oxidation.
 - a. Follow the experimental procedure provided in Appendix A to this regulatory guide to retest cladding performance on an established periodic basis.
 - b. It is acceptable to measure the onset of breakaway oxidation for only the temperature at which the minimum time to breakaway oxidation was measured. Also, as-manufactured cladding may be used if the initial testing (see Regulatory Position 1) showed that surface scratches and postmanufacture cleaning processes have insignificant effects (i.e., results are within data scatter) on breakaway oxidation time.
 - c. Address variability by conducting five repeat tests at the temperature at which the minimum time to breakaway oxidation was determined during the initial testing (see Regulatory Position 1).
3. Report the results.
 - a. As specified by 10 CFR 50.46(c), the 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."
 - b. It is acceptable to report only changes in the time to the onset of breakaway oxidation.

D. IMPLEMENTATION

The purpose of this section is to provide information to applicants and licensees regarding the NRC's plans for using this regulatory guide.

This regulatory guide provides the NRC's first guidance on a new rule. When there is an issuance of a new rule, the agency backfitting considerations have been taken into account in the related rulemaking. The position of this guide is one methodology to meet the requirements of the rule. While an applicant or licensee is not required to use the methodology set forth in this guidance, they are required to comply with the rule. Should the applicant or licensee elect to use a different methodology, the NRC staff may require a demonstration of how the proposed methodology complies with rule. This regulatory guidance complies with backfit requirements set forth in 10 CFR 50.109.

GLOSSARY

alpha layer—For the purposes of this regulatory guide, refers to the zirconium phase that is characterized by a hexagonally close-packed crystal structure and is stable at room temperature. At high temperatures, the beta phase is stable; however, dissolved oxygen can stabilize the alpha phase at high temperature.

beta layer—For the purposes of this regulatory guide, refers to the zirconium phase that is characterized by a cubic crystal structure and is stable at elevated temperatures of approximately 1,000 °C.

breakaway oxidation—For the purposes of this regulatory guide, the fuel-cladding oxidation phenomenon in which the weight gain rate deviates from normal kinetics. This change occurs with a rapid increase of hydrogen pickup during prolonged exposure to a high-temperature steam environment, which promotes loss of cladding ductility.

corrosion—For the purposes of this regulatory guide, the formation of a zirconium oxide layer resulting from the reaction of zirconium with coolant water during normal operation.

loss-of-coolant accident (LOCA)—A hypothetical accident that would result from the loss of reactor coolant, at a rate in excess of the capability of the reactor coolant makeup system, from breaks in pipes in the reactor coolant pressure boundary up to and including a break equivalent in size to the double-ended rupture of the largest pipe in the reactor coolant system.

oxidation—For the purpose of this regulatory guide, the formation of a zirconium oxide layer resulting from the reaction of zirconium with high-temperature steam during LOCA conditions.

monoclinic oxide—For the purposes of this regulatory guide, the oxide phase that develops during normal operation and is neither fully dense nor protective. Although the oxide phase that typically develops under LOCA conditions is the tetragonal oxide phase, conditions might occur during a small-break LOCA (such as extended time-at-temperature around 1,000 °C (1,832 °F)) that promote a transformation to the monoclinic phase.

tetragonal oxide—For the purposes of this regulatory guide, the oxide phase that develops under LOCA conditions that is dense and adherent and that is observed to be protective with respect to hydrogen pickup.

REFERENCES¹

1. 7X FR XXXXX, “Proposed Rule FRN,” *Federal Register*, Volume 7X, Number XXX, p. XXXX, Washington, DC, June 31, 2011. (*insert FRN of proposed rule reference when available*)
2. NUREG/IA-0211, “Experimental Study of Embrittlement of Zr-1%Nb VVER Cladding under LOCA-Relevant Conditions,” U.S. Nuclear Regulatory Commission, Washington, DC, March 2005. (ADAMS Accession No. ML051100343)
3. IFE/KR/E-2008/004, “LOCA Testing of High Burnup PWR Fuel in the HBWR. Additional PIE on the Cladding of the Segment 650-5,” Institute for Energy Technology, Kjeller, Norway, April 2008. (ADAMS Accession No. ML081750715)
4. Research Information Letter 0801, “Technical Basis for Revision of Embrittlement Criteria in 10 CFR 50.46,” U.S. Nuclear Regulatory Commission, Washington, DC, May 30, 2008. (ADAMS Accession No. ML081350225)
5. NUREG/CR-6967, “Cladding Embrittlement during Postulated Loss-of-Coolant Accidents,” U.S. Nuclear Regulatory Commission, Washington, DC, July 2008. (ADAMS Accession No. ML082130389)
6. Yan, Y., T.A. Burtseva, and M.C. Billone, “High-Temperature Steam-Oxidation Behavior of Zr-1Nb Cladding Alloy E110,” *Journal of Nuclear Materials*, 393(3): 433–448.

¹ Publicly available NRC published documents are available electronically through the Electronic Reading Room on the NRC’s public Web site at: <http://www.nrc.gov/reading-rm/doc-collections/>. The documents can also be viewed on-line or printed for a fee in the NRC’s Public Document Room (PDR) at 11555 Rockville Pike, Rockville, MD; the mailing address is USNRC PDR, Washington, DC 20555; telephone 301-415-4737 or (800) 397-4209; fax (301) 415-3548; and e-mail pdr.resource@nrc.gov.

APPENDIX A

PROCEDURE FOR CONDUCTING BREAKAWAY OXIDATION TESTS WITH ZIRCONIUM-BASED CLADDING ALLOYS

Contents

A-1. PURPOSE AND SCOPE OF THE TESTS	A-3
A-2. BACKGROUND	A-3
A-3. SAMPLE SELECTION AND TESTING FREQUENCY	A-7
A-3.1. Sample Selection	A-7
A-3.2. Frequency of Testing	A-8
A-4. SAMPLE PREPARATION AND CHARACTERIZATION	A-8
A-4.1. Hydrogen-Content Determination for As-Fabricated Samples	A-8
A-4.2. Minimum Sample Lengths for One- and Two-Sided Oxidation Tests	A-8
A-4.3. End-Cap Mass and Welding Procedure for One-Sided Oxidation Test Samples	A-8
A-4.4. Length, Outer-Diameter, and Wall-Thickness Measurements	A-9
A-4.5. Pretest Cleaning with Chemical Detergent or Organic Solvent and Rinsing	A-9
A-4.6. Pretest Sample Weight Measurement (after Drying)	A-9
A-5. TEMPERATURE HEATUP AND COOLDOWN RATES AND HEATING METHODS	A-9
A-5.1. Temperature Heatup and Cooldown Rates	A-9
A-5.2. Radiant Heating	A-10
A-5.3. Resistance Heating	A-10
A-5.4. Induction Heating	A-10
A-5.5. Direct Electrical Heating	A-10
A-6. TEMPERATURE CONTROL AND MONITORING	A-10
A-6.1. Thermocouples	A-10
A-6.2. Thermal Benchmarks	A-11
A-6.3. Weight-gain Benchmarks	A-11
A-7. WATER QUALITY, STEAMFLOW RATE, AND STEAM PRESSURE	A-12
A-7.1. Water Quality	A-12
A-7.2. Steamflow Rate	A-12
A-7.3. Steam Pressure	A-13
A-8. TEST PROCEDURE	A-13
A-8.1. Test Train and Steam Chamber	A-13
A-8.2. Purging Steam Chamber and Stabilizing Steam Flow	A-13
A-8.3. Ramping Temperature and Holding Temperature at Target Value	A-14
A-8.4. End of Heating Phase and Cooldown	A-14
A-8.5. Determination of Test Time	A-14

A-9. POSTTEST MEASUREMENTS AND CHARACTERIZATION	A-14
A-9.1. Sample Drying Time	A-14
A-9.2. Weight Measurement and Use of Weight Gain to Verify Oxidation Temperature	A-15
A-9.3. Visual Examination of Sample Outer Surface	A-15
A-9.4. Hydrogen Analysis for Samples with Outer-Surface Discoloration (Relative to Lustrous Black)	A-15
A-9.5. Criterion (200-wppm Hydrogen Pickup) for Breakaway Oxidation Based on Retention of Ductility	A-16
A-9.6. Characterization for One-Sided and Two-Sided Oxidation Test Samples	A-16
A-10. TEST TEMPERATURES	A-17
A-11. REFERENCES	A-20

A-1. Purpose and Scope of the Tests

Performance-based tests are needed to ensure that fuel-rod cladding retains ductility following long-time oxidation in steam at temperatures in the range of 650–1,050 degrees Celsius (°C). Such long-time exposure to steam is especially relevant to postulated small-break loss-of-coolant accidents (LOCAs). All zirconium (Zr)-based cladding alloys will experience breakaway oxidation within this temperature range if steam exposure times are long enough. Concurrent with breakaway oxidation is an increase in hydrogen pickup, which can cause cladding embrittlement. This procedure describes isothermal tests to be conducted with fresh cladding samples to determine the minimum breakaway time. The minimum breakaway time is defined as the time required to pick up 200-weight parts per million (wppm) hydrogen through the cladding outer-surface oxide.

A-2. Background

During a LOCA, the cladding outer surface will be exposed to steam at elevated temperatures. The oxide phase (tetragonal) formed on the cladding outer surface under LOCA conditions is typically lustrous black, dense, and protective with respect to hydrogen pickup (Refs. 1, 2, and 3). In contrast, the corrosion layer formed during normal operation is monoclinic, partially cracked, and only partially protective with respect to hydrogen pickup.

For stoichiometric zirconium oxide (ZrO_2) formed under stress-free conditions, the tetragonal-to-monoclinic phase transformation temperature is high ($\approx 1,150$ °C). However, the tetragonal phase is stabilized at lower steam-oxidation temperatures by a combination of hypo-stoichiometry ($ZrO_{(2-x)}$), compressive stress, and perhaps grain size. Stress reversals (from compressive to tensile) and chemical impurities (e.g., fluorine) in the oxide layer and at the oxide–metal interface can induce early transformation from the tetragonal to the monoclinic phase. As this transformation results in an increase in the growth rate of the oxide-layer thickness and weight gain, it has been referred to in the literature as breakaway oxidation. Stress reversals generally develop at the oxide–metal interface after long-time (3,000–6,000 seconds (s)) exposure to steam at $\leq 1,050$ °C. The precursor to breakaway oxidation is the transition from a smooth oxide–metal interface to a scalloped interface. The amplitude of the scallops grows with increasing time until breakaway oxidation occurs. Based on surface appearance, metallographic imaging, and local hydrogen content, the instability initiates locally in the cladding outer-surface oxide and grows rather quickly in the circumferential and axial directions. For Zircaloy-4 (Zry-4) oxidized at 1,000 °C, areas of gray spots or thin axial lines observed on the outer surface occur during the phase transformation. For ZIRLO™ oxidized at the same temperature, these areas are yellow or tan. Following the full transformation to monoclinic oxide, the metal–oxide interface is once again smooth and the outer-surface color is uniformly gray or yellow.

The presence of destabilizing trace impurities, especially fluorine, and possibly the absence of stabilizing impurities (e.g., calcium), can induce early breakaway oxidation at temperatures as high as the nominal phase transition temperature for stress-free ZrO_2 . The Russian Zr-1% niobium (Nb) alloy E110 cladding is a classic example of a material that experiences early breakaway oxidation (<600 s), possibly because of the presence of fluorine impurities at the metal surface and within the metal substrate (Refs. 3 and 4).

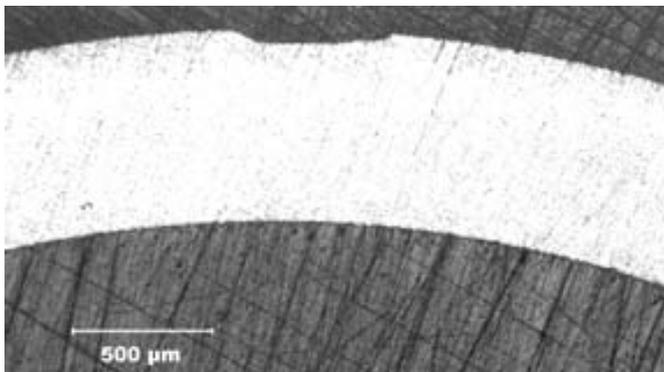
The increase in oxide-layer-thickness growth rate associated with breakaway oxidation does not directly cause cladding embrittlement within LOCA-relevant times. The low-oxygen beta or mixed alpha-beta layer remains ductile within LOCA-relevant times due to low oxygen concentration. However, hydrogen pickup associated with breakaway does cause ductility decrease and embrittlement. As shown in NUREG/CR-6967, “Cladding Embrittlement during Postulated Loss-of-Coolant Accidents,”

issued July 2008 (Ref. 3), cladding oxidized for 3,000–4,000 s at 970–1,000 °C loses ductility for hydrogen pickup values >400 wppm (see Appendix B). In order to ensure ductility as measured by ring-compression tests conducted at 135 °C (275 degrees Fahrenheit (°F)), the breakaway oxidation time in NUREG/CR-6967 (Ref. 3) is defined as the time corresponding to 200-wppm hydrogen pickup. The term “hydrogen pickup” refers to the measured hydrogen level for a sample normalized to the preoxidation mass of the sample from which the as-fabricated hydrogen content is subtracted. The term “hydrogen content” refers to the total hydrogen content in the postoxidized sample normalized to the mass of the oxidized sample. At 200-wppm hydrogen pickup, there is little difference between the measured posttest hydrogen content of the sample and the hydrogen pickup. The hydrogen pickup rate following initiation of breakaway oxidation can be very fast, such that the time to increase from 200 wppm to >400 wppm can be as short as 100 s at oxidation temperatures in the range of 970–1,000 °C. At lower oxidation temperatures, particularly <900 °C, the oxidation rate and hydrogen generation rate are considerably lower. As the hydrogen generation rate decreases, the rate of hydrogen pickup also decreases.

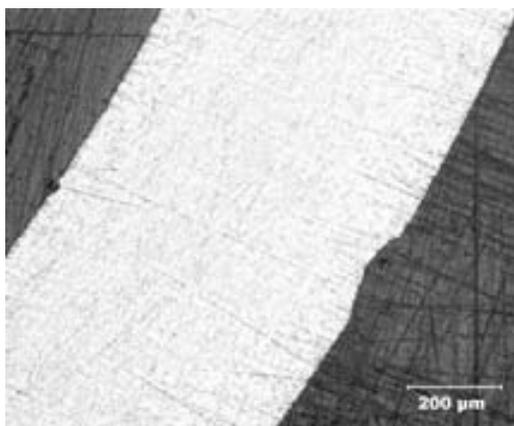
The transition from tetragonal to monoclinic oxide is an instability phenomenon dependent on many manufacturing variables, particularly those affecting cladding outer-surface conditions. For susceptible alloys such as E110 (Ref. 3), the presence of geometrical discontinuities due to scratches, sample ends, and a thermocouple (TC) welded to the cladding will induce earlier breakaway oxidation. Also, for E110, high-surface roughness coupled with pretest cleaning in a hydrofluoric (HF)-containing acid induces very early breakaway oxidation in terms of both surface appearance and hydrogen pickup. For E110, the sequence of finishing operations is important. Etching with an HF-containing acid before polishing seems to have no significant effect on breakaway oxidation, while etching after polishing can have a very detrimental effect on breakaway oxidation time. Modern cladding alloys currently used in the United States are considerably more stable than E110. However, even these polished alloys with low surface roughness are sensitive to postpolishing cleaning methods. A good example of this is the breakaway oxidation times reported in the literature for Zry-4. For an older variant of Zry-4, the data generated by Leistikow and Schanz (Ref. 2) give the minimum time to accumulate 200 wppm of hydrogen as 1,800 s, which occurs at an oxidation temperature of 1,000 °C. Mardon, et al. (Ref. 5) report a hydrogen content of 200 wppm at ≈5,400 s for modern, polished AREVA Zry-4 also oxidized at 1,000 °C. NUREG/CR-6967 (Ref. 3) determined breakaway oxidation times at ≈1,000 °C (based on 200-wppm hydrogen pickup) of 3,800 s for an older variant of Zry-4 and 5,000 s for modern, polished AREVA Zry-4. Baik and Jeong (Ref. 6) oxidized polished Zry-4 for 3,600 s at 1,000 °C and measured >600 wppm of hydrogen. For this case, the estimated time for 200-wppm hydrogen pickup is in the range of 3,000–3,300 s. The two studies with the lower breakaway oxidation times for Zry-4 have one critical step in common. In both studies, Zry-4 samples were cleaned in an HF-containing acid before steam oxidation: nitric-fluoric acid mixture and final cleaning in boiling water for the Leistikow and Schanz (Ref. 2) tests; and 5% HF + 45% HNO₃ + 50% H₂O with final ultrasonic cleaning in an ethanol and acetone solution for the Baik and Jeong (Ref. 6) tests. In the Argonne National Laboratory (ANL) study described in NUREG/CR-6967 (Ref. 3), samples used to generate breakaway oxidation data were cleaned ultrasonically in ethanol followed by water. In the Mardon study (Ref. 5), samples were degreased in acetone before testing.

As breakaway oxidation may be sensitive to many variables related to surface finishing and cleaning, it is important to test samples that have undergone the full cleaning cycle, from the polishing phase through the operations at the fuel fabrication plant to the insertion of assemblies into the reactor. Cleaning with water, chemical detergents (e.g., Alconox), or organic solvents appears to have no significant effect on breakaway oxidation time. However, postpolishing steps involving etching in an HF-containing acid, even a very light etching in a 1% HF-acid mixture for 15 s, must be simulated. In addition to simulation of the postpolishing cleaning processes, scratching of the outer surface that may occur during insertion of rods into assemblies must also be simulated. Cladding surface imperfections and scratches should be quantified and simulated in the testing laboratory because they act as initiation

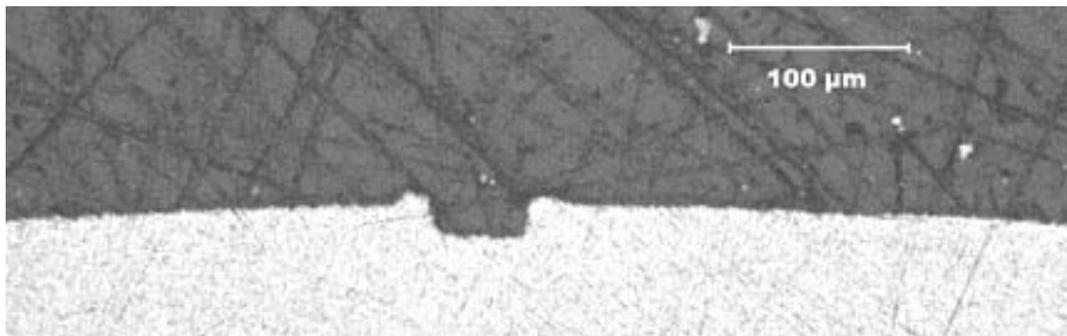
sites for breakaway oxidation due to the effects of the geometrical discontinuity on the stress state in the oxide and at the metal–oxide interface. A “design-basis” scratch should be established based on manufacturing experience and may be assembly-design specific or cladding-material specific. Documentation should be provided to justify the scratch depth and width. If no documentation is provided, then the scratch should extend along the length of the sample and have a depth of 50 ± 5 micrometers (μm) and a width of $\geq 50\pm 5$ μm , defined as bounding based on metallographic observations made of scratches induced by repeated insertion of fuel rod cladding into and out of grid spacers. Examples of bounding, design-basis, and ANL-machined scratches are shown in Figure A-1. The scratches shown in Figure A-1(a) and (b) were induced by repeated insertion of fuel rod cladding into and out of grid spacers.



(a) Example of a bounding scratch ($\approx 50\text{-}\mu\text{m}$ deep into wall)



(b) Example of a design-basis scratch ($\approx 30\text{-}\mu\text{m}$ deep into wall)



(c) ANL-machined scratch used for breakaway oxidation studies ($\approx 20\text{-}\mu\text{m}$ deep into wall)

Figure A-1. Examples of scratches on the outer surface of cladding: (a) low-magnification image of a bounding scratch induced by excessive number of insertions in grid spacers, (b) medium-magnification image of an example design-basis scratch from insertion into grid spacers, and (c) high-magnification image of an ANL-machined scratch used in breakaway oxidation studies.

Breakaway oxidation test results reported in the literature are based on isothermal test conditions. The test times listed in NUREG/CR-6967 (Ref. 3) include the time (≈ 80 s) to ramp from 300 °C to the target temperature and the hold time at that temperature. The added ramp time is small relative to the hold times associated with breakaway oxidation. Additional studies by Yan et al. (Ref. 19) indicate that isothermal temperature tests generally give lower bound breakaway oxidation times as compared to breakaway times determined from tests with transient temperature histories. In one of the transient tests conducted by Yan et al., the temperature was held at the critical temperature (980 °C) for 2,000 s, cycled five times between 930 °C and 1,030 °C for 400 s, and then held at 980 °C for 400 s. The hydrogen content and pickup were 230 ± 80 wppm, which indicated that breakaway oxidation had occurred for this particular cladding alloy. Previous isothermal results for as-fabricated, prescratched, and preoxidized ($< 1 \mu\text{m}$ film) samples gave a minimum breakaway time of $3,100 \pm 300$ s. For this particular transient, breakaway oxidation occurred at the lower bound of this range and was consistent with results for a prescratched sample oxidized under isothermal conditions.

The test times for the breakaway studies reported in NUREG/CR-6967 (Ref. 3) were generally $\leq 5,000$ s. Some early tests, conducted at 7,200 s, resulted in excessive breakaway oxidation. Although there is no generic maximum time at elevated temperature for a LOCA, a maximum isothermal test time of 5,000 s appears reasonable based on other considerations, such as the Cathcart-Pawel equivalent cladding reacted (CP-ECR) limit in the balloon ($< 17\%$) when ballooning and rupture are predicted to occur. The minimum breakaway oxidation time is expected to occur in the temperature range of 950–1,000 °C. For modern cladding alloys, the as-fabricated cladding wall thickness varies from 0.57 millimeter (mm) to 0.71 mm. For thin cladding that ruptures, 17% CP-ECR corresponds to $< 2,400$ s at 1,000 °C, $< 3,300$ s at 975 °C, and $< 4,600$ s at 950 °C. These times decrease significantly if wall thinning is included in the calculation. For thick cladding that ruptures, 17% CP-ECR corresponds to $< 3,300$ s at 1,000 °C, $< 5,100$ s at 975 °C, and $< 7,100$ s at 950 °C. With a modest 20% diametral ballooning or creep strain, these times for thicker cladding are reduced to $< 2,610$ s at 1,000 °C, $< 3,580$ s at 975 °C, and $< 5,000$ s at 950 °C. Thus, for most of these cases, breakaway oxidation times $> 5,000$ s would not be relevant because of the $\leq 17\%$ CP-ECR limit. The procedure for conducting tests for $\leq 5,000$ s with emphasis on 950–1,000 °C oxidation temperatures is described in the following sections.

A-3. Sample Selection and Testing Frequency

A-3.1 Sample Selection

The samples selected for testing should be representative of the fueled cladding that is loaded into the reactor. In particular, samples should be exposed to the same postpolishing, outer-surface cleaning processes used before loading fuel assemblies into the reactor. Cleaning agents that have been found to be benign with respect to breakaway oxidation include water, chemical detergents (e.g., Alconox), and organic solvents (e.g., ethanol, acetone). However, the use of etching in an HF-containing acid mixture can initiate early breakaway oxidation in some alloys. These cleaning processes may be simulated in the laboratory.

Also, the samples should have at least one design-basis or bounding scratch observed to occur from insertion of fuel rods into assembly grid spacers. Documentation should be provided to justify the scratch depth and width. If no documentation is provided, then the scratch should extend along the length of the sample and have a depth of $50 \pm 5 \mu\text{m}$ and a width of $\geq 50 \pm 5 \mu\text{m}$, defined as bounding based on metallographic observations made of scratches induced by repeated insertion of fuel rod cladding into and out of grid spacers. Cladding tube scratching may be simulated in the laboratory.

Although as-fabricated cladding may be used for scoping studies, the minimum breakaway oxidation time should be determined from scratched samples exposed to all postpolishing cleaning processes.

A-3.2 Frequency of Testing

Because breakaway oxidation is an instability phenomenon that is sensitive to surface roughness, surface and substrate impurities, and alloy constituents and impurities, testing should be repeated after significant changes to these variables. Some processing factors that may be significant are revised specifications that allow $>0.2\text{-}\mu\text{m}$ surface roughness, a change of polishing material, introduction of postpolishing cleaning with an HF-containing acid mixture, and changing the cladding vendor. As it would take an extensive study to determine the breakaway-oxidation sensitivity for a particular cladding material to each of these variables, some periodic testing should be done even if minor changes are made.

If it has been shown that scratches and postpolishing cleaning have an insignificant effect (i.e., results within data scatter) on the minimum breakaway oxidation time, then as-manufactured cladding may be used for periodic testing.

A-4. Sample Preparation and Characterization

A-4.1 Hydrogen-Content Determination for As-Fabricated Samples

The hydrogen content of as-fabricated cladding is expected to be low (5–15 wppm) and to be available from the tubing vendor. It is used in the calculation to determine the hydrogen pickup during breakaway oxidation. If it is not available, it should be measured.

A-4.2 Minimum Sample Lengths for One- and Two-Sided Oxidation Tests

Most breakaway-oxidation testing has been performed with cladding sample lengths in the range of 25–50 mm for two-sided oxidation tests. These lengths were sufficient to minimize end effects. Therefore, the minimum sample length should be 25 mm. Although there is no maximum limit prescribed, it should be no longer than the length of the uniform temperature region of the furnace. Uniform is defined as $\leq \pm 10\text{ }^{\circ}\text{C}$ variation at the target temperature.

In preparing samples for one-sided oxidation tests, welded end caps are used to prevent steam from coming into contact with the cladding inner surface. In order to minimize larger end effects due to the presence of welding heat-affected zones, the minimum sample length for one-sided oxidation tests should be 75 mm.

A-4.3 End-Cap Mass and Welding Procedure for One-Sided Oxidation Test Samples

Standard procedures are available for circumferential welding of end caps to cladding samples. Because the welds and end caps are not subjected to pressure, the end caps should be small and the masses should be minimized as they serve as sinks for hydrogen.

The room-temperature pressure inside the welded cladding sample should be low enough to give an internal pressure at the target oxidation temperature that is less than the external steam pressure. Also, it is recommended that the gas remaining inside the cladding sample be free of impurities (e.g., nitrogen).

A-4.4 Length, Outer-Diameter, and Wall-Thickness Measurements

Outer diameter and wall thickness vary somewhat along the length of fuel rod cladding. They should be measured and recorded for each sample. For cladding with a nominal diameter of 9.50 mm, the actual diameter of the sample can vary from 9.46 to 9.50 mm. The outer diameter should be determined to two decimal places (in mm) based on the average of the maximum and minimum diameters. For cladding with a nominal wall thickness of 0.57 mm, the actual wall thickness can vary from about 0.56 to 0.60 mm. Wall thickness should be determined for each sample to two decimal places (in mm) based on four readings at locations $\approx 90^\circ$ apart. The actual sample length should be measured and recorded to one decimal place accuracy (e.g., 25.1 mm). Also, the ends of the sample should be polished to remove burrs before sample-length measurement. While removing burrs, it is important to avoid scratching the cladding inner surface, especially with circumferential grooves, which would induce early hydrogen pickup. Also, the ends of the sample should be relatively flush ($90 \pm 5^\circ$ relative to the longitudinal axis). Outer diameter, wall thickness, and length are used to normalize sample weight gain to exposed surface area.

A-4.5 Pretest Cleaning with Chemical Detergent or Organic Solvent and Rinsing

Appendix X1, "Guide to Specimen Preparation," to American Society for Testing and Materials (ASTM) G2/G2M-06, "Standard Test Method for Corrosion Testing of Products of Zirconium, Hafnium, and Their Alloys in Water at 680°F [360°C] or in Steam at 750°F [400°C]," describes sample cleaning procedures in Section X1.2 (Ref. 7). These procedures should be followed for breakaway oxidation tests. Specifications and requirements in Sections X1.1 (on tubes with a second material on the inner diameter) and X1.3 (on etching) should be ignored. Based on NUREG/CR-6967 (Ref. 3) and subsequent work by ANL, samples should not be etched with an HF-containing acid mixture as part of the test cleaning process (see Appendix B). After cleaning, direct contact with the sample should be avoided by using surgical gloves for handling.

A-4.6 Pretest Sample Weight Measurement (after Drying)

Pretest sample weight should be measured to the nearest 0.1 milligram (mg) as specified in Section 7.1.3 of ASTM G2/G2M-06 (Ref. 7). Because drying after cleaning may take several hours, it is also permissible to measure pretest sample weight after cleaning with an organic solvent, such as ethanol, that vaporizes quickly. The pretest weight is used in the determination of sample weight gain. Although weight gain is not used as a metric for breakaway oxidation in these tests, it is used as a partial validation of the reported isothermal oxidation temperatures and a check on steamflow conditions.

A-5. Temperature Heatup and Cooldown Rates and Heating Methods

A-5.1 Temperature Heatup and Cooldown Rates

For long-time isothermal tests, heating and cooling rates are not expected to be critical parameters. However, long heating and cooling times should be avoided because they may induce breakaway oxidation at earlier isothermal-temperature times. The total ramp time from 650 °C to the target temperature (heating phase) and from the target temperature to 650 °C should be <10% of the isothermal test time. It is also not clear if temperature overshoot during the heating phase has any effect on isothermal breakaway oxidation time. However, temperature overshoot should be limited to ≤ 20 °C for ≤ 20 s.

Rapid cooling by means of water quench is not required for breakaway oxidation tests. However, for very slow-cooling furnaces, quench may be used to reduce the cooling time.

A-5.2 Radiant Heating

Radiant heating in a quad-elliptical furnace has been used to generate breakaway-oxidation data (Refs. 1, 3, and 6). This heating method, along with furnace power controlled by feedback from a TC on or near the sample, allows for controlled heating rates and relatively fast cooling times (<100 s from 1,000 °C to 650 °C). For 25-mm-long samples with a 9.50-mm outside diameter, axial temperature variations are negligible, but circumferential temperature variations are in the range of 10–15 °C. These can be reduced by using radiant-heating furnaces with more than four lamps. However, the circumferential variation has a practical value because a range of temperatures (e.g., 1,000±10 °C) can be investigated with a single sample. With proper thermal benchmarking, radiant-heating furnaces are acceptable for conducting breakaway oxidation tests.

A-5.3 Resistance Heating

Most breakaway oxidation tests (e.g., Refs. 2, 4, and 5) have been conducted in resistance-heating furnaces. Compared to radiant-heating furnaces, these furnaces have a larger uniform temperature zone and have very slow heating and cooling rates. Faster heating and cooling rates are achieved by controlled movement of the sample into and out of the furnace. Benchmark tests should be performed to determine the heating and cooling rates—necessary information for the determination of the time to reach the target isothermal temperature. Resistance-heating furnaces are acceptable for conducting breakaway oxidation tests.

A-5.4 Induction Heating

Induction heating has the advantage of rapid heating and cooling rates. It has been used in the CINOG program in France (Ref. 8) to generate weight-gain kinetics data for Zry-4, M5, and developmental alloys. Although the weight gain data appear reliable, it is not clear what impact this heating method would have on initiation of breakaway oxidation. It is also not clear whether the use of optical pyrometry to measure temperature requires etching of the cladding surface. Because of the uncertainties about induction heating, optical pyrometry, and required surface preparation, induction heating is not recommended for breakaway oxidation studies.

A-5.5 Direct Electrical Heating

Direct electrical heating of cladding has been used in the past for LOCA-relevant studies. Because resistance and heating rate change with temperature and because of the unknown effects of such heating on breakaway oxidation, direct electrical heating of cladding is not recommended for breakaway oxidation studies. However, indirect electrical heating may be an acceptable method for internal heating of another material inside the cladding to generate a heat flux simulating heating of the cladding by means of decay heat from the fuel.

A-6. Temperature Control and Monitoring

A-6.1 Thermocouples

For the temperatures relevant to this breakaway oxidation test procedure, the TCs used to record temperature and control furnace power may be either Type K (chromel-alumel) or Type S (platinum (Pt)/10% rhodium-Pt). The TCs must be calibrated using instrumentation and standards that

are traceable to the National Institute of Standards and Technology (NIST). Typically, this service is provided by the TC vendor, who, for an extra fee, provides a certificate of calibration. Every TC used in the breakaway oxidation study to monitor sample temperature, either directly or indirectly, must have a certificate of calibration showing the results of the calibration at a minimum of two temperatures: 800 °C and 1,000 °C. Copies of these certificates should accompany the data report. Verification should be provided demonstrating that the vendor actually did the calibration according to the standards in internationally recognized standards organizations, such as the International Organization for Standardization (ISO), and American National Standards Institute/National Conference of Standards Laboratories (ANSI/NCSL).

A-6.2 Thermal Benchmarks

Welding TCs directly onto the outer surface of the breakaway oxidation sample is not recommended. The geometric discontinuity at the TC-sample junction can induce early breakaway oxidation, which would be an artifact. Also, the presence of the TC during testing and its removal after testing will affect the accuracy of the posttest sample weight.

In most cases, the control TC will be welded onto the sample holder or as close to the sample as possible without contacting the sample. This requires thermal benchmarks to be performed to establish the relationship between the control TC that will be used during data-generating tests and the temperature of the sample outer surface. The thermal benchmarking should be performed at a minimum of two temperatures: 1,000 °C and 800 °C. For the work reported in NUREG/CR-6967 (Ref. 3), two or three TCs (120° apart) were welded directly onto the benchmark sample outer surface. These readings were compared to the readings of three TCs welded onto the sample holder at a location just above the sample. For radiant-heating and large-diameter (≈ 11 mm) cladding, three TCs were welded directly to the cladding outer surface to better define the average and one-standard-deviation cladding temperature. For smaller diameter cladding (9.50 mm), only two TCs welded directly to the cladding surface were needed. For the thermal benchmark tests, it is important that these be conducted under the same flowing steam conditions used in the data-generating tests.

For resistance-heating furnaces, the same thermal-benchmarking method described for radiant-heating furnaces can be used. However, other methods can be used to determine the relationship between the sample temperature and the holder temperature. These furnaces come with a built-in TC that controls the power to the furnace. Thermal benchmarking can be done with a suspended and moveable TC to map out the axial variation in temperature for a sample assembled into a test train. Recorded temperatures should be compared to the TC or TCs welded to the sample holder. Circumferential temperature variations are generally small for such furnaces. The results of the thermal benchmark tests should be documented and included in the data report.

A-6.3 Weight-Gain Benchmarks

After thermal benchmarking, samples should be tested without TCs welded onto the sample to determine the weight gain. These tests should be conducted at 800 °C and 1,000 °C. The test times should be less than those that result in breakaway oxidation. For 1,000 °C, an isothermal test time of 2,000 s is recommended. For Zircaloy-2 (Zry-2), Zry-4, and ZIRLO™ alloys oxidized at 1,000 °C for $\leq 2,000$ s, the measured weight gain (normalized to the surface area exposed to steam) was in good agreement with the Cathcart-Pawel (CP) correlation predictions (Ref. 3). If the measured weight gain differs from the CP-predicted weight gain by $\geq 10\%$, then data-generating testing should not be initiated until the discrepancy is resolved. For Zr-lined Zry-2 and Zr-1Nb alloys, the measured weight gain at 1,000 °C was considerably less than the CP-predicted weight gain (Ref. 3). For these materials, the results of the weight-gain benchmark should be compared to the vendor-generated database or the results

given in NUREG/CR-6967 (Ref. 3) for these alloys. Below 1,000 °C, especially below 950 °C, the CP correlation deviates from the well-established databases for cladding alloys and ceases to be a best-estimate correlation. For the weight-gain benchmark at 800 °C, the normalized measured weight-gain should be compared to a well-established vendor-generated database. The results of the weight-gain benchmark tests should be documented and included in the data report.

A-7. Water Quality, Steamflow Rate, and Steam Pressure

A-7.1 Water Quality

The NRC staff strongly recommends that purified water be used for generating steam. NUREG/CR-6967 (Ref. 3) testing indicated that water quality can influence the measured time to the onset of breakaway oxidation. The recommendations on water quality are intended to prevent initiating early breakaway oxidation due to experimental artifacts.

ASTM G2/G2M-06 (Ref. 7) specifies that Grade A water with ≤ 45 parts per billion of oxygen should be used for corrosion tests in pressurized water and steam. Laboratory-grade Type I (distilled or deionized) water is also of sufficient purity for breakaway oxidation tests at ≥ 650 °C. ASTM, the National Committee for Clinical Laboratory Standards (now the Clinical and Laboratory Standards Institute), and ISO 3696 have similar definitions for Type I purified water.

A-7.2 Steamflow Rate

The average steamflow rate used in breakaway oxidation studies should be determined (and reported) from the mass of condensed water collected during these long-time tests or by the mass of water that is input to the steam chamber divided by the test time and normalized to the net cross-sectional area of the steam chamber. The average steamflow rate should be in the range of 0.5 to 30 mg/square centimeter per second ($\text{cm}^2 \cdot \text{s}$). Justification for this range is provided in the following paragraphs.

Leistikow and Schanz (Ref. 2) and Uetsuka (Ref. 9) studied the effects of low steamflow rates on the oxidation kinetics of Zry-4 at 1,000 °C. Their results are summarized in Leistikow and Schanz, Figure 9 (Ref. 2). In terms of flow rate normalized to the cross-sectional area of the steam chamber, the oxidation kinetics began to decrease due to steam starvation for flow rates < 0.05 $\text{mg}/(\text{cm}^2 \cdot \text{s})$. For the Leistikow and Schanz work, the sample length was 30 mm and oxidation was two-sided. Aomi, et al. (Ref. 10) studied the relationship between weight gain and steamflow rate for oxidation temperatures up to 1,200 °C. They found that the weight gain for fixed test times and temperatures was independent of steamflow rates in the range of 0.8 to 7.8 $\text{mg}/(\text{cm}^2 \cdot \text{s})$. Kawasaki, et al. (Ref. 11) also performed high-temperature oxidation tests to determine the range of steamflow rates for which the weight gain for a given test time was independent of steamflow rate. They report this range as 3 to 28 $\text{mg}/(\text{cm}^2 \cdot \text{s})$.

For breakaway oxidation studies conducted in steam at $\leq 1,050$ °C, the results of Leistikow and Schanz, Uetsuka, and Aomi, et al. (Refs. 2, 9, and 10) are particularly relevant for the minimum steamflow rate. However, because individual sample lengths (≥ 25 mm for two-sided tests and ≥ 75 mm for one-sided tests) include lengths longer than used in the Leistikow and Schanz study and as many as five two-sided test samples may be stacked inside the steam chamber, the minimum steamflow rate is set at 0.5 $\text{mg}/(\text{cm}^2 \cdot \text{s})$, which is 10 times the minimum given in Leistikow and Schanz and Uetsuka (Refs. 2 and 9). For the results presented in NUREG/CR-6967 (Ref. 3), the normalized steamflow rate was 5.3 ± 0.8 $\text{mg}/(\text{cm}^2 \cdot \text{s})$. This rate is well above the minimum rates determined from Leistikow and Schanz (Ref. 2), Uetsuka (Ref. 9), Aomi, et al. (Ref. 10), and Kawasaki, et al. (Ref. 11).

Although Aomi, et al. (Ref. 10) and Kawasaki, et al. (Ref. 11) give maximum steamflow rates of 7.8 and 28 mg/(cm² · s) respectively, it is not clear why higher steamflow rates would have an effect on weight gain and oxidation kinetics. It is desirable to have a steamflow rate higher than 0.5 mg/(cm² · s) to reduce temperature overshoot during the heating phase for bare cladding. Baek and Jeong (Ref. 6) cite a fast heating rate of 50 °C/s and a temperature overshoot for about 20 s at the end of the heating ramp with a steamflow rate of 10 mg/(cm² · s). Although the maximum steamflow rate may not be as critical as the minimum steamflow rate, it should be limited to ≤30 mg/(cm² · s) for the purposes of breakaway oxidation tests.

A-7.3 Steam Pressure

Breakaway oxidation tests should be conducted at a steam pressure at or slightly above atmospheric pressure. This is consistent with the pressures that were used in previous breakaway oxidation studies (Refs. 2, 3, 6, and 9).

A-8. Test Procedure

The specific details of the test procedure depend on the heating furnace used. Described below are the steps used in NUREG/CR-6967 (Ref. 3), along with some generalizations that would apply to other heating and cooling methods than the radiant-heating furnace used in that study. Detailed steps for NUREG/CR-6967 testing are documented in Reference 13.

A-8.1 Test Train and Steam Chamber

The test train or sample holder and the steam chamber form a unit that should be designed to contain the steam flow and to prevent impurities, especially nitrogen, from entering the chamber. By using steam that has a pressure slightly greater than the surrounding atmosphere, the test train and steam chamber do not have to be leak-tight to a high level to serve the functions of providing a pathway for steam flow and protecting the sample from gas-phase impurities.

In choosing the material for the test train or sample holder, it is desirable to have a nonoxidizing or limited-oxidizing material such as stainless steels or nickel (Ni) alloys (e.g., Inconel 600). However, the sample must be protected from direct contact with materials such as iron (Fe) and Ni alloys because of the low-temperature eutectics for Zr and these elements. Hofmann and Markiewicz (Ref. 12) studied the reaction rates and eutectics of Zry-4 and Inconel 718. They also presented binary phase diagrams for Zr-Fe and Zr-Ni, which have eutectic temperatures as low as ≈930 °C and 980 °C, respectively. In NUREG/CR-6967 (Ref. 3), alumina inserts and zirconia washers were used between the Inconel holder and the sample to prevent such reactions from occurring. Testing laboratories may institute controls other than those used in NUREG/CR-6967 to prevent eutectic reactions between Zr-based alloys and the test train materials.

A-8.2 Purging Steam Chamber and Stabilizing Steam Flow

Before heating and initiating steam flow, the steam chamber is filled with gas representative of the environment of the test facility (e.g., usually air). It is strongly recommended that the test chamber be purged with a high-purity inert gas (e.g., argon) before introducing steam flow or that it be purged with low-temperature steam before the temperature ramp. Deviations that may have a significant effect on test results include heating the sample to the target temperature in an inert gas before introduction of steam flow. Impurities in the inert gas will result in an oxide or oxide-nitride film on the cladding that is not LOCA-relevant. If steam is used to purge the steam chamber, then steam flow should be maintained for 500 s before the temperature ramp.

Steam flow should be initiated at a test chamber temperature of ≈ 30 °C. After introduction of steam into the chamber, furnace heating should commence for a pretest hold temperature of 300 °C. Stabilization of steam flow and 300 °C sample temperature will occur within 500 s.

A-8.3 Ramping Temperature and Holding Temperature at Target Value

The target test temperature is predetermined. It should be based on the average sample temperature. Depending on the heating method used, axial and circumferential variations could be significant. For a single sample, the axial temperature variation should be ≤ 10 °C and the circumferential temperature variation should be ≤ 20 °C. These variations are the differences between the maximum and minimum temperatures.

For resistance furnaces, the sample heating rate is controlled by the rate of movement of the sample into the furnace heating zone. For radiant-heating furnaces, the heating rate is controlled through feedback from a TC welded onto the holder to the furnace power. For the radiant heating used in NUREG/CR-6967 (Ref. 3), the temperature ramp rate was programmed to be very fast (>50 °C/s) from 300 °C to within 50–100 °C of the target temperature and slow (2–3 °C/s) from that temperature to the target temperature. This programmed ramp was designed to eliminate temperature overshoot. Typical test times from 650 °C to 1,000 °C were <80 s. It is recommended that the test time from 650 °C to the target temperature be <100 s for long-time isothermal tests.

A-8.4 End of Heating Phase and Cooldown

After the target test time has been reached, furnace power should be turned off while steam flow is maintained. The rate of temperature decrease will depend on the heating method used and the method of removing the sample from the furnace. For in situ cooling, the steam flow should be maintained until the sample temperature reaches 800 °C. For the NUREG/CR-6967 (Ref. 3) work, this corresponded to a holder temperature of 700–720 °C. Following this step, there should be ample moisture in the steam chamber to maintain a steam environment for cooling from 800 to 650 °C.

A-8.5 Determination of Test Time

The isothermal test time should be the time interval between reaching within 20 °C of the target temperature during the heating ramp to cooling within 20 °C of the target temperature during the cooling ramp. Depending on heating and cooling rates, this time will be about equal to the time at which the sample is at constant temperature. If recommended heating and cooling times are used, the test time can be determined as the time above 650 °C or the time between initiation of the heating ramp and the initiation of the cooling ramp (as was done in the ANL study).

A-9. Posttest Measurements and Characterization

A-9.1 Sample Drying Time

In order to determine an accurate posttest sample weight, it is important that the sample be free of moisture. For drying in stagnant air, the drying time should be ≥ 2 hours. This time can be reduced significantly by the use of forced-air drying. Sample weight will continue to decrease during the drying process until it reaches a minimum and holds at that minimum. Whatever drying method is used, the drying time should be verified by weight measurements.

A-9.2 Weight Measurement and Use of Weight Gain to Verify Oxidation Temperature

The posttest sample weight should be measured to the nearest 0.1 mg as specified in Section 7.1.3 of ASTM G2/G2M-06 (Ref. 7). The weight gain (in mg) is determined by subtracting the pretest weight from the posttest weight and normalizing this value to the steam-exposed surface area of the sample. Although this normalized weight gain is not used to determine breakaway oxidation time, it is used to validate temperature control and monitoring as well as the adequacy of steam flow and test procedures.

A-9.3 Visual Examination of Sample Outer Surface

The sample outer surface should be examined visually and photographed. If the outer surface is smooth and lustrous black, then breakaway oxidation has not occurred and no further characterization is needed. If the outer surface is rough and dull black, then the sample may be well beyond the breakaway oxidation time as defined by the 200-wppm hydrogen pickup criterion. This condition is rarely observed at high temperature and would occur only if the discolored (gray or yellow) oxide completely delaminated and spalled off during cooling. If the sample shows any indication of discoloration (see Appendix C), further characterization is needed.

Because of stress reversal at the ends of the sample due to the geometric discontinuity, it is possible that discoloration will appear only at the ends of the sample. Such a discontinuity is an experimental artifact. Beyond photographing such samples, no further characterization is required. However, discoloration and breakaway only at the sample ends are useful data because they indicate that the cladding material is sensitive to stress discontinuities and is close to the breakaway oxidation time. This artifact can be minimized or eliminated by machining a longitudinal scratch (25 ± 5 μm deep and $>25 \pm 5$ μm wide) along the sample. Based on results presented in NUREG/CR-6967 (Ref. 3), such a scratch will induce breakaway oxidation away from the sample ends before the ends experience breakaway oxidation (see Appendix C).

A-9.4 Hydrogen Analysis for Samples with Outer-Surface Discoloration (Relative to Lustrous Black)

Samples with outer-surface discoloration away from the sample ends and samples with rough, dull-black outer-surface oxide should be further characterized by measuring the hydrogen content within the middle two-thirds of the sample. The hydrogen-analysis sample should be a ring that is sectioned to be 2–3 mm long and to include a region of discoloration. The selection of this ring is very important for scratch-free samples, as hydrogen concentration is likely to have local variations ranging from 20 to 600 wppm for a corresponding average ring hydrogen content of 200 wppm. For prescratched samples, the hydrogen concentration along the sample is relatively uniform. As such, the precise location of the hydrogen-analysis ring is not critical. For some cladding materials, breakaway spreads very rapidly at high-oxidation temperatures (e.g., 1,000 °C) along the length and around the circumference of the sample, such that the average hydrogen content increases from 200 wppm to 600–1000 wppm in <200 s (Ref. 3). However, for lower oxidation temperatures (e.g., 800 °C), the time lag between the observation of surface discoloration and significant hydrogen pickup may be much longer (Ref. 2).

For the case of multiple samples (e.g., five) tested at the same temperature and time, the hydrogen content for this set of samples should be reported as the average value plus or minus one standard deviation. The average minus-one standard deviation should be compared to the 200-wppm hydrogen pickup to determine if breakaway has occurred. It is also acceptable to use the 200-wppm hydrogen content of the postoxidized sample (i.e., total sample hydrogen mass normalized to mass of oxidized sample) as the breakaway oxidation criterion.

There are several ways to measure hydrogen content in metals. Vacuum fusion is one method. The recommended method is documented in ASTM E1447-09, “Standard Test Method for Determination of Hydrogen in Titanium and Titanium Alloys by the Inert Gas Fusion Thermal Conductivity/Infrared Detection Method” (Ref. 14). This method has been used successfully to determine the hydrogen content in other metals, such as Zr alloys. The detailed procedure used to generate the results in NUREG/CR-6967 (Ref. 3) are documented in Reference 15.

Along with the necessary instrumentation (e.g., LECO RH-404 hydrogen determinator), calibration standards, which are NIST-traceable and provided by the vendor, are needed. These calibration standards are titanium coupons with hydrogen contents traceable to NIST standards. Titanium coupons with 218 wppm are recommended for calibration and verification of calibration. As these machines are very sensitive, it is important to perform calibration at least once in any given day before data generation. For hydrogen-content output that does not match visual observations (e.g., high hydrogen for lustrous black oxide or low hydrogen for gray or yellow regions of oxidized cladding), posttest calibration verification should be performed by testing a 218-wppm standard as an unknown (i.e., with the same calibration constant determined before testing).

A-9.5 Criterion (200-wppm Hydrogen Pickup) for Breakaway Oxidation Based on Retention of Ductility

As shown in Appendix B, cladding rings with hydrogen pickup values ≤ 440 wppm oxidized at 970–1,000 °C are ductile at 135 °C and brittle for hydrogen pickup values ≥ 600 wppm. The ductile-to-brittle transition is likely to occur for a hydrogen pickup of ≈ 500 wppm. Thus, ductility is retained with an appropriate amount of conservatism for average hydrogen pickup values and posttest hydrogen values ≤ 200 wppm. At 970–1,000 °C oxidation temperatures, the transition from ductile to brittle behavior may occur within 100–200 s. The 200-wppm -hydrogen breakaway criterion is reasonable and justified at the higher oxidation temperatures at which the minimum breakaway oxidation time is most likely to occur.

A-9.6 Characterization for One-Sided and Two-Sided Oxidation Test Samples

For one-sided oxidation tests, oxide is grown only on the sample outer surface. Thus, hydrogen pickup can only occur through the outer-surface oxide. However, possible hydrogen loss to the end caps, which act as a sink for hydrogen, needs to be quantified. Hydrogen loss to the end caps may occur by means of solid-state diffusion or gas-phase transport within the sample interior. Of these two mechanisms, gas-phase transport may be the dominant mechanism for hydrogen transport. The inner surface is in the beta or mixed alpha-beta phase regime. Diffusion across the thin cladding wall, desorption from the cladding inner surface, and adsorption on the inner end-cap surfaces will result in a decrease in hydrogen content in the cladding metal. This effect will be more significant at the higher oxidation temperatures.

For two-sided oxidation tests, low breakaway oxidation times could be confirmed through metallographic examination to verify that breakaway occurred at the outer-surface oxide before it occurred at the inner-surface oxide. Based on one test result reported in NUREG/CR-6967 (Ref. 3), a cladding sample oxidized for $\approx 3,500$ s at 1,000 °C experienced complete tetragonal-to-monoclinic transformation at the cladding inner surface and no such transformation at the cladding outer surface. However, the associated hydrogen pickup was only 100 wppm. Because of the curvature of the inner surface, the oxide tends to be under higher compressive stress than on the outer surface. As such, cracks that form in the monoclinic oxide tend to be very tight, which limits the amount of steam absorbed into these cracks and the amount of hydrogen released and available for pickup.

A-10. Test Temperatures

Leistikow and Schanz (Ref. 2) studied the oxidation kinetics and breakaway oxidation for Zry-4 over a range of temperatures (600–1,600 °C, with temperature increments of 50 °C) for very long times (≤ 25 hours). The results are extremely useful in demonstrating that breakaway oxidation time is not a monotonic function of oxidation temperature. Reinterpreting their data in terms of the 200-wppm-hydrogen criterion for breakaway, Leistikow and Schanz found minimum breakaway times of $\approx 1,800$ s at 1,000 °C and $\approx 3,600$ s at 800 °C. These minimum times occurred at temperatures close to the phase change temperatures for Zry-4 (≈ 980 °C for the $\alpha+\beta \rightarrow \beta$ transition and ≈ 810 °C for the $\alpha+\beta \rightarrow \alpha$ transition). Intermediate temperatures (e.g., 1,025 °C, 985 °C, 825 °C, and 775 °C) were not investigated, and relatively few oxidation temperatures (1,000 °C, 900 °C, 800 °C, and 650 °C) were characterized in terms of increase in hydrogen content with test time. Also, although Zry-4 may be less sensitive to HF-containing acid cleaning than Nb-bearing alloys, it is not clear whether or not the cleaning process (HF-acid mixture) influenced the results.

Others have measured breakaway times for various Zr alloys. Based on the results presented in References 2, 3, 6, 16, 17, and 18, it appears highly likely that the minimum breakaway oxidation time will occur at a temperature near the upper phase-transformation temperature at which oxidation and hydrogen-generation rates are high relative to the lower phase-transformation temperature. For Zircalloys, Zr-1Nb-1Sn, and Zr-1Nb alloys, the upper phase-transformation temperatures are in a rather narrow range (≈ 965 – 985 °C). The lower phase-transformation temperatures for these alloys span a larger range (≈ 650 – 810 °C).

To determine the minimum breakaway oxidation times, oxidation temperatures should include the following high temperatures: 1,050 °C, 1,030 °C, 1,015 °C, 1,000 °C, 985 °C, 970 °C, and 950 °C—resulting in seven separate tests. The maximum test time should be 5,000 s. If the outer surface is smooth and lustrous black, then breakaway oxidation has not occurred and no further characterization is needed. If the outer surface is smooth and lustrous black, indicating breakaway oxidation has not occurred for any of the test temperatures, then four additional tests should be conducted at 1,000 °C to confirm repeatability. Finally, two additional tests should be conducted: a test at 800 °C and a second test at 1,000 °C on a sample with a bounding or design-basis scratch. If the outer surface is smooth and lustrous black following all of the nine test conditions, no further testing is necessary to characterize the breakaway behavior.

If the outer surface is rough and dull black following any test in the initial oxidation temperature set (950 °C–1,050 °C), then the sample may be well beyond the breakaway oxidation time as defined by the 200-wppm hydrogen pickup criterion, and the hydrogen content should be measured. If breakaway oxidation is observed to occur at $< 5,000$ s, the minimum time and corresponding temperature should be reported. Four additional tests should be conducted at this minimum time because of anticipated data scatter for hydrogen content or pickup. After the minimum breakaway time is determined for 950–1,050 °C, a test should be conducted at 800 °C to confirm that breakaway oxidation does not occur at this lower temperature for this particular time. Finally, five repeat tests at the minimum breakaway time should be conducted on a sample with a bounding or design-basis scratch to determine the influence of a surface defect on the measured time to breakaway behavior.

Appendix E provides an overview and logic diagram to illustrate the testing matrix described above.

Although not recommended, these tests may be conducted first with polished and cleaned cladding material before testing cladding with simulated fuel-fabrication plant cleaning and scratching. Such tests may be helpful in determining the breakaway sensitivity of a cladding material to oxidation

temperature. However, the tests should be repeated with cladding that has been exposed to any HF-acid mixture cleaning used at the fuel fabrication facility and that has been scratched to a wall-thickness depth of 50 ± 5 μm or whatever design-basis scratch depth that can be justified. The final results for minimum breakaway oxidation time are based on such cladding samples.

In order to minimize the number of tests, the NRC staff recommends that all tests be conducted with scratched samples that have experienced the full postpolishing cleaning process. If breakaway is not observed to occur under any of the test conditions, then the total number of tests would be reduced to eight scoping tests, along with four confirmation tests at 1,000 °C. For the five tests run at 1,000 °C, all five samples must exhibit lustrous black oxides or <200-wppm hydrogen to conclude that the minimum breakaway oxidation time is >5,000 s. If >200-wppm hydrogen pickup is observed after 5,000 s at one or more temperatures, then the test time would have to be reduced until the hydrogen pickup fell below 200 wppm.

The NRC staff recommends that testing be initiated at 1,000 °C for a test time of 5,000 s. If breakaway is observed based on visual examination and the hydrogen content is >200 wppm, then the test time at 1,000 °C should be reduced until the hydrogen content is <200 wppm or until no discoloration is observed on the cladding outer surface. Subsequent tests at higher (e.g., 1,015 °C) and lower (e.g., 985 °C) temperatures should be conducted at the minimum time for 1,000 °C ($\leq 5,000$ s). If breakaway is observed at a lower test time for a temperature other than 1,000 °C, then that minimum time should be used as the maximum test time for subsequent temperatures. This process is documented in NUREG/CR-6967 (Ref. 3).

Test results reported in NUREG/CR-6967 (Ref. 3) and Yan, et al. (Ref. 16) indicate significant temperature sensitivity for the breakaway oxidation of one cladding material. The minimum breakaway oxidation time was found to occur at 970–985 °C. Also, as breakaway oxidation is an instability phenomenon, considerable scatter was observed in the data for hydrogen pickup versus time. For an oxidation temperature of 1,000 °C, there appeared to be less scatter, and the breakaway oxidation time was determined to be $4,000\pm 200$ s for 200-wppm hydrogen pickup (see Figure A-2). However, as shown in Figure A-3, considerably more data scatter was observed within the critical temperature range of 970–985 °C, for which the minimum breakaway time was determined to be $3,100\pm 300$ s for 200-wppm hydrogen pickup.

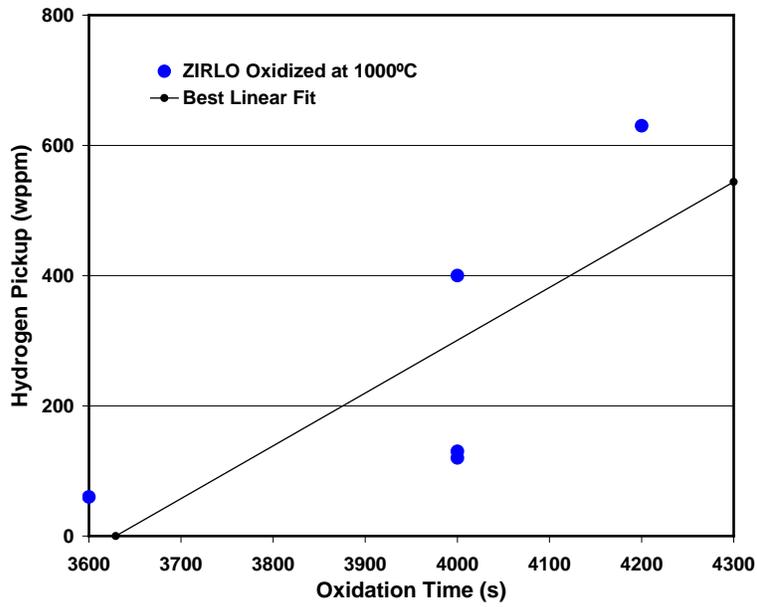


Figure A-2. Hydrogen pickup vs. test time data for as-fabricated ZIRLO™ oxidized at 1,000 °C

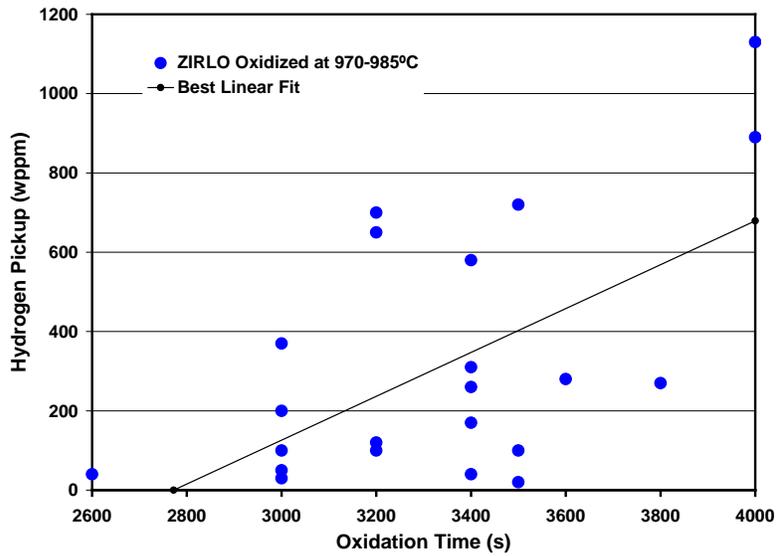


Figure A-3. Hydrogen pickup vs. test time for as-fabricated, prescratched, and preoxidized (≈1-μm thick) ZIRLO™ oxidized at 970–985 °C

A-11. References¹

1. ORNL/NUREG-17, "Zirconium Metal-Water Oxidation Kinetics IV. Reaction Rate Studies," U.S. Nuclear Regulatory Commission, Washington, DC, August 1977.
2. Leistikow, S., and G. Schanz, "Oxidation Kinetics and Related Phenomena of Zircaloy-4 Fuel Cladding Exposed to High Temperature Steam and Hydrogen-Steam Mixtures under PWR Accident Conditions," *Nuclear Engineering and Design*, 103: 65–84.
3. NUREG/CR-6967, "Cladding Embrittlement during Postulated Loss-of-Coolant Accidents," U.S. Nuclear Regulatory Commission, Washington, DC, July 2008. (Agencywide Documents Access and Management System. (ADAMS) Accession No. ML082130389)
4. NUREG/IA-0211, "Experimental Study of Embrittlement of Zr-1%Nb VVER Cladding under LOCA-Relevant Conditions," U.S. Nuclear Regulatory Commission, Washington, DC, March 2005. (ADAMS Accession No. ML051100343)
5. Mardon, J.P., J.C. Brachet, L. Portier, V. Maillot, T. Forgeron, A. Lesbros, et al., "Influence of Hydrogen Simulating Burn-Up Effects on the Metallurgical and Thermal-Mechanical Behavior of M5™ and Zircaloy-4 Alloys under LOCA Conditions," ICONE13-50457, 13th International Conference on Nuclear Engineering, Beijing, China, May 16-20, 2005.
6. Baek, J.H., and Y.H. Jeong, "Breakaway Phenomenon of Zr-based Alloys during a High-Temperature Oxidation," *Journal of Nuclear Materials*, 372: 152–159. (Available at www.sciencedirect.com.)
7. ASTM G2/G2M-06, "Standard Test Method for Corrosion Testing of Products of Zirconium, Hafnium, and Their Alloys in Water at 680°F [360°C] or in Steam at 750°F [400°C]," ASTM International, West Conshohocken, PA, 2006.²
8. Claude Grandjean and Georges Hache, "A State of the Art Review of Past Programmes Devoted to Fuel Behaviour under Loss-of-Coolant Conditions. Part 3. Cladding Oxidation. Resistance to Quench and Post-Quench Loads," IRSN Technical Report DPAM/SEMCA 2008-093, Institut de Radioprotection et de Sécurité Nucléaire, Fontenay-aux-Roses, France, 2008.
9. H. Uetsuka, "Oxidation of Zircaloy-4 under Limited Steam Supply at 1000 and 1300°C," Kernforschungszentrum Karlsruhe (KfK) 3848, Kernforschungszentrum Karlsruhe GmbH, Postfach 360, 76021 Karlsruhe, 1984.
10. M. Aomi, M. Nakatuka, et al., "Behavior of BWR Fuel Cladding Tubes under Simulated LOCA Conditions," ICONE-7435, 7th International Conference on Nuclear Engineering, 1999.

¹ Publicly available NRC published documents are available electronically through the Electronic Reading Room on the NRC's public Web site at: <http://www.nrc.gov/reading-rm/doc-collections/>. The documents can also be viewed on-line or printed for a fee in the NRC's Public Document Room (PDR) at 11555 Rockville Pike, Rockville, MD; the mailing address is USNRC PDR, Washington, DC 20555; telephone 301-415-4737 or (800) 397-4209; fax (301) 415-3548; and e-mail pdr.resource@nrc.gov.

² Copies of American Society for Testing and Materials (ASTM) standards may be purchased from ASTM, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, Pennsylvania 19428-2959; telephone (610) 832-9585. Purchase information is available through the ASTM Web site at <http://www.astm.org>.

11. Kawasaki, S., T. Furuta, and M. Suzuki, "Oxidation of Zircaloy-4 under High Temperature Steam Atmosphere and Its Effect on Ductility of Cladding," *Journal of Nuclear Science and Technology*, 15(8): 589–596.
12. P. Hofmann and M. Markiewicz, "Chemical Interactions between As-Received and Pre-Oxidized Zircaloy-4 and Inconel-718 at High Temperatures, Kernforschungszentrum Karlsruhe (KfK) 4729, Kernforschungszentrum Karlsruhe GmbH, Postfach 360, 76021 Karlsruhe, June 1994.
13. Y. Yan, "Work Plan for the Breakaway Oxidation of ZIRLO™ Cladding at 800-1015°C," ANL Intra-Laboratory Memo, IPS-490-00-01, Feb. 9, 2007.
14. ASTM E1447-05, "Standard Test Method for Determination of Hydrogen in Titanium and Titanium Alloys by the Inert Gas Fusion Thermal Conductivity/Infrared Detection Method," ASTM International, West Conshohocken, PA, 2005.
15. T. Burtseva, "Procedure for Hydrogen Analysis of Refractory Metals," ANL Intra-Laboratory Memo, IPS-467-00-00, Nov. 25, 2005.
16. Y. Yan, T. Burtseva, and M. Billone, "Update on Breakaway Oxidation of Westinghouse ZIRLO™ Cladding," ANL letter report to NRC, Jan. 8, 2009. (ADAMS Accession No. ML091330334)
17. Y. Yan, T. A. Burtseva and M.C. Billone, "Breakaway Oxidation Tests for M5 Cladding," ANL letter report to NRC, July 31 2009. (ADAMS Accession No. ML092710536)
18. Y. Yan, T. Burtseva and M.C. Billone, "Progress Report on Breakaway Oxidation of Bare and Prefilmed ZIRLO™," ANL letter report to NRC, May 30, 2007. (ADAMS Accession No. ML080800314)
19. Y. Yan, T.A. Burtseva, and M.C. Billone, "Breakaway Oxidation of ZIRLO™ Exposed to Transient Temperature Histories," ANL letter report to NRC, July 31, 2009. (ADAMS Accession No. ML092710523)

APPENDIX B

RATIONALE FOR THE 200-WPPM HYDROGEN PICKUP CRITERION FOR BREAKAWAY OXIDATION

Table B-1 summarizes the increase in hydrogen pickup, with test times for three of the cladding materials tested by Argonne National Laboratory (see NUREG/CR-6967, “Cladding Embrittlement during Postulated Loss-of-Coolant Accidents,” issued July 2008, Agencywide Documents Access and Management System Accession No. ML082130389). The hydrogen pickup rate was rapid for two of the cladding materials and more gradual for one of them. Given that breakaway oxidation is an instability phenomenon that can spread rapidly in the axial and circumferential directions, it is important to establish a hydrogen pickup or content limit for which cladding retains ductility. The criterion of 200-weight parts per million (wppm) hydrogen pickup was established before initiation of the NUREG/CR-69673 breakaway oxidation study. It was subsequently confirmed by conducting ring compression tests for samples sectioned from the breakaway oxidation samples. Table B-2 and Figure B-1 summarize the results of these ring-compression tests. Ductility is maintained for a ≤ 435 wppm average hydrogen pickup. Thus, the 200-wppm hydrogen pickup criterion is conservative by a factor of at least two. However, it is not overly conservative for high oxidation temperatures because the time needed to increase from 200 wppm to >400 wppm hydrogen pickup could be as low as 100 seconds (s).

Table B-1. Summary of Hydrogen Pickup vs. Test Time for Several Cladding Materials Oxidized at 970–1,000 °C

Cladding Material	Test T, °C	Test Time, s	Hydrogen Content, wppm	Hydrogen Pickup, wppm	Comment
15×15 Low-Tin Zry-4 (Old)	985	3,600 3,800 3,900	186 40–60 1,260	170 20–40 1,320	Prescratched Lustrous Black outer surface Large Gray Areas on outer surface
15×15 Low-Tin Zry-4 (Modern)	985	5,000 5,400	286 411	280 410	Gray Line on outer surface Large Gray Area on outer surface
17×17 ZIRLO™ (Modern)	985	3,400 3,400 3,600	174 50 267	175 20 270	Yellow Area along Prescratch Lustrous Black outer surface Yellow Circle on outer surface

Table B-2. Ductility at 135 °C vs. Hydrogen Pickup for Several Cladding Materials Oxidized at 970–1,000 °C

Cladding Material	Test T, °C	Hydrogen Content, wppm	Hydrogen Pickup, wppm	Offset Strain at 135 °C, %
15×15 Low-Tin Zry-4 (Old)	985	186	170	5.2
		1,260	1,320	0.9
15×15 Low-Tin Zry-4 (Modern)	985	286	280	6.0
		270	260	5.9
17×17 ZIRLO™ (Modern)	985	174	175	5.1
	985	214	215	>2
	970	416	435	4.8
	1,000	555	600	0.8
	985	731	765	0.8
	985	987	1040	0.8

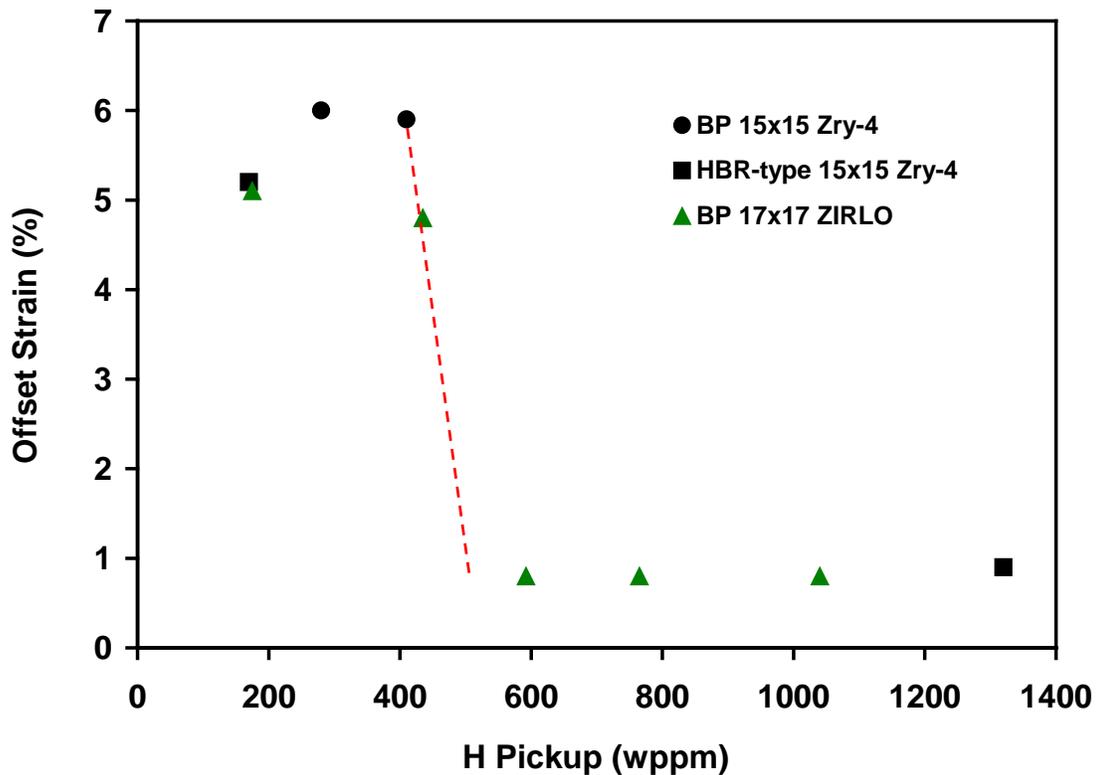
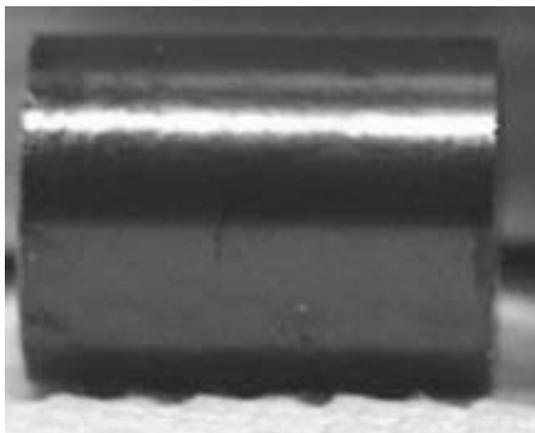


Figure B-1. Ductility (from ring compression tests at 135 °C) vs. hydrogen pickup for breakaway oxidation samples oxidized at 970–1,000 °C. Ductile-to-brittle transition occurs at ≈500 wppm hydrogen pickup. “BP” refers to “belt polished” cladding and HBR-type refers to cladding comparable to H.B. Robinson vintage cladding.

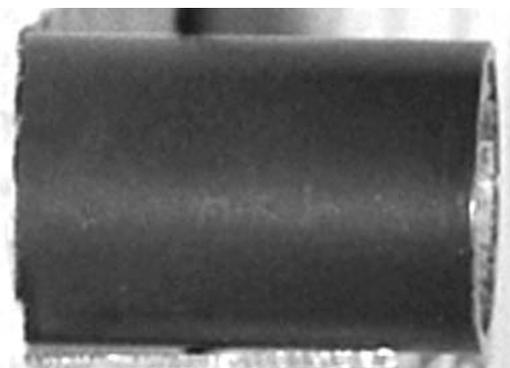
APPENDIX C

NEGATIVE EFFECTS OF ETCHING WITH HYDROFLOURIC-CONTAINING ACID AS PART OF SAMPLE CLEANING

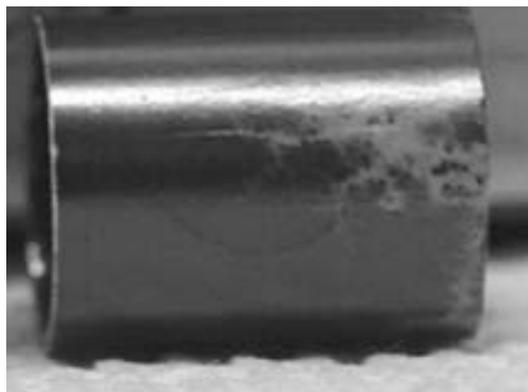
As part of the work in NUREG/CR-6967, "Cladding Embrittlement during Postulated Loss-of-Coolant Accidents," issued July 2008 (Agencywide Documents Access and Management System Accession No. ML082130389), 17×17 low-tin Zircaloy-4 (Zry-4), 17×17 ZIRLO™, and 17×17 M5 alloy cladding samples were subjected to etching for 180 seconds (s) in a hydrofluoric (HF)-containing solution (3.5%-HF + 45%-HNO₃ + 51.5%-H₂O) before ultrasonic cleaning with ethanol and water. The samples were then oxidized for 2,400 s at 1,000 degrees Celsius (°C). The cladding materials showed different sensitivity to etching based on visual observation, with the inner surface showing more discoloration than the outer surface for each material. Hydrogen-content measurements were not performed because of the likely hydrogen pickup from inner surfaces. The outer cladding surfaces for the three oxidized materials are shown in Figure C-1. Pre-etched Zry-4 and M5 exhibited lustrous black outer-surface oxides, while ZIRLO™ showed signs of discoloration indicative of tetragonal-to-monoclinic transformation and breakaway oxidation.



(a) Zry-4



(b) M5



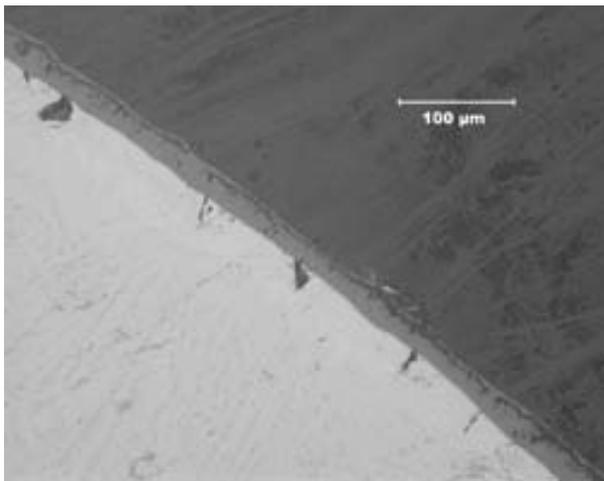
(c) ZIRLO™

Figure C-1. Outer surfaces of samples etched for 180 s in a 3.5%-HF acid mixture before oxidation at 1,000 °C for 2,400-s hold time: (a) Zry-4, (b) M5, and (c) ZIRLO™. (Note: The surface of M5 was lustrous black, but the quality of the photograph is not high enough to show it.)

For the spent nuclear fuel program, ZIRLO™ samples were etched in a 1%-HF acid solution for 180 s before hydriding. This worked well for the spent nuclear fuel application, for which cladding temperatures are ≤ 400 °C and the cladding is in a nonoxidizing environment (helium-filled storage, transport, or storage-and-transport casks). However, HF-etching before hydriding caused breakaway oxidation for samples oxidized for only 280 s total test time with a hold time of 180 s at 1,200 °C. Figure C-2a shows the appearance of the outer cladding surface after oxidation, and Figures C-2b and C-2c show regions of breakaway and intact oxide layers, respectively. The surface discoloration is significant. Some of the discoloration may be due to impurities picked up during the hours of argon purging and exposure to Ar+30%H₂ at 400 °C. Additional studies were performed with lightly etched samples exposed to the 1%-HF acid mixture for 60 s, 30 s, and 15 s. These samples were not exposed to the hydriding environment, so the only source of impurity was from the acid etching. The 15-s sample was cleaned in 80 °C distilled water before the standard ultrasonic cleaning in ethanol and distilled water. Figure C-3 shows that surface discoloration persists even for the 15-s-etch sample following oxidation at $\leq 1,200$ °C for 280 s.



(a)



(b)



(c)

Figure C-2. Appearance and morphology of outer-surface oxide following etching for 180 s in 1%-HF acid bath, exposure to flowing argon (Ar) and Ar+30%H₂ for <10 hours at 400 °C and oxidation for 280 s with a 180-s hold time at 1,200 °C: (a) appearance of outer surface, (b) metallographic image showing breakaway oxidation under area of discoloration, and (c) metallographic image of intact oxide layer under black surface region.

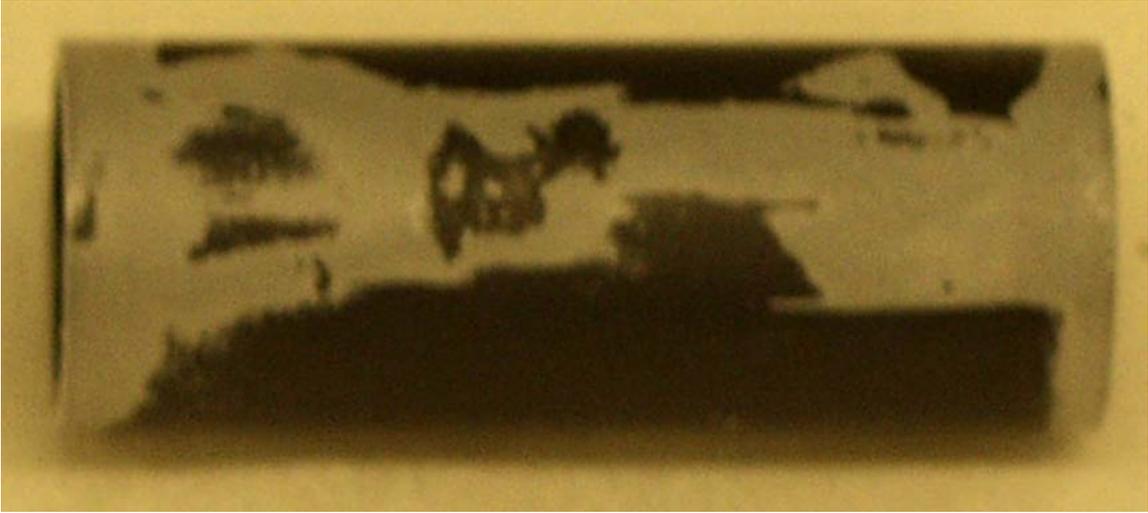


Figure C-3. Outer-surface appearance of ZIRLO™ sample that was etched for 15 s in a 1%-HF acid mixture, rinsed in 80 °C distilled water, ultrasonically cleaned in ethanol and water baths, and heated in steam from 300 °C to 1,200 °C in 100 s and held at 1,200 °C for 180 s. The hydrogen pickup was 510 ± 30 wppm.

APPENDIX D

CORRELATION BETWEEN CLADDING OUTER-SURFACE APPEARANCE AND HYDROGEN PICKUP

The breakaway oxidation tests documented in Ref. 1 were conducted with a furnace equipped with a viewing port. The window allowed viewing of about half the sample outer surface. Initial scoping tests were conducted for a fixed oxidation time. This process was refined such that tests were terminated when discoloration was observed to initiate on the cladding outer surface. As a result, a considerable database was generated for outer-surface appearance versus hydrogen content and hydrogen pickup. Examples from the Ref. 3 work are presented here to guide investigators on what to expect from small discoloration spots and from larger areas of surface discoloration. These examples are from test samples exposed to higher steam oxidation temperatures (970–1,000 degrees Celsius (°C)). For these samples, small areas of discoloration correlated with hydrogen pickups in the range of 50–250 weight parts per million (wppm), while larger areas of discoloration correlated to >400 wppm of hydrogen. At lower oxidation temperatures (e.g., 800 °C) with corresponding lower hydrogen generation rates, significant surface discoloration may precede 200-wppm hydrogen pickup.

For Zircaloy-4 (Zry-4) cladding materials, the surface discoloration (indicative of breakaway oxidation and high hydrogen pickup) progresses from lustrous black to dull black to gray. Figure D-1 shows prebreakaway H.B. Robinson (HBR)-type 15×15 Zry-4 following oxidation at ≈1,000 °C for 3,600 seconds (s). The sample is lustrous black but the hydrogen pickup is 40 wppm, indicating that breakaway is likely to occur within a few hundred seconds beyond 3,600 s. The other two samples were oxidized for long test times (5,400 s and 7,200 s). The outer surface of these samples is completely gray and the hydrogen pickup values are high. For Zry-4, by the time that the outer surface transforms from lustrous black to gray, the sample is well beyond breakaway initiation.

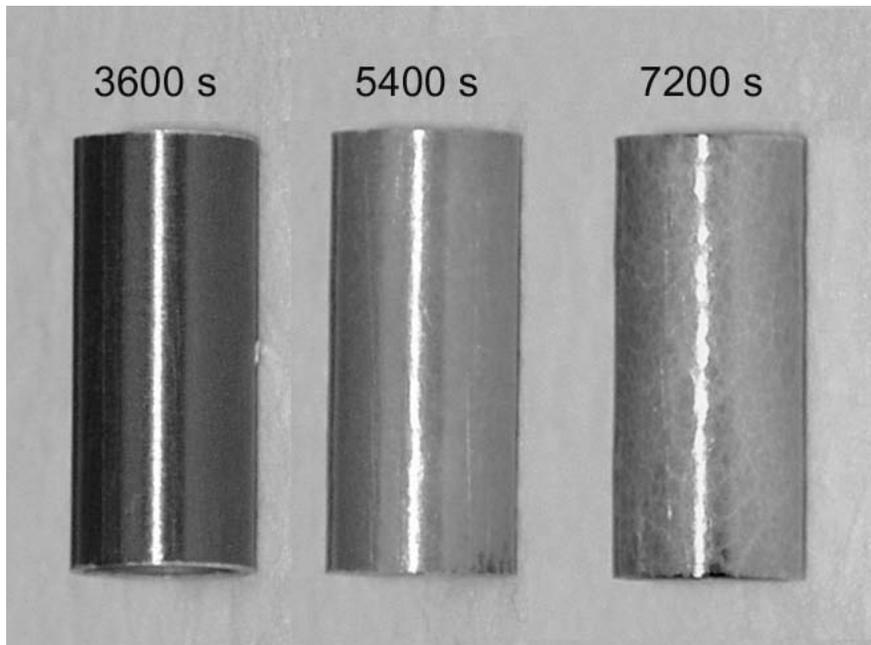
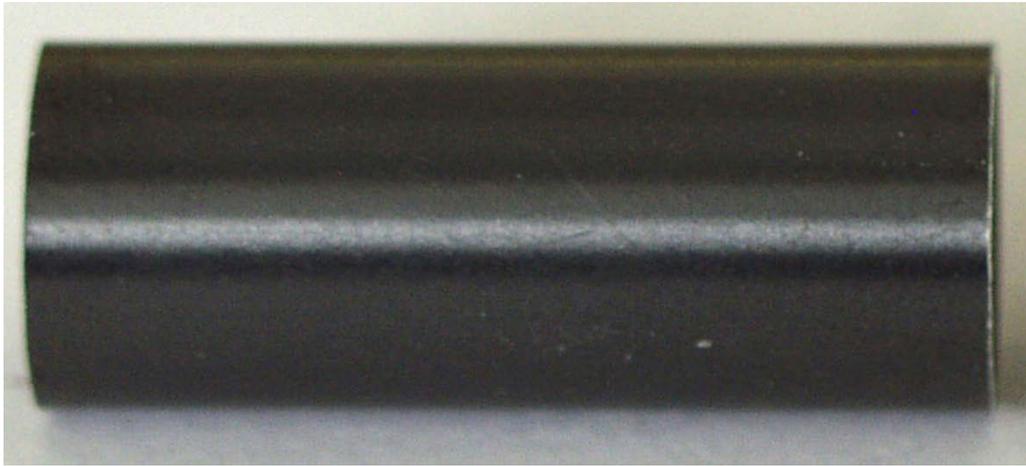


Figure D-1. Outer-surface appearance of an older vintage (HBR) of 15×15 Zry-4 following oxidation at $\approx 1,000$ °C for 3,600 s (lustrous black with 40-wppm hydrogen pickup), 5,400 s (gray with 2,300-wppm hydrogen pickup), and 7,200 s (with 3,100-wppm hydrogen pickup).

Similar results were obtained for 17×17 ZIRLO™ oxidized at 1,000 °C. However, for ZIRLO™, the color change of the outer surface was from lustrous black to yellow (or tan). Figure D-2 shows the transformation of colors from lustrous black to lustrous black with yellow spots to yellow.



(a) 1,500 s at 1,000 °C; 5-wppm hydrogen pickup



(b) 3,600 s at 1,000 °C; 60-wppm hydrogen pickup



(c) 5,000 s at 1,000 °C; 1,350-wppm hydrogen pickup

Figure D-2. Outer-surface appearance and hydrogen pickup for ZIRLO™ samples oxidized at 1,000 °C: (a) lustrous black at 1,500 s, (b) lustrous black with yellow spots at 3,600 s, and (c) yellow at 5,000 s.

For polished 15x15 Zry-4, the minimum breakaway oxidation time is $\approx 5,000$ s and occurs at a long-time oxidation temperature of 985 °C. Figure 38a in Ref. 1 shows the appearance of the outer surface of the sample oxidized at 985 °C for 5,000 s (it is included below as Figure D-3 for the convenience of the reader). The sample exhibited a gray line along the axial direction. Metallography (Figures 38b and c in Ref. 1) confirmed that the outer-surface oxide under this gray region was in breakaway, while the inner-surface oxide was still intact. Also, the circumferential variation of hydrogen was significant, with a peak in hydrogen concentration under the gray layer. The sample picked up 280-wppm hydrogen, which is just beyond the 200-wppm criterion.

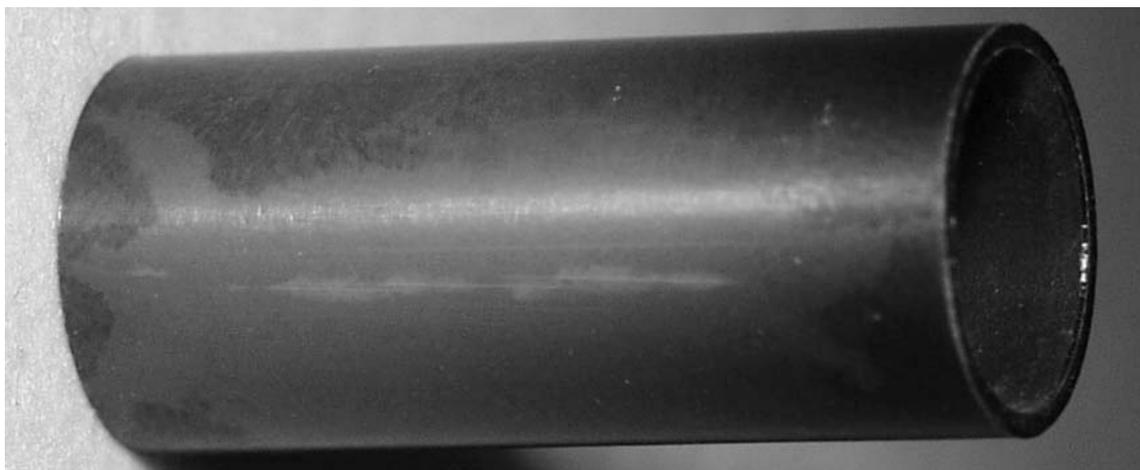


Figure D-3. Polished 15x15 Zry-4 cladding oxidized at 985 °C for 5,000 s. The gray line along about two-thirds of the sample length is the region under which breakaway oxidation had occurred. Circumferentially averaged hydrogen pickup was 280 ± 160 wppm. Hydrogen pickup under the gray streak was >460 wppm.

Figures D-4 to D-9 show ZIRLO™ samples with surface discoloration and the corresponding hydrogen pickup. It is clear from these photographs that any visual evidence of breakaway oxidation, even small spots, is indicative of initiation of local breakaway oxidation and hydrogen pickup. Figures D-4 to D-6 correspond to Figures 81 to 83 in Ref. 1. Figure D-7 is taken from Ref. 2, Figure 2, and Figures D-8 and D-9 are taken from Ref. 3, Figures 2 and 4.

Figure D-10 is from Ref. 4. The sample was oxidized at an isothermal temperature of 980 °C for 2,000 s. The temperature was cycled five times from 1,030 °C to 930 °C for 400 s before an additional 400-s isothermal oxidation at 980 °C. The surface-discoloration pattern is different from those obtained from isothermal tests, and the color is a mixture of yellow and gray.

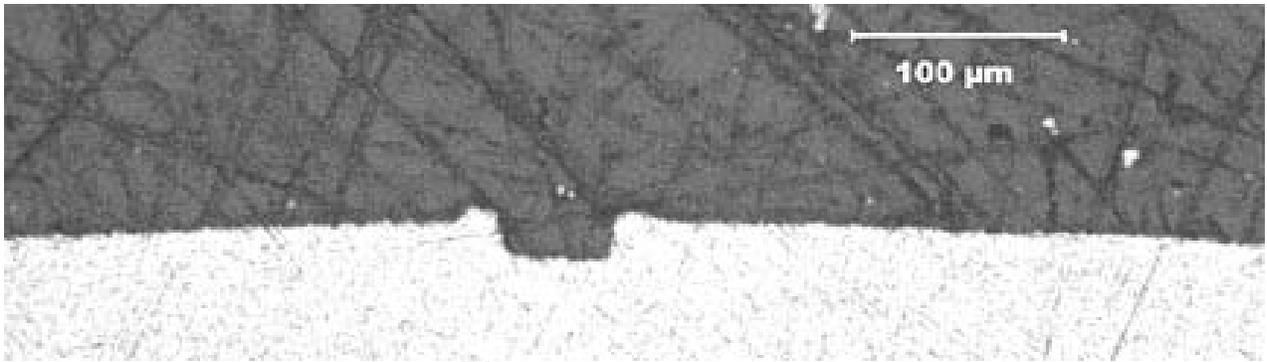


Figure D-4. Cross section of ZIRLO™ cladding with machined scratch \approx 20-micrometers deep into outer surface



Figure D-5. Outer surface of scratched ZIRLO™ sample following oxidation at 985 °C for 3,400 s. Local hydrogen pickup under the yellow surface was 440 wppm; average pickup was 175 wppm.

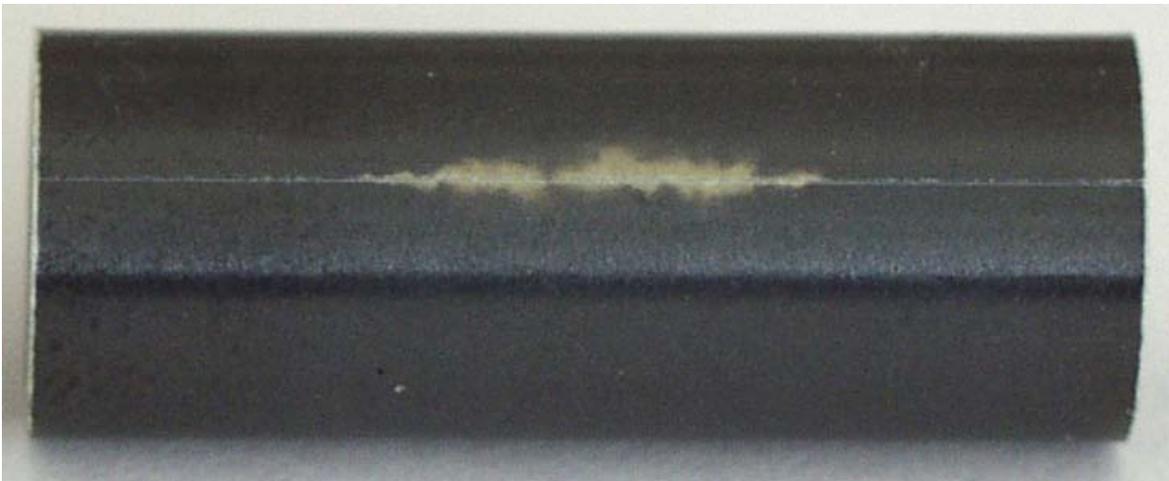


Figure D-6. Outer surface of scratched ZIRLO™ sample following oxidation at 970 °C for 2,600 s. Local hydrogen pickup under the yellow surface was 120 wppm; average pickup was 44 wppm.

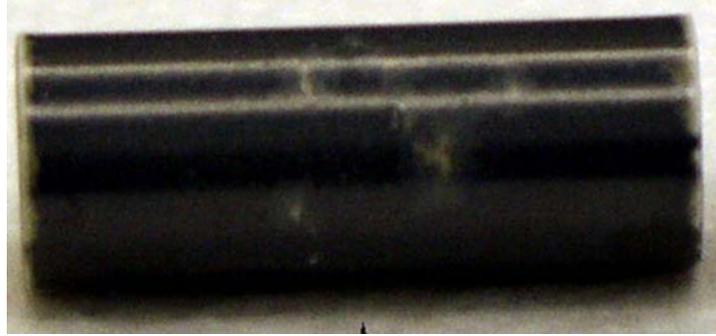


Figure D-7. Outer-surface appearance for ZIRLO™ sample oxidized at 1,000 °C for 4,000 s. Hydrogen pickup was 120 ± 110 wppm with >280 wppm under the yellow spots.

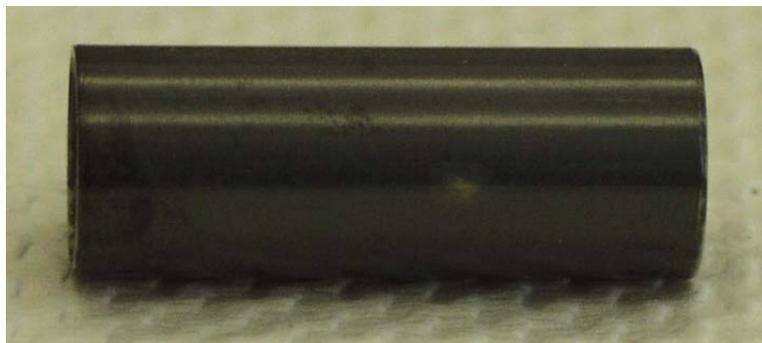


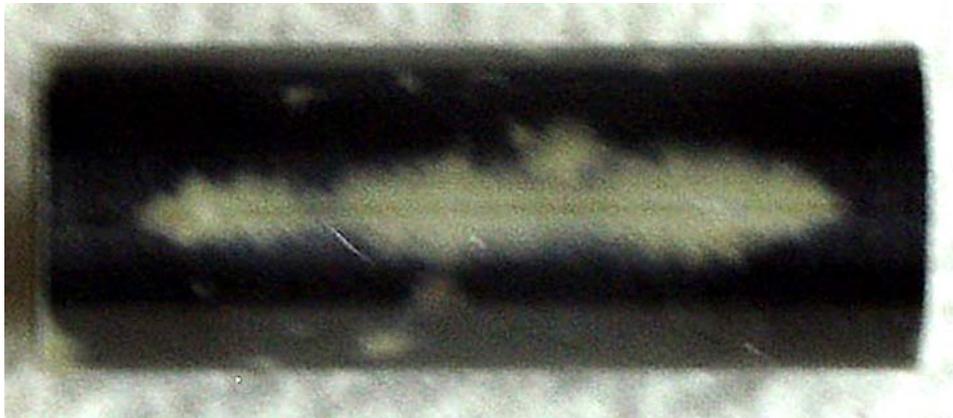
Figure D-8. Outer surface of prefilmed ZIRLO™ oxidized at 985 °C for 3,000 s. One yellow spot can be seen just to the right of the sample midplane. Hydrogen pickup in a 2-mm-long ring including the yellow spot was 50 ± 40 wppm.



Figure D-9. Outer surface of prefilmed ZIRLO™ oxidized at 980 °C for 3,200 s. Two small yellow spots can be observed. Hydrogen pickup in a 2-mm-long ring sectioned to include a yellow spot was 120 ± 120 wppm, with 300-wppm hydrogen under the spot. For a sibling sample tested under the same conditions, the local hydrogen content under the yellow spot was 470 wppm.



(a)



(b)

Figure D-10. Outer-surface appearance of as-fabricated ZIRLO™ sample oxidized for a total test time of 2,800 s: 2,400 s at 980 °C and 400 s with five temperature cycles from 930 to 1,030 °C. Hydrogen content was measured to be 230 ± 80 wppm, indicating breakaway oxidation for a total test time of 2,800 s.

References¹

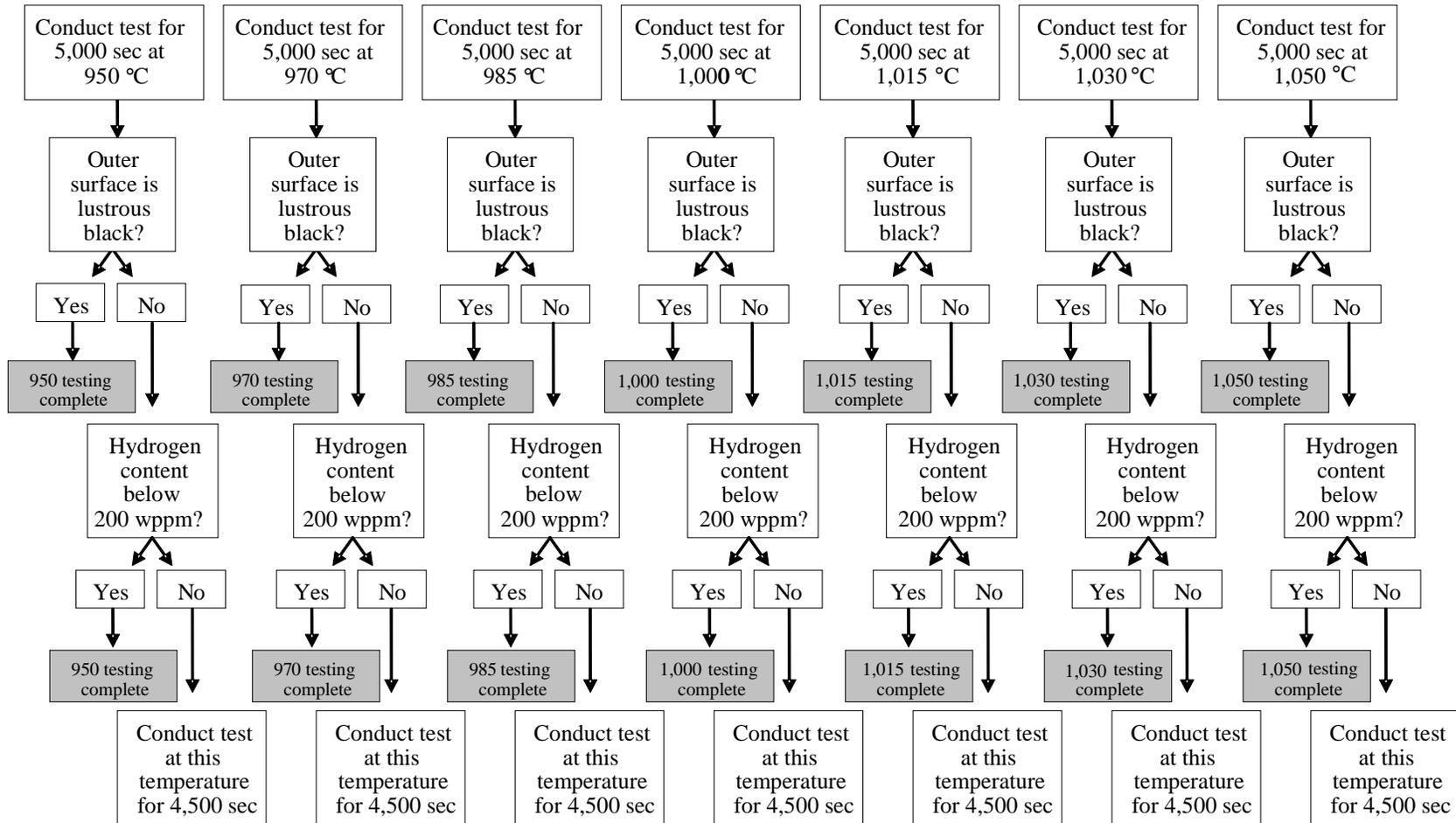
1. NUREG/CR 6967, "Cladding Embrittlement during Postulated Loss-of-Coolant Accidents," U.S. Nuclear Regulatory Commission, Washington, DC, July 2008. (Agencywide Documents Access and Management System. (ADAMS) Accession No. ML082130389)
2. Y. Yan, T. Burtseva, and M. Billone, "Update on Breakaway Oxidation of Westinghouse ZIRLOTM Cladding," ANL letter report to NRC, Jan. 8, 2009. (ADAMS Accession No. ML091330334)
3. Y. Yan, T. Burtseva and M.C. Billone, "Progress Report on Breakaway Oxidation of Bare and Prefilmed ZIRLOTM," ANL letter report to NRC, May 29, 2007. (ADAMS Accession No. ML080800314)
4. Y. Yan, T.A. Burtseva, and M.C. Billone, "Breakaway Oxidation of ZIRLOTM Exposed to Transient Temperature Histories," ANL letter report to NRC, April, 2009. (ADAMS Accession No. ML092710523)

¹ Publicly available NRC published documents are available electronically through the Electronic Reading Room on the NRC's public Web site at: <http://www.nrc.gov/reading-rm/doc-collections/>. The documents can also be viewed on-line or printed for a fee in the NRC's Public Document Room (PDR) at 11555 Rockville Pike, Rockville, MD; the mailing address is USNRC PDR, Washington, DC 20555; telephone 301-415-4737 or (800) 397-4209; fax (301) 415-3548; and e-mail pdr.resource@nrc.gov.

APPENDIX E

OVERVIEW AND LOGIC DIAGRAM TO ILLUSTRATE SAMPLE TEST MATRICES

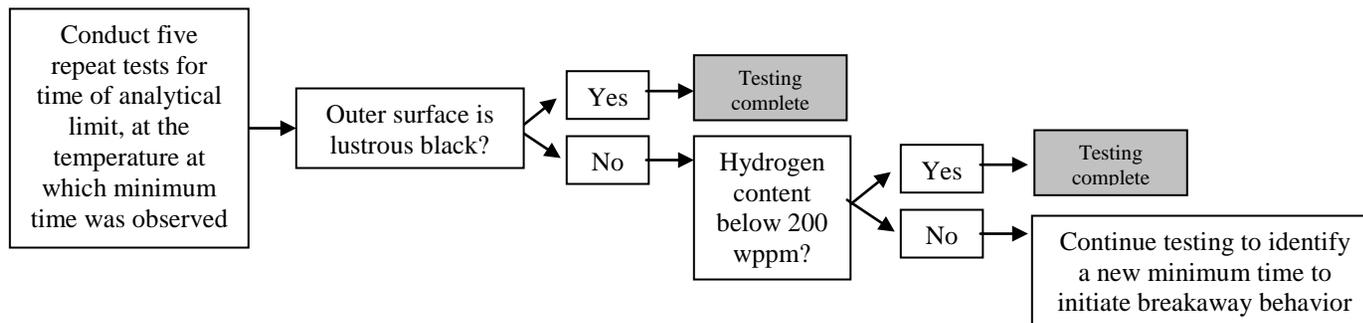
The test matrix below illustrates the sample test matrix described in Section A-10, “Test Temperatures,” of Appendix A to this regulatory guide for initial characterization of a cladding alloy’s breakaway oxidation behavior. The test matrix begins with seven tests, conducted incrementally within the range of temperature at which breakaway may occur.



The logic diagram can be repeated for each reduction in time increment. Time reduction increments of 500 seconds are recommended as a practical increment to search for a reduced time scale at which breakaway oxidation does not occur. Once each temperature has been tested with a logic diagram conclusion of “xxx °C testing complete,” 10 additional tests may be conducted to demonstrate repeatability and to characterize the influence of a surface scratch. To confirm reliable measurement of the minimum test time, four of the additional tests could be conducted at the temperature at which the minimum test time was recorded (if none of the initial test series resulted in observation of breakaway behavior, four tests at 1,000 °C should be conducted). To characterize the influence of a surface scratch, five repeat tests, at the conditions (time and temperature) of the minimum observed breakaway behavior, could be conducted on samples with a bounding or design-basis scratch. Finally, a test conducted at 800 °C could be used to confirm that breakaway oxidation does not occur at this lower temperature for the time identified as the minimum time within the range of 950–1,050 °C.

To elaborate on the two possible breakaway criteria within the logic diagram, it is useful to refer to Figure D-2b in Appendix D to this regulatory guide. In this image, yellow spots are observed on the surface of the cladding. This observation would lead to the “No” tree of the logic diagram above, which asks if the outer surface is lustrous black. The logic tree then calls for a hydrogen content measurement. In this case, 60-wppm hydrogen was measured. This observation would lead to the “Yes” tree of the logic diagram above and therefore complete testing for a particular temperature with the conclusion that breakaway oxidation had not occurred for the test temperature and time combination.

In the case of periodic testing, the U.S. Nuclear Regulatory Commission staff considers it acceptable to measure the onset of breakaway oxidation annually for only the temperature at which the minimum time to breakaway oxidation was measured and to demonstrate that breakaway oxidation is not experienced within the time of the established analytical limit. The test matrix below illustrates the reduced test matrix described in the body of this regulatory guide.



REGULATORY ANALYSIS

Draft Regulatory Guide, DG-1261, “Conducting Periodic Testing for Breakaway Oxidation Behavior.” (Proposed New Regulatory Guide 1.222)

Statement of the Problem

In 1996, the U.S. Nuclear Regulatory Commission (NRC) initiated a fuel-cladding research program¹ intended to investigate the behavior of high-exposure fuel cladding under accident conditions. The research program identified new cladding embrittlement mechanisms and expanded NRC’s knowledge of previously identified mechanisms. One of the new cladding embrittlement mechanisms identified in NRC’s loss-of-coolant accident (LOCA) research program is called “breakaway oxidation.” Breakaway oxidation is a term used to identify the fuel-cladding oxidation phenomenon in which the weight gain rate deviates from normal kinetics. This change occurs with a rapid increase of hydrogen pickup during prolonged exposure to a high-temperature steam environment, which promotes loss of cladding ductility. NRC’s LOCA research program revealed that different zirconium-based alloys have varying susceptibility to breakaway oxidation that is dependent on factors such as alloy content, manufacturing process, and surface preparation among others.

NRC initiated rulemaking activities (Ref. 1) to revise Emergency Core Cooling System (ECCS) acceptance criteria to reflect recent research findings on these new cladding embrittlement mechanisms, including breakaway oxidation. The revisions to the ECCS acceptance criteria were developed to enhance performance-based features of 10 CFR 50.46. Therefore, 10 CFR 50.46(c) calls for measurement of the onset of breakaway oxidation for a zirconium-based alloy based on an acceptable experimental technique, evaluation of the measurement relative to ECCS performance, and periodic testing and reporting of the values measured. With this approach, the limits imposed on each zirconium-based alloy are consistent with the alloy’s particular behavior because they are based on measurements for that zirconium-based alloy. In addition, the possibility that manufacturing and production changes could impact the behavior of a zirconium-based alloy is addressed with periodic testing and reporting.

This regulatory guidance makes it possible to revise 10 CFR 50.46(c) in a performance-based manner by providing a means of consistent, comparable generation of data to establish regulatory limits related to the breakaway behavior of zirconium-based alloys during LOCA conditions. Development of this regulatory guidance captures the experimental technique used in NRC’s LOCA research program to measure the onset of breakaway oxidation, thereby establishing an experimental technique acceptable to the NRC staff. This regulatory guide also describes a method acceptable to NRC to implement the periodic testing and reporting requirements in 10 CFR 50.46(c).

Objective

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

¹ The research program included an extensive loss-of-coolant accident (LOCA) research and testing program at Argonne National Laboratory (ANL) as well as jointly funded programs at the Kurchatov Institute (Ref. 2) and the Halden Reactor (Ref. 3) project to develop the body of technical information needed to evaluate LOCA regulations for high-exposure fuel. The research findings have been summarized in Research Information Letter (RIL) 0801, “Technical Basis for Revision of Embrittlement Criteria in 10 CFR 50.46,” dated May 30, 2008 (Ref. 4), and the detailed experimental results from the program at ANL are contained in NUREG/CR-6967, “Cladding Embrittlement During Postulated Loss-of-Coolant Accidents” (Ref. 5).

Alternative Approaches

The NRC staff considered the following alternative approaches:

Alternative 1: Do Not Create Draft Regulatory Guide-1261

Under this alternative, NRC would not create Draft Regulatory Guide (DG)-1261. If NRC does not take action, no changes would occur in costs or benefit to the public, licensees, or NRC. However, the “no-action” alternative would not provide a clear, acceptable approach for implementing the performance-based regulatory requirements proposed for 50.46(c). NRC would have to review the experimental techniques used to generate the data provided by licensees to support zirconium-based alloy limits related to breakaway oxidation on a case-by-case basis.

The impact associated with not creating the regulatory guide is that NRC and its licensees and applicants may interpret differently the extent and details of experiential techniques acceptable to support a zirconium-based alloy analytical limit for breakaway oxidation. In addition, the NRC resources required to review the experimental technique used to produce the data, which supports a licensee’s proposed zirconium-based alloy analytical limit for breakaway oxidation, would be significant.

Alternative 2: Create Draft Regulatory Guide-1261

Under this alternative, NRC would create DG-1261. Creating DG-1261 will (1) enable implementation of the performance-based regulatory requirements proposed for 50.46(c) by providing a means of consistent, comparable generation of data to establish regulatory limits related to the breakaway behavior of zirconium-based alloys during LOCA conditions; (2) simplify the staff’s review process; and (3) reduce regulatory uncertainty and thereby help to minimize the costs associated with the implementation of the regulatory requirements proposed for 50.46(c). A benefit of this action is that it would enhance reactor safety by ensuring that clear guidance is available for defining a zirconium-based alloy’s susceptibility to breakaway oxidation.

The impact to NRC would be the costs associated with preparing and creating the regulatory guide. The impact to the public would be the voluntary costs associated with reviewing and providing comments to NRC during the public comment period. The value to NRC and its applicants would be the benefits associated with enhanced efficiency and effectiveness in using common experimental techniques for generating data to establish and periodically confirm regulatory limits related to the breakaway behavior of zirconium-based alloys during LOCA conditions.

Conclusions

Based on this regulatory analysis, the NRC staff recommends creating DG-1261. The staff concludes that the proposed action will enhance reactor safety by ensuring clear guidance is available for defining a zirconium-based alloy’s susceptibility to breakaway oxidation. The creation of this guide also could reduce regulatory uncertainties and thereby minimize costs for the industry.

REFERENCES²

1. 7X FR XXXXX, "Proposed Rule FRN," *Federal Register*, Volume 7X, Number XXX, p. XXXX, Washington, DC, June 31, 2011. (*insert FRN of proposed rule reference when available*)
2. NUREG/IA 0211, "Experimental Study of Embrittlement of Zr 1%Nb VVER Cladding under LOCA-Relevant Conditions," U.S. Nuclear Regulatory Commission, Washington, DC, March 2005. (ADAMS Accession No. ML051100343)
3. IFE/KR/E 2008/004, "LOCA Testing of High Burnup PWR Fuel in the HBWR. Additional PIE on the Cladding of the Segment 650 5," Institute for Energy Technology, Kjeller, Norway, April 2008. (ADAMS Accession No. ML081750715)
4. Research Information Letter 0801, "Technical Basis for Revision of Embrittlement Criteria in 10 CFR 50.46," U.S. Nuclear Regulatory Commission, Washington, DC, May 30, 2008. (ADAMS Accession No. ML081350225)
5. NUREG/CR 6967, "Cladding Embrittlement during Postulated Loss-of-Coolant Accidents," U.S. Nuclear Regulatory Commission, Washington, DC, July 2008. (ADAMS Accession No. ML082130389)

²

Publicly available NRC-published documents are available electronically through the Electronic Reading Room on the NRC's public Web site at: <http://www.nrc.gov/reading-rm/doc-collections>. The documents also can be viewed online or printed for a fee in NRC's Public Document Room (PDR) at 11555 Rockville Pike, Rockville, MD; the mailing address is USNRC PDR, Washington, DC 20555; telephone 301-415-4737 or 800-397-4209; fax 301-415-3548; and e-mail pdresource@nrc.gov.

NOTE: The availability of this draft rule language, as it exists in this document, is intended to inform stakeholders of the current status of the NRC's activities to revise the requirements for emergency core cooling systems to support an upcoming meeting with the Advisory Committee on Reactor Safeguards. The NRC staff is considering restructuring the current Section 50.46 regulation to distinguish ECCS performance requirements (i.e., criteria governing acceptable capability of ECCS to perform its cooling function during and after a design basis LOCA) from fuel/cladding performance requirements (i.e., criteria intended to ensure that the fuel and cladding do not result in prevention of successful cooling during and after a design basis LOCA, and any other effects with adverse impacts on the capability or other safety systems). Additionally, the NRC staff may add new paragraphs to address long standing issues and concerns with the current regulation. As such, this draft rule language may be incomplete or in error in one or more respects, and will be subject to further revisions during the rulemaking process. The NRC is not requesting formal public comments on this draft rule language. The NRC may post updated materials, including updated draft rule language, to this page. Interested stakeholders should periodically check this page for updates and added materials.

Draft Rule Language for 10 CFR 50.46c

§ 50.46c Requirements for emergency core cooling systems for light-water nuclear power reactors.

(a) *Applicability.* The requirements of this section apply to each holder of an operating license for any light water nuclear power reactor (LWR), regardless of fuel design or cladding material, except for a licensee who has submitted the certifications required under 10 CFR 50.82(a)(1) to the NRC.

(b) *Definitions.* As used in this section:

(1) *Loss-of-coolant accident (LOCA)* means a hypothetical accident that would result from the loss of reactor coolant, at a rate in excess of the capability of the reactor coolant makeup system, from breaks in pipes in the reactor coolant pressure boundary up to and including a break equivalent in size to the double-ended rupture of the largest pipe in the reactor coolant system.

(2) *Evaluation model* means the calculational framework for evaluating the behavior of the reactor system during a postulated loss-of-coolant accident (LOCA). It includes one or more computer programs and all other information necessary for application of the calculational framework to a specific LOCA, such as mathematical models used, assumptions included in the programs, procedure for treating the program input and output information, specification of those portions of analysis not included in computer programs, values of parameters, and all other information necessary to specify the calculational procedure.

(3) *Breakaway oxidation* means, for the purposes of this section, the fuel cladding oxidation phenomenon in which weight gain rate deviates from normal kinetics. This change occurs with a rapid increase of hydrogen pickup during prolonged exposure to a high temperature steam environment, which promotes loss of cladding ductility

(c) *General performance requirements for any fuel design or cladding material.* Each LWR must be provided with an emergency core cooling system (ECCS) designed so that, when fueled with an acceptable fuel design, the following performance requirements are satisfied in the event of a postulated loss-of-coolant accident (LOCA):

- (1) Core geometry remains amenable to cooling;
- (2) Generation of combustible gas is limited to the maximum extent practicable;
- (3) Core temperature is maintained at a value sufficient to ensure compliance with criteria in paragraphs (c)(1) and (c)(2) of this section;

NOTE: The availability of this draft rule language, as it exists in this document, is intended to inform stakeholders of the current status of the NRC's activities to revise the requirements for emergency core cooling systems to support an upcoming meeting with the Advisory Committee on Reactor Safeguards. The NRC staff is considering restructuring the current Section 50.46 regulation to distinguish ECCS performance requirements (i.e., criteria governing acceptable capability of ECCS to perform its cooling function during and after a design basis LOCA) from fuel/cladding performance requirements (i.e., criteria intended to ensure that the fuel and cladding do not result in prevention of successful cooling during and after a design basis LOCA, and any other effects with adverse impacts on the capability or other safety systems). Additionally, the NRC staff may add new paragraphs to address long standing issues and concerns with the current regulation. As such, this draft rule language may be incomplete or in error in one or more respects, and will be subject to further revisions during the rulemaking process. The NRC is not requesting formal public comments on this draft rule language. The NRC may post updated materials, including updated draft rule language, to this page. Interested stakeholders should periodically check this page for updates and added materials.

(4) Decay heat is removed for the extended period of time required by the long-lived radioactivity remaining in the core.

(5) ECCS cooling performance must be calculated in accordance with an acceptable evaluation model and must be calculated for a number of postulated loss-of-coolant accidents of different sizes, locations, and other properties sufficient to provide assurance that the most severe postulated loss-of-coolant accidents are calculated. The evaluation model must include sufficient supporting justification to show that the analytical technique realistically describes the behavior of the reactor system during a loss-of-coolant accident. Comparisons to applicable experimental data must be made and uncertainties in the analysis method and inputs must be identified and assessed so that the uncertainty in the calculated results can be estimated. This uncertainty must be accounted for, so that when the calculated ECCS cooling performance is compared to the applicable specified and acceptable analytical limits there is a high level of probability that the limits would not be exceeded. Appendix K, Part II Required Documentation, sets forth the documentation requirements for each evaluation model.

(d) *Specific requirements for fuel designs consisting of uranium oxide or mixed uranium-plutonium oxide pellets within zirconium-alloy cladding material.* Each LWR must be provided with an ECCS designed so that, when fueled with an acceptable fuel design consisting of uranium oxide or mixed uranium-plutonium oxide pellets within cylindrical zirconium-alloy cladding, the following performance requirements are satisfied in the event of a postulated LOCA:

(1) *Coolable geometry.* Calculated changes in core geometry shall be such that the core remains amenable to cooling.

(i) *Peak cladding temperature.* Except as provided in paragraph (d)(1)(ii) of this section, the calculated maximum fuel element cladding temperature shall not exceed 2200° F.

(ii) *Cladding embrittlement.* 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 2200° F limit specified in (d)(1)(i), then the lower temperature shall be used in place of the 2200° F limit.

iii) *Zirconium fuel cladding oxidation limits.* 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

NOTE: The availability of this draft rule language, as it exists in this document, is intended to inform stakeholders of the current status of the NRC's activities to revise the requirements for emergency core cooling systems to support an upcoming meeting with the Advisory Committee on Reactor Safeguards. The NRC staff is considering restructuring the current Section 50.46 regulation to distinguish ECCS performance requirements (i.e., criteria governing acceptable capability of ECCS to perform its cooling function during and after a design basis LOCA) from fuel/cladding performance requirements (i.e., criteria intended to ensure that the fuel and cladding do not result in prevention of successful cooling during and after a design basis LOCA, and any other effects with adverse impacts on the capability or other safety systems). Additionally, the NRC staff may add new paragraphs to address long standing issues and concerns with the current regulation. As such, this draft rule language may be incomplete or in error in one or more respects, and will be subject to further revisions during the rulemaking process. The NRC is not requesting formal public comments on this draft rule language. The NRC may post updated materials, including updated draft rule language, to this page. Interested stakeholders should periodically check this page for updates and added materials.

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.

(2) *Maximum hydrogen generation.* The calculated total amount of hydrogen generated from the chemical reaction of the cladding with water or steam shall not exceed 0.01 times the hypothetical amount that would be generated if all of the metal in the cladding cylinders surrounding the fuel, excluding the cladding surrounding the plenum volume, were to react.

(3) *Long-term cooling.* After any calculated successful initial operation of the ECCS, the calculated core temperature shall be maintained at an acceptably low value and decay heat shall be removed for the extended period of time required by the long-lived radioactivity remaining in the core.

(4) *Evaluation model.* ECCS cooling performance must be calculated in accordance with an acceptable evaluation model and must be calculated for a number of postulated loss-of-coolant accidents of different sizes, locations, and other properties sufficient to provide assurance that the most severe postulated loss-of-coolant accidents are calculated. Except as provided in paragraph (d)(4)(i) of this section, the evaluation model must include sufficient supporting justification to show that the analytical technique realistically describes the behavior of the reactor system during a loss-of-coolant accident. Comparisons to applicable experimental data must be made and uncertainties in the analysis method and inputs must be identified and assessed so that the uncertainty in the calculated results can be estimated. This uncertainty must be accounted for, so that when the calculated ECCS cooling performance is compared to the analytical limits established in accordance with paragraph (d)(1), (2), and (3) of this section, there is a high level of probability that the limits would not be exceeded. Appendix K, Part II Required Documentation, sets forth the documentation requirements for each evaluation model.

(i) Alternatively, an ECCS evaluation model may be developed in conformance with the required and acceptable features of appendix K ECCS Evaluation Models.

(ii) Oxygen diffusion from the cladding inside surfaces will reduce the allowable time at elevated temperature to embrittlement. If an oxygen source is present on the inside surfaces of the cladding at the onset of the LOCA, the effects of oxygen diffusion from the cladding inside surfaces shall be considered in the evaluation model.

- (e) [Reserved]
- (f) [Reserved]
- (g) [Reserved]
- (h) [Reserved]
- (i) [Reserved]

NOTE: The availability of this draft rule language, as it exists in this document, is intended to inform stakeholders of the current status of the NRC's activities to revise the requirements for emergency core cooling systems to support an upcoming meeting with the Advisory Committee on Reactor Safeguards. The NRC staff is considering restructuring the current Section 50.46 regulation to distinguish ECCS performance requirements (i.e., criteria governing acceptable capability of ECCS to perform its cooling function during and after a design basis LOCA) from fuel/cladding performance requirements (i.e., criteria intended to ensure that the fuel and cladding do not result in prevention of successful cooling during and after a design basis LOCA, and any other effects with adverse impacts on the capability or other safety systems). Additionally, the NRC staff may add new paragraphs to address long standing issues and concerns with the current regulation. As such, this draft rule language may be incomplete or in error in one or more respects, and will be subject to further revisions during the rulemaking process. The NRC is not requesting formal public comments on this draft rule language. The NRC may post updated materials, including updated draft rule language, to this page. Interested stakeholders should periodically check this page for updates and added materials.

(j) [Reserved]

(k) *Reporting.*

(1) Each applicant for or holder of an operating license or construction permit issued under this part, applicant for a standard design certification under part 52 of this chapter (including an applicant after the Commission has adopted a final design certification regulation), or an applicant for or holder of a standard design approval, a combined license or a manufacturing license issued under part 52 of this chapter, shall estimate the effect of any change to or error in an acceptable evaluation model or in the application of such a model to determine if the change or error is significant. For this purpose, a significant change or error is one which results in a calculated peak fuel cladding temperature different by more than 50 °F from the temperature calculated for the limiting transient using the last acceptable model, or is a cumulation of changes and errors such that the sum of the absolute magnitudes of the respective temperature changes is greater than 50 °F.

(2) For each change to or error discovered in an acceptable evaluation model or in the application of such a model that affects the temperature calculation, the applicant or holder of a construction permit, operating license, combined license, or manufacturing license shall report the nature of the change or error and its estimated effect on the limiting ECCS analysis to the Commission at least annually as specified in § 50.4 or § 52.3 of this chapter, as applicable. If the change or error is significant, the applicant or licensee shall provide this report within 30 days and include with the report a proposed schedule for providing a reanalysis or taking other action as may be needed to show compliance with § 50.46 requirements. This schedule may be developed using an integrated scheduling system previously approved for the facility by the NRC. For those facilities not using an NRC approved integrated scheduling system, a schedule will be established by the NRC staff within 60 days of receipt of the proposed schedule. Any change or error correction that results in a calculated ECCS performance that does not conform **to the analytical limits established in accordance with this section, as applicable**, is a reportable event as described in §§ 50.55(e), 50.72, and 50.73. The affected applicant or licensee shall propose immediate steps to demonstrate compliance or bring plant design or operation into compliance with § 50.46 requirements.

(3) For each change to or error discovered in an acceptable evaluation model or in the application of such a model that affects the temperature calculation, the applicant or holder of a standard design approval or the applicant for a standard design certification (including an applicant after the Commission has adopted a final design certification rule) shall report the nature of the change or error and its estimated effect on the limiting ECCS analysis to the Commission and to any applicant or licensee referencing the design approval or design certification at least annually as specified in § 52.3 of this chapter. If the change or error is significant, the applicant or holder of the design approval or the applicant for the design certification shall provide this report within 30 days and include with the report a proposed schedule for providing a reanalysis or taking other action as may be needed to show

NOTE: The availability of this draft rule language, as it exists in this document, is intended to inform stakeholders of the current status of the NRC's activities to revise the requirements for emergency core cooling systems to support an upcoming meeting with the Advisory Committee on Reactor Safeguards. The NRC staff is considering restructuring the current Section 50.46 regulation to distinguish ECCS performance requirements (i.e., criteria governing acceptable capability of ECCS to perform its cooling function during and after a design basis LOCA) from fuel/cladding performance requirements (i.e., criteria intended to ensure that the fuel and cladding do not result in prevention of successful cooling during and after a design basis LOCA, and any other effects with adverse impacts on the capability or other safety systems). Additionally, the NRC staff may add new paragraphs to address long standing issues and concerns with the current regulation. As such, this draft rule language may be incomplete or in error in one or more respects, and will be subject to further revisions during the rulemaking process. The NRC is not requesting formal public comments on this draft rule language. The NRC may post updated materials, including updated draft rule language, to this page. Interested stakeholders should periodically check this page for updates and added materials.

compliance with § 50.46 requirements. The affected applicant or holder shall propose immediate steps to demonstrate compliance or bring plant design into compliance with § 50.46 requirements.

(l) *Authority to impose restrictions on operation.* The Director of the Office of Nuclear Reactor Regulation (for licenses issued under 10 CFR 50) or the Director of the Office of New Reactors (for licenses issued under 10 CFR 52) may impose restrictions on reactor operation if it is found that the evaluations of ECCS cooling performance submitted are not consistent with the requirements of this section.

(m) *Relationship to other NRC regulations.* The requirements of this section are in addition to any other requirements applicable to ECCS set forth in this part. The analytical limits established in accordance with this section, with cooling performance calculated in accordance with an acceptable evaluation model, are in implementation of the general requirements with respect to ECCS cooling performance design set forth in this part, including in particular Criterion 35 of appendix A of this part.

(n) *Implementation.*

- (1) Construction permits issued under Part 50 after [EFFECTIVE DATE OF RULE] must comply with the requirements of this section.
- (2) Operating licenses issued under Part 50 which are based upon construction permits in effect as of [EFFECTIVE DATE OF RULE] (including deferred and reinstated construction permits) must comply with the requirements of § 50.46c by no later than the applicable data set forth in Table 1. Until such compliance is achieved, the requirements of this section continue to apply.
- (3) Operating licenses issued under Part 50 after [EFFECTIVE DATE OF RULE] must comply with the requirements of this section.
- (4) Operating licenses issued under Part 50 as of [EFFECTIVE DATE OF RULE] must comply with the requirements § 50.46c by no later than the applicable date set forth in Table 1. Until such compliance is achieved, the requirements of this section continue to apply.
- (5) Standard design certifications under part 52 of this chapter, whose applications (including applications for amendment) are pending as of or docketed after [EFFECTIVE DATE OF RULE], and new branches of these certifications whose applications are pending as of or docketed after [EFFECTIVE DATE OF RULE] must be amended to reflect compliance with this section no later than 36 months after [EFFECTIVE DATE OF RULE]. For purposes of this paragraph, a "branch" represents an alternative to the

NOTE: The availability of this draft rule language, as it exists in this document, is intended to inform stakeholders of the current status of the NRC's activities to revise the requirements for emergency core cooling systems to support an upcoming meeting with the Advisory Committee on Reactor Safeguards. The NRC staff is considering restructuring the current Section 50.46 regulation to distinguish ECCS performance requirements (i.e., criteria governing acceptable capability of ECCS to perform its cooling function during and after a design basis LOCA) from fuel/cladding performance requirements (i.e., criteria intended to ensure that the fuel and cladding do not result in prevention of successful cooling during and after a design basis LOCA, and any other effects with adverse impacts on the capability or other safety systems). Additionally, the NRC staff may add new paragraphs to address long standing issues and concerns with the current regulation. As such, this draft rule language may be incomplete or in error in one or more respects, and will be subject to further revisions during the rulemaking process. The NRC is not requesting formal public comments on this draft rule language. The NRC may post updated materials, including updated draft rule language, to this page. Interested stakeholders should periodically check this page for updates and added materials.

certified design as approved in the original design certification rulemaking. Such amendments are not subject to either the issue finality provisions under 10 CFR 52.103(g) or the backfitting requirements under 10 CFR 50.109.

- (6) Standard design certifications under part 52 of this chapter, or branches of standard design certifications in effect on [EFFECTIVE DATE OF RULE] but not referenced in an application for combined license or in a combined license, must be amended to reflect compliance with this section 36 months after the design certification rule is referenced in a combined license application or upon renewal, whichever is later. Such amendments are not subject to either the issue finality provisions under 10 CFR 52.103(g) or the backfitting requirements under 10 CFR 50.109.
- (7) Combined licenses under part 52 of this chapter must comply with this section no later than completion of the first refueling outage after initial fuel load. Until such compliance is achieved, the requirements in § 50.46 continue to apply.
- (8) Standard design approvals under part 52 of this chapter issued before [EFFECTIVE DATE OF RULE] must comply with this section before the design approval may be referenced in a construction permit, operating license, design certification, combined license or manufacturing license issued by the NRC.
- (9) Applications for standard design approvals under part 52 of this chapter issued after [EFFECTIVE DATE OF RULE] must comply with this section.
- (10) Applications for manufacturing licenses under part 52 of this chapter submitted after [EFFECTIVE DATE OF RULE] must comply with this section.

NOTE: The availability of this draft rule language, as it exists in this document, is intended to inform stakeholders of the current status of the NRC’s activities to revise the requirements for emergency core cooling systems to support an upcoming meeting with the Advisory Committee on Reactor Safeguards. The NRC staff is considering restructuring the current Section 50.46 regulation to distinguish ECCS performance requirements (i.e., criteria governing acceptable capability of ECCS to perform its cooling function during and after a design basis LOCA) from fuel/cladding performance requirements (i.e., criteria intended to ensure that the fuel and cladding do not result in prevention of successful cooling during and after a design basis LOCA, and any other effects with adverse impacts on the capability or other safety systems). Additionally, the NRC staff may add new paragraphs to address long standing issues and concerns with the current regulation. As such, this draft rule language may be incomplete or in error in one or more respects, and will be subject to further revisions during the rulemaking process. The NRC is not requesting formal public comments on this draft rule language. The NRC may post updated materials, including updated draft rule language, to this page. Interested stakeholders should periodically check this page for updates and added materials.

Table 1: Implementation dates for Nuclear Power Plants with operating licenses as of [EFFECTIVE DATE OF RULE] or operating licenses which are based upon construction permits in effect as of [EFFECTIVE DATE OF RULE] (including deferred and reinstated construction permits).

Calculated Local Oxidation (ECR ¹) Reported in UFSAR	Latest Date for Demonstrating Compliance
$ECR \geq 10.0$	No later than 36 months from effective date of rule
$10.0 > ECR > 5.0$	No later than 48 months from effective date of rule
$ECR \leq 5.0$	No later than 60 months from effective date of rule

¹ Equivalent cladding reacted

NOTE: The availability of this draft rule language, as it exists in this document, is intended to inform stakeholders of the current status of the NRC's activities to revise the requirements for emergency core cooling systems to support an upcoming meeting with the Advisory Committee on Reactor Safeguards. The NRC staff is considering restructuring the current Section 50.46 regulation to distinguish ECCS performance requirements (i.e., criteria governing acceptable capability of ECCS to perform its cooling function during and after a design basis LOCA) from fuel/cladding performance requirements (i.e., criteria intended to ensure that the fuel and cladding do not result in prevention of successful cooling during and after a design basis LOCA, and any other effects with adverse impacts on the capability or other safety systems). Additionally, the NRC staff may add new paragraphs to address long standing issues and concerns with the current regulation. As such, this draft rule language may be incomplete or in error in one or more respects, and will be subject to further revisions during the rulemaking process. The NRC is not requesting formal public comments on this draft rule language. The NRC may post updated materials, including updated draft rule language, to this page. Interested stakeholders should periodically check this page for updates and added materials.

In Appendix K to 10 CFR Part 50: (I)(B)

(B). Swelling and Rupture of the Cladding and Fuel Rod Thermal Parameters

Each evaluation model shall include a provision for predicting cladding swelling and rupture from consideration of the axial temperature distribution of the cladding and from the difference in pressure between the inside and outside of the cladding, both as functions of time. To be acceptable the swelling and rupture calculations shall be based on applicable data in such a way that the degree of swelling and incidence of rupture are not underestimated. The degree of swelling and rupture shall be taken into account in calculations of gap conductance, cladding oxidation and embrittlement, and hydrogen generation.

The calculations of fuel and cladding temperatures as a function of time shall use values for gap conductance and other thermal parameters as functions of temperature and other applicable time-dependent variables. The gap conductance shall be varied in accordance with changes in gap dimensions and any other applicable variables. The thermal effects of crud and oxide layers that accumulate on the fuel cladding during plant operation must be evaluated.

In Appendix K to 10 CFR Part 50: (II)(5)

5. General Standards for Acceptability—Elements of evaluation models reviewed will include technical adequacy of the calculation methods, including: For models covered by §50.46c(d)(4)(i) compliance with required features of section I of this Appendix K; and, for models covered by § 50.46c(d)(4), assurance of a high level of probability that the performance criteria of § 50.46c(b) would not be exceeded.

ROUTING AND TRANSMITTAL SLIP			4/15/2011		
TO:	NAME	ACTION REQUESTED	COMMENTS	INITIALS	DATE
	Jennifer Borges	Concur	via e-mail	JLB	4/1/11
PM	Angelisa Hicks	Concur		ALH	4/7/11
BC	Thomas Boyce	Concur/SUNSI Review		TB	4/7/11
DD	Michael Case	Concur/Sign Memo		MC	4/14/11
OFFICE	RES	<input type="checkbox"/>			
DD	N/A	Concur			
OFFICE	FSME	<input type="checkbox"/>			
LIAISON	Liaison	Distribution			
DD	Division Director	Concur			
OFFICE	NMSS	<input type="checkbox"/>			
LIAISON	Liaison	Distribution			
DD	N/A	Concur			
OFFICE	NRO	<input checked="" type="checkbox"/>			
LIAISON	Tanya Hood, DNRL	Distribution			
BC	Charles Ader, DSRA	Concur			
OFFICE	NRR	<input checked="" type="checkbox"/>			
LIAISON	Holly Cruz, DPR	Distribution			
DD	William Ruland, DSS	Concur			
OFFICE	NSIR	<input type="checkbox"/>			
LIAISON	Liaison	Distribution			
DD	Division Director	Concur			
OFFICE	OGC	<input checked="" type="checkbox"/>			
AGC	Bradley Jones, OGC	No Legal Objection (NLO)			

SUBJECT:	Request for Concurrence on Draft Regulatory Guide (DG) -1262, "Testing for Postquenched Ductility."		
REMARKS:	Proposed New Regulatory Guide.		
FROM:	Angelisa Hicks	Room No.:	2C27
		Phone No.:	301-251-7448

April 14, 2011

MEMORANDUM TO: William H. Ruland, Director
Division of Safety Systems
Office of Nuclear Reactor Regulation

Charles E. Ader, Director
Division of Safety Systems and Risk Assessment
Office of New Reactors

Bradley W. Jones, Assistant General Counsel
for Reactors and Materials Rulemaking
Office of the General Counsel

FROM: Michael J. Case, Director */RA/*
Division of Engineering
Office of Nuclear Regulatory Research

SUBJECT: REQUEST FOR CONCURRENCE ON DRAFT REGULATORY GUIDE,
DG-1262, "TESTING FOR POSTQUENCH DUCTILITY"

I am forwarding for your concurrence Draft Guide (DG) DG-1262, "Testing for Postquench Ductility." The enclosed DG-1262 is a proposed new regulatory guide. This draft has been developed by the Office of Nuclear Regulatory Research (RES) with close cooperation and coordination with the following organizations and individuals:

- Office of New Reactors: Paul Clifford
- Office of Nuclear Reactor Regulation: Ralph Landry

The agency will publish a notice in the *Federal Register* concerning the issuance and availability of DG-1262. The public comment period for this guide will be 60 days from the date of issuance. If there are only editorial changes following internal concurrence and resolution of public comments, your concurrence will not be needed for publication of the final regulatory guide.

CONTACT: Michelle Flanagan, RES/DE
(301) 251-7547

Angelisa Hicks, RES/DE
(301) 251-7448

W. Ruland, et al.

- 2 -

Please contact either Michelle Flanagan or Angelisa Hicks as early as possible during the concurrence review period to resolve any questions or issues in a timely manner.

Enclosures:

1. DG-1262
2. Regulatory Analysis

Please contact either Michelle Flanagan or Angelisa Hicks as early as possible during the concurrence review period to resolve any questions or issues in a timely manner.

Enclosures:

1. DG-1262
2. Regulatory Analysis

DISTRIBUTION: DE r/f

ADAMS Accession No. ML110840174

OFFICE	RES/DE	RES/DE	RES/DE	SUNSI Review	RES/DE	NRO
NAME	J. Borges via email	A. Hicks	T. Boyce	T. Boyce	M. Case	C. Ader
DATE	4/1/11	4/7/11	4/7/11	4/7/11	4/14/11	/ /11
OFFICE	NRR	OGC	QTE			
NAME	W. Ruland	B. Jones	Via e-mail			
DATE	/ /11	/ /11	2/14/11			

OFFICIAL RECORD COPY



DRAFT REGULATORY GUIDE

Contact: M. Flanagan
(301) 521-7547

DRAFT REGULATORY GUIDE DG-1262 (Proposed New Regulatory Guide 1.223)

TESTING FOR POSTQUENCH DUCTILITY

A. INTRODUCTION

This guide describes an experimental technique that is acceptable to the U.S. Nuclear Regulatory Commission (NRC) for measuring the ductile-to-brittle transition for a zirconium (Zr)-based cladding alloy, as called for in Title 10, Section 50.46(c), of the *Code of Federal Regulations* (Ref. 1). The experimental technique utilizes ring-compression testing (RCT) of Zr-based cladding alloys following exposure to oxidation and quench conditions related to a loss-of-coolant accident (LOCA).

The experimental technique described in this guide is acceptable for generating data for new Zr-based cladding alloys. These data can be used to demonstrate comparable performance with the database established in the NRC's LOCA research program. In some instances, a Zr-based cladding alloy may experience the transition from ductile-to-brittle behavior at a higher level of oxidation than indicated in the database established in the NRC's LOCA research program. The experimental technique provided in this guide is acceptable for generating data to support the development of specific analytical limits on peak cladding temperature and time at elevated temperature for Zr-based cladding alloys. Further, some emergency core cooling systems (ECCSs) may perform such that the maximum oxidation temperature is significantly below 2,200 degrees Fahrenheit (°F) (1,204 degrees Celsius (°C)). The database in the NRC's LOCA research program is intended to bound ECCS performance by testing materials at the maximum oxidation temperature. Oxidation at lower temperatures has been shown to increase the allowable calculated oxidation before embrittlement. Therefore, conducting tests at lower peak temperatures may provide additional margin for some Zr-based cladding alloys. The experimental technique provided in this guide is acceptable for generating data to support the development of specific analytical limits for Zr-based cladding alloys at peak oxidation temperatures below 2,200 °F (1,204 °C).

The NRC issues regulatory guides to describe to the public methods that the staff considers acceptable for use in implementing specific parts of the agency's regulations, to explain techniques that the staff uses in evaluating specific problems or postulated accidents, and to provide guidance to applicants. Regulatory guides are not substitutes for regulations and compliance with them is not required.

This regulatory guide is being issued in draft form to involve the public in the early stages of the development of a regulatory position in this area. It has not received final staff review or approval and does not represent an official NRC final staff position. Public comments are being solicited on this draft guide (including any implementation schedule) and its associated regulatory analysis or value/impact statement. Comments should be accompanied by appropriate supporting data. Written comments may be submitted to the Rules, Announcements, and Directives Branch, Office of Administration, U.S. Nuclear Regulatory Commission, Washington, DC 20555-0001; submitted through the NRC's interactive rulemaking Web page at <http://www.nrc.gov>; or faxed to (301) 492-3446. Copies of comments received may be examined at the NRC's Public Document Room, 11555 Rockville Pike, Rockville, MD. Comments will be most helpful if received by **[insert date - 60 days from issuance]**.

Electronic copies of this draft regulatory guide are available through the NRC's interactive rulemaking Web page (see above); the NRC's public Web site under Draft Regulatory Guides in the Regulatory Guides document collection of the NRC's Electronic Reading Room at <http://www.nrc.gov/reading-rm/doc-collections/>; and the NRC's Agencywide Documents Access and Management System (ADAMS) at <http://www.nrc.gov/reading-rm/adams.html>, under Accession No. ML110840283. The regulatory analysis may be found in ADAMS under Accession No. ML110910421.

This regulatory guide contains information collection requirements covered by 10 CFR Part 50 that the Office of Management and Budget (OMB) approved under OMB control number 3150-0011. The NRC may neither conduct nor sponsor, and a person is not required to respond to, an information collection request or requirement unless the requesting document displays a currently valid OMB control number. The NRC has determined that this regulatory guide is not a major rule as designated by the Congressional Review Act and has verified this determination with OMB.

	<u>Page</u>
A. INTRODUCTION	1
B. DISCUSSION	4
Background	4
Hydrogen-Enhanced Beta-Layer Embrittlement	4
Addressing Hydrogen-Enhanced Beta-Layer Embrittlement with Performance-Based Requirements ..	5
C. REGULATORY POSITION.....	6
Procedure for Conducting Oxidation and Postquench Ductility Tests with Zirconium-Based Cladding Alloys	6
1. Purpose and Scope of the Tests	6
2. Background	6
3. Sample Selection and Testing Frequency	7
3.1 Sample Selection	7
3.2 Frequency of Testing	8
4. Sample Preparation and Characterization	8
4.1 Hydrogen-Content Determination for As-Fabricated and Prehydrided Samples	8
4.2 Minimum Sample Lengths for One- and Two-Sided Oxidation Tests	8
4.3 End-Cap Mass and Welding Procedure for One-Sided Oxidation Test Samples	9
4.4 Length, Outer Diameter, and Wall Thickness Measurements	9
4.5 Pretest Cleaning with Chemical Detergent or Organic Solvent and Rinsing	9
4.6 Pretest Sample Weight Measurement (after drying)	9
5. Temperature Heatup and Cooldown Rates and Heating Methods	10
5.1 Temperature Heatup and Cooldown Rates	10
5.2 Radiant Heating	10
5.3 Resistance Heating	11
5.4 Induction Heating	11
5.5 Direct Electrical Heating	11
6. Temperature Control and Monitoring	11
6.1 Thermocouples	11
6.2 Thermal Benchmarks	12
6.3 Weight-Gain Benchmarks	13
7. Water Quality, Steamflow Rate, and Steam Pressure	13
7.1 Water Quality	13
7.2 Steamflow Rate	14
7.3 Steam Pressure	14
8. Procedure for Oxidation and Quench Tests	14
8.1 Test Train and Steam Chamber	14
8.2 Purging Steam Chamber and Stabilizing Steamflow	15
8.3 Ramping Temperature and Holding Temperature at Target Value	15
8.4 End of Heating Phase and Cooldown	15
8.5 Determination of Equivalent Cladding Reacted	16
9. Post-Oxidation-Quench Measurements and Characterization	16
9.1 Sample Drying Time	16

9.2 Weight Measurement and Use of Weight Gain To Verify Oxidation Temperature	16
9.3 Hydrogen Content Measurement	16
10. Matrix for Oxidation and Quench Tests	17
10.1 As-Fabricated Cladding	17
10.2 Prehydrided Cladding	17
11. Procedure for Conducting Ring-Compression Postquench Ductility Tests	18
11.1 Pretest Activities	18
11.2 Test Temperature and Crosshead Displacement Rate	19
11.3 Test Conduct	19
11.4 Test Termination	20
11.5 Posttest Measurements	20
12. Data Reporting and Assessment	21
12.1 Hydrogen Level, Test Temperature, Test Time, CP-ECR, Offset Strain, and Permanent Strain	21
12.2 Determination of Ductile-to-Brittle Transition CP-ECR	21
13. References for Experimental Procedure	23
D. IMPLEMENTATION	25
GLOSSARY	26
REFERENCES	27
APPENDIX A: Ring-Compression Results for Room Temperature and 135 °C Tests with As-Fabricated Cladding Samples	A-1
APPENDIX B: Examples of Load-Displacement Curves, Offset Strains, and Permanent Strains for Oxidized and Quenched Cladding Samples.....	B-1
APPENDIX C: Relationship between Offset Strain and Permanent Strain	C-1

B. DISCUSSION

Background

In 1996, the NRC initiated a fuel-cladding research program intended to investigate the behavior of high-exposure fuel cladding under accident conditions. This program included an extensive LOCA research and testing program at Argonne National Laboratory (ANL), as well as jointly funded programs at the Kurchatov Institute (Ref. 2) and the Halden Reactor project (Ref. 3), to develop the body of technical information needed to evaluate LOCA regulations for high-exposure fuel. The research findings have been summarized in Research Information Letter 0801, "Technical Basis for Revision of Embrittlement Criteria in 10 CFR 50.46," dated May 30, 2008 (Ref. 4). The detailed experimental results from the program at ANL are contained in NUREG/CR-6967, "Cladding Embrittlement During Postulated Loss-of-Coolant Accidents," issued July 2008 (Ref. 5).

The research program identified new cladding embrittlement mechanisms and expanded the NRC's knowledge of previously identified mechanisms. The research results revealed that alloy composition has a minor effect on embrittlement, but cladding corrosion, which occurs as fuel burnup increases, has a substantial effect on embrittlement. One of the major findings of the NRC's research program was that hydrogen, which is absorbed in the cladding as a result of waterside corrosion under normal operation, has a significant influence on embrittlement during a hypothetical accident.

Hydrogen-Enhanced Beta-Layer Embrittlement

As explained in Section 1.4 of NUREG/CR-6967 (Ref. 5), oxygen diffusion into the base metal under LOCA conditions promotes a reduction in the size (referred to as beta-layer thinning) and ductility (referred to as beta-layer embrittlement) of the metallurgical structure within the cladding which provides its overall ductility. The presence of hydrogen within the cladding enhances this embrittlement process.

During normal operation, some hydrogen from the corrosion process is absorbed in the cladding metal. When that cladding is exposed to high-temperature LOCA conditions, the elevated hydrogen levels increase the solubility of oxygen in the beta phase and the rate of diffusion of oxygen into the beta phase. Thus, even for LOCA temperatures below 2,200 °F (1,204 °C), embrittlement can occur for times corresponding to less than 17% oxidation in corroded cladding with significant hydrogen pickup.

Figure 1 illustrates the effect of hydrogen on RCT ductility measurements. The figure shows that ductility is lost in high-burnup Zircaloy-4 at a lower calculated equivalent cladding reacted (ECR) than as-fabricated (fresh) 15×15 Zircaloy-4. Significantly, Figure 1 indicates that ductility is lost in this high-burnup Zircaloy-4 cladding at a level of oxidation well below 17%.

As shown in Figure 1, ductility measurements were made on segments oxidized to a number of Cathcart-Pawel (CP) calculated oxidation levels. In characterizing the ductile-to-brittle transition behavior of the alloys tested in the NRC's LOCA research program, multiple postquench ductility (PQD) measurements were made at the same oxidation level to characterize the variability in test results. This is reflected in the test procedure described in the Regulatory Position section of this guide.

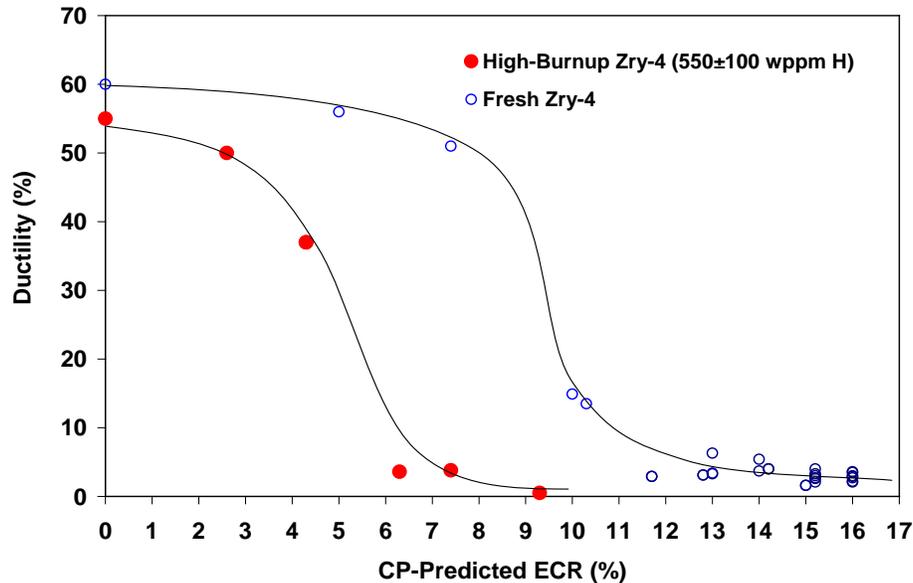


Figure 1. Measured offset strains¹
 (Source: NUREG/CR-6967 (Ref. 5))

Addressing Hydrogen-Enhanced Beta-Layer Embrittlement with Performance-Based Requirements

In the 1973 version of the ECCS performance rule, the preservation of cladding ductility, through compliance with regulatory criteria for peak cladding temperature and local cladding oxidation, provided a level of assurance that fuel cladding would not experience gross failure. Hence, the fuel rods would remain within their coolable lattice arrays. The recent LOCA research program identified new cladding embrittlement mechanisms, which demonstrate that the current combination of peak cladding temperature (2,200 °F (1,204 °C)) and local cladding oxidation (17% ECR) criteria may not always ensure PQD.

The rule in 10 CFR 50.46(c) considers the findings of the NRC’s LOCA research program and calls for the establishment of analytical limits on peak cladding temperature and time that correspond to the measured ductile-to-brittle transition for the Zr-alloy cladding material. This guide describes an experimental technique that is acceptable for measuring the ductile-to-brittle transition for a Zr-alloy cladding by RCT, which can be used to (1) justify the use of the analytical limit defined in Draft Regulatory Guide (DG)-1263, “Regulatory Guidance on Establishing Analytical Limits for Zirconium-Based Alloy Cladding” (Ref. 6), for alloys not tested in the NRC’s LOCA research program, (2) support the development of a specific limit for Zr-based cladding alloy, or (3) support the development of analytical limits at peak oxidation temperatures less than 2,200 °F (1,204 °C).

¹ Test specimens included high-burnup Zircaloy (Zry)-4 (corrosion-layer thickness of 71–74 micrometers) and as-fabricated (fresh) HBR-type 15×15 Zry-4. Cladding samples were two-side oxidized at ≈1,200 °C and cooled at ≈11 °C/second (s) to 800 °C. As-fabricated samples were quenched at 800 °C, while the high-burnup samples were slow-cooled from 800 °C to room temperature. The ductile-to-brittle transition oxidation level for high-burnup cladding is 8% for cladding cooled without quench and 5% for cladding quenched at 800 °C.

C. REGULATORY POSITION

The following procedure describes an acceptable experimental technique that can be used to measure the ductile-to-brittle transition for a Zr-based cladding alloy to establish specified and acceptable analytical limits on peak cladding temperature and time at elevated temperature, as called for by the proposed language of 10 CFR 50.46(c).

Procedure for Conducting Oxidation and Postquench Ductility Tests with Zirconium-Based Cladding Alloys

1. Purpose and Scope of the Tests

Performance-based tests are needed to ensure that fuel rod cladding retains ductility following oxidation in steam at $\leq 1,200$ °C and quench at ≤ 800 °C.² This procedure describes the tests to be conducted with fresh and prehydrided cladding samples for determination of the ductile-to-brittle transition oxidation level as a function of hydrogen content and either the hold temperature or the maximum oxidation temperature for samples that embrittle during the heating ramp. The procedure for conducting in-cell oxidation-quench tests with high-burnup cladding samples is similar to the one described for out-of-cell tests with unirradiated cladding samples. The critical differences in a procedure for conducting testing on irradiated, high-burnup material are in the area of thermal and weight-gain benchmarks. The sections addressing thermal and weight-gain benchmarks highlight the differences in test procedure for irradiated material.

The oxidation level is defined as the ECR calculated using the CP weight gain correlation. Retention of PQD is defined as the accumulation of $\geq 1.0\%$ permanent strain prior to failure during ring-compression loading at a temperature of 135 °C³ and a displacement rate of 0.033 millimeters (mm)/s. The ductile-to-brittle transition oxidation level is defined as the maximum CP-ECR (rounded to the nearest percent) for which ductility is retained.

2. Background

During a LOCA, the cladding outer surface will be exposed to steam at elevated temperatures. This results in the growth of an outer surface oxide layer, an oxygen-stabilized metal alpha layer, and a metal beta layer with low oxygen content. The oxide and alpha layers are brittle, but the beta layer will retain ductility as long as its oxygen content is low (e.g., < 0.6 weight parts per million (wppm)). This is close to the oxygen solubility limit at $1,200$ °C for the beta layer of as-fabricated cladding. As such, modern cladding alloys used in U.S. reactors oxidized at $1,200$ °C will retain ductility up to a time-at-temperature corresponding to a calculated oxidation level of 17–20% CP-ECR (Experimental Procedures (EP)-Ref. 1), where CP refers to the use of the Cathcart-Pawel (EP-Ref. 2) weight-gain correlation for the ECR calculation. During a LOCA, cladding embrittlement is the result of oxygen diffusion into the beta layer of the base metal and is not directly related to the growth of the Zr dioxide layer on the outside cladding diameter. The calculated maximum local oxidation limit is used as a surrogate to limit time at

² These test conditions were selected with the objective of bounding the performance of ECCSs. They are considered relevant and bounding for current light-water reactor ECCSs. However, it may be necessary to evaluate and possibly modify the conditions accordingly for the ECCSs of advanced reactor designs.

³ During the 1973 hearing, investigators suggested that a test temperature no higher than the saturation temperature during reflood (i.e., ≈ 135 °C) be considered. This test condition is considered relevant for current light-water reactor ECCSs. However, it may be necessary to evaluate and possibly modify the conditions accordingly for the ECCSs of advanced reactor designs.

elevated temperature, associated oxygen diffusion into the beta layer, and ductility decrease caused by the increased oxygen content in the beta layer. This surrogate approach works because both oxidation rate and diffusion rate share similar temperature dependences. In particular, for as-fabricated alloys tested at 1,200 °C, there is a linear correlation for CP-ECR $\leq 17\%$ between calculated oxidation level (CP-ECR) and increase in average oxygen content in the beta layer, which is the cause of embrittlement. However, for some alloys tested at 1,000 °C, the measured oxide-layer thickness growth rate and weight-gain rate decrease significantly with oxidation time, while the ductility continues to decrease with oxidation time. This demonstrates that diffusion of oxygen into the beta layer and oxygen solubility in the beta layer control embrittlement. In general, the decrease in ductility with time correlates quite well with the increase in CP-predicted ECR.

However, hydrogen pickup during reactor operation can cause a significant decrease in the ductile-to-brittle transition oxidation level (e.g., from 19% to 5% for 550 wppm hydrogen (EP-Ref. 1)). Hydrogen increases the oxygen solubility limit in the beta layer, as well as the rate of diffusion of oxygen into that layer. In addition, for oxidized cladding that undergoes very rapid cooling during quench, hydrogen is intrinsically embrittling. As hydrogen does not influence measured or calculated weight gain and ECR, the combinations of hydrogen content and calculated oxidation level (CP-ECR) that lead to embrittlement need to be determined.

In addition to oxygen pickup from the cladding outer surface, the cladding inner surface can pick up oxygen from the fuel-cladding bond and from fuel that may be adherent to this bond. This burnup-dependent phenomenon results in an oxygen-stabilized alpha layer on the inner surface and additional oxygen pickup by the beta layer.

For cladding that balloons and ruptures during the LOCA heating ramp, a third source of oxygen is available from the steam that enters through the rupture opening. Thus, within the localized balloon region (≈ 75 –100 mm), an oxide layer will form on the cladding inner surface, and hydrogen pickup (secondary hydriding) will occur through this surface, especially near the neck regions of the balloon which experience delayed inner-surface oxide formation. The procedure outlined in this document provides a method to characterize the PQD of cladding as a function of initial hydrogen, which is present before the LOCA begins. This test procedure does not measure other effects, such as secondary hydriding, on the behavior of the ballooned region.

To characterize the PQD of cladding outside the balloon region, it is sufficient to perform tests using nonpressurized and nondeformed cladding samples. Such tests have been conducted using two-sided oxidation (EP-Ref. 1) and outer-surface-only oxidation (EP-Ref. 3) with cladding samples sectioned from as-fabricated Zircaloy (Zry-2, Zry-4), ZIRLO™, and M5, prehydrided Zry-4 (EP-Ref. 1, 3) and M5 (EP-Ref. 3), and high-burnup Zry-4, ZIRLO™, and M5 (EP-Ref. 1). The procedures used by ANL for conducting oxidation-quench testing and PQD testing are documented in EP-Ref. 1. The purposes of the procedures that follow are both to generalize the ANL methods to include a range of acceptable methods and to describe the methods in finer detail.

3. Sample Selection and Testing Frequency

3.1 Sample Selection

Although it is desirable to use samples representative of the fueled cladding that is loaded into the reactor, generally it is sufficient to select samples from finished cladding after polishing and cleaning processes. The one exception would be if postpolishing cleaning at the fuel fabrication facility includes etching with a hydrofluoric (HF)-containing acid mixture. If this is the case, then this step should also be

used on cladding before sample selection, as such treatment can result in early embrittlement even at temperatures as high as 1,200 °C.

3.2 *Frequency of Testing*

Unlike breakaway-oxidation embrittlement, high-temperature embrittlement is relatively insensitive to trace elements and minor variations in alloy composition (within established ranges) and surface finishing. For cladding materials fabricated within specifications, PQD testing should be performed once for a particular cladding material and does not have to be repeated at a specified frequency. The effects of hydrogen on PQD are far more detrimental to cladding ductility than are minor changes to fabrication processes.

4. **Sample Preparation and Characterization**

4.1 *Hydrogen Content Determination for As-Fabricated and Prehydrided Samples*

The hydrogen content of as-fabricated cladding is expected to be low (5–15 wppm) and to be available from the tubing vendor. If it is not available, it should be measured. For prehydrided cladding used to simulate high-burnup effects, measurement of hydrogen content from locations close to sample locations is essential. Most techniques for prehydriding cladding are company-proprietary. However, based on reported results, the methods used result in samples with relatively uniform (<10% variation) hydrogen concentration along the axis and circumference of the sample. As shown in EP-Ref. 4, the pretest radial distribution of hydrogen is relatively unimportant as hydrogen homogenizes across the cladding wall very quickly for temperatures ≥ 900 °C.

There are several ways to measure hydrogen content in metals. Vacuum fusion is one method. American Society for Testing and Materials (ASTM) E1447, “Standard Test Method for Determination of Hydrogen in Titanium and Titanium Alloys by the Inert Gas Fusion Thermal Conductivity Method” (EP-Ref. 5), documents the recommended method. This method has been used successfully to determine the hydrogen content in other metals such as Zr alloys. EP-Ref. 6 documents the detailed procedure used to generate the results in EP-Ref. 1.

Along with the instrumentation needed (e.g., LECO RH-404 hydrogen determinator), calibration coupons are available from the vendor. These titanium coupons have hydrogen contents traceable to National Institute of Standards and Technology (NIST) standards. Titanium coupons with 218 wppm are recommended for calibration. As these machines are very sensitive, it is important to perform the calibration at least once in any given day before data generation. For measurements of hydrogen content that appear to be inconsistent, postmeasurement calibration verification should be performed using standard coupons as unknown samples. If low hydrogen content (e.g., <140 wppm) is measured for a cladding sample, then vendor standard coupons with 24 to 71 wppm may be tested as unknown samples to determine the error in extrapolating to lower hydrogen contents. Also, standard titanium coupons are available directly from NIST. In addition to the NIST titanium standard with about 215-wppm hydrogen, NIST also provides a standard with 114-wppm hydrogen.

4.2 *Minimum Sample Lengths for One- and Two-Sided Oxidation Tests*

The minimum sample length for two-sided oxidation samples should be 25 mm. This length was used for the oxidation-quench phase of the testing reported in EP-Ref. 1. Part of the reason for using this relatively short sample length was the limited supply of high-burnup cladding available for use in the ANL program. A length of 30 mm would have been more convenient, as it would have allowed three 8-mm-long ring-compression samples and a few postoxidation hydrogen samples to be sectioned from a

single oxidation-quench sample. Although there is no maximum limit prescribed, the two-sided oxidation sample should be no longer than the length of the uniform temperature region of the furnace. “Uniform” is defined as less than or equal to ± 10 °C variation at the target temperature.

In preparing samples for one-sided oxidation tests, welded end-caps have been used to prevent steam from coming into contact with the cladding inner surface. To minimize larger end effects resulting from the heat-affected zones and possible hydrogen diffusion from the sample to the end-caps, the minimum sample length for one-sided oxidation tests should be 75 mm. For prehydrided samples, axial distribution of hydrogen before end-cap welding and after oxidation testing should be measured to determine how much of the 75 mm is available for PQD testing. Also, samples should be evacuated before end-cap welding. An alternative approach is to introduce the flow of high-purity inert gas inside the cladding. It is important to minimize impurities (e.g., nitrogen) and gas pressure (less than or equal to steam pressure) acting on the inner surface of the cladding.

4.3 End-Cap Mass and Welding Procedure for One-Sided Oxidation Samples

Standard procedures are available for circumferential welding of end-caps to cladding samples. Because the welds and end-caps are not subjected to pressure, the end-caps should be small and the masses should be minimized as they serve as sinks for hydrogen.

4.4 Length, Outer Diameter, and Wall Thickness Measurements

Outer diameter and wall thickness vary somewhat along the length of fuel rod cladding. They should be measured and recorded for each sample. For cladding with a nominal diameter of 9.50 mm, the actual diameter of the sample can vary from 9.46 to 9.50 mm. The outer diameter should be determined to two decimal places (in mm) based on the average of the maximum and minimum diameters. For cladding with a nominal wall thickness of 0.57 mm, the actual wall thickness can vary from about 0.56 to 0.60 mm. Wall thickness should be determined for each sample to two decimal places (in mm) based on four readings at locations $\approx 90^\circ$ apart. The sample length should be measured and recorded to one decimal place accuracy (e.g., 25.1 mm). Also, the ends of the sample should be polished to remove burrs before the sample length measurement. The ends of the sample should be relatively flush ($90 \pm 5^\circ$ relative to longitudinal axis). Outer diameter, wall thickness, and length are used to normalize sample weight gain to exposed surface area. The average wall thickness is used to calculate the CP-ECR.

4.5 Pretest Cleaning with Chemical Detergent or Organic Solvent and Rinsing

Appendix X1 (“Guide to Specimen Preparation”) to ASTM G2/G2M–06, “Standard Test Method for Corrosion Testing of Products of Zirconium, Hafnium, and Their Alloys in Water at 680 °F [360 °C] or in Steam at 750 °F [400 °C],” describes sample cleaning procedures in Section X1.2 (EP-Ref. 7). These procedures should be followed for oxidation-quench test sample preparation. Specifications and requirements in Sections X1.1 (“Tubes with a Second Material on Inner Diameter”) and X1.3 (“Etching”) should be ignored. Based on EP-Ref. 1 and subsequent work at ANL, samples should not be etched with an HF-containing acid mixture as part of the test cleaning process. However, ANL has demonstrated that polishing of about 1 micron from the etched surface is sufficient to negate the possible negative effects of HF. Following cleaning, direct contact with the sample should be avoided by using surgical gloves for handling.

4.6 Pretest Sample Weight Measurement (after Drying)

Pretest sample weight should be measured to the nearest 0.1 milligram (mg) as specified in 7.1.3 of EP-Ref. 7. As drying after cleaning may take several hours, it is also permissible to measure pretest

sample weight after cleaning with an organic solvent such as ethanol that vaporizes rather quickly. The pretest weight is used in the determination of sample weight gain. Although measured weight gain is not used to determine oxidation level (i.e., ECR) for these tests, it is used as a partial validation of the reported isothermal oxidation temperatures and a check on steamflow conditions.

5. Temperature Heatup and Cooldown Rates and Heating Methods

5.1 Temperature Heatup and Cooldown Rates

For a given oxidation level and hydrogen content, the heating rate to 1,200 °C is a critical parameter for samples that embrittle after short test times; weight gain accumulated at lower temperatures results in lower beta-layer oxygen content at the end of the heating phase and higher ductility. For samples with as-fabricated levels of hydrogen, test times at 1,200 °C leading to embrittlement are in the range of 300–500 seconds for cladding with a thickness 0.57–0.67 mm that is exposed to two-sided oxidation. Embrittlement times at 1,200 °C for one-sided oxidation tests with as-fabricated cladding samples are considerably longer than 500 seconds. As such, the embrittlement oxidation level is less sensitive to heating rate for as-fabricated cladding than it is for prehydrided cladding. The heating rate from 300 °C to 1,000 °C should be relatively fast (>20 °C/s or <35 seconds to reach 1,000 °C), and the heating rate from 1,000 °C to 1,200 °C should be >2 °C/s (<100 -second duration). Use of slower heating rates that lead to higher embrittlement oxidation levels should be justified. The cooling rate from 1,200 °C to the quench temperature (i.e., the wetting temperature at which very rapid cooling occurs) may be important, but it is less critical than the heating rate. The cooling rate to the quench temperature should be >2 °C/s (e.g., <200 seconds from 1,200 °C to 800 °C). Use of slower cooling rates should be justified. The recommended quench temperature is 800 °C. Use of lower quench temperatures should be justified. Based on results presented in EP-Ref. 1, no difference in ductile-to-brittle transition was observed for as-fabricated cladding materials cooled with or without quench. For prehydrided Zry-4, no significant difference was found in ductility for samples quenched at 800 °C, 700 °C, and 600 °C, as all samples were brittle. However, prehydrided samples at the same hydrogen content and CP-ECR were ductile following cooling without quench. Temperature overshoot during the heating phase can have a significant effect on embrittlement oxidation level for prehydrided samples. As such, temperature overshoot should be limited to ≤ 20 °C for ≤ 20 seconds.

As the target oxidation temperature is decreased from 1,200 °C to 1,100 °C to 1,000 °C, the embrittlement oxidation level becomes less sensitive to heating rate. However, to standardize heating rates for these lower temperatures, the heating rate to within 100 °C of the target hold temperature should be >20 °C/s, and the heating rate from that temperature (e.g., 1,000 °C or 900 °C) to the hold temperature should be >2 °C/s. Similarly, the cooling rate to the quench temperature (800 °C) should be >2 °C/s. The use of lower heating rates, cooling rates, and quench temperatures should be justified. However, the use of higher cooling rates to the quench temperature and higher quench temperatures does not have to be justified as these conditions will lead to embrittlement at lower oxidation levels.

For “uncontrolled” cooling rates (e.g., those resulting from furnace and sample cooling alone), the cooling rate will decrease with cooling time. The rates listed above refer to average values determined from $\Delta T/\Delta t$. For controlled cooling rates (e.g., by means of a thermocouple (TC) welded to the sample with feedback to furnace power), constant cooling rates may be achieved. For a postulated LOCA transient temperature history, the cooling rate increases from the maximum temperature to the wetting temperature. Although this cooling history is difficult to simulate experimentally, a constant cooling rate comes closer than one that decreases with time.

5.2 *Radiant Heating*

Radiant heating in a quad-elliptic furnace has been used to generate the PQD data reported in EP-Ref. 1. This heating method, along with furnace power controlled by feedback from a TC on or near the sample, allows for controlled heating rates and relatively fast cooling rates (>10 °C/s or <40 seconds for cooling from 1,200 °C to 800 °C). For 25-mm-long samples, axial temperature variations are negligible, but circumferential temperature variations are in the range of 10–20 °C for cladding outer diameters ranging from 9.50 to 11.0 mm. These variations can be reduced by using radiant-heating furnaces with more than four lamps. With proper thermal benchmarking, radiant-heating furnaces are acceptable for generating PQD specimens for ductility determination.

5.3 *Resistance Heating*

Resistance heating has been used to generate the results reported in EP-Ref. 3. As compared to radiant-heating furnaces, these furnaces are characterized as having a larger uniform temperature zone and as having very slow heating and cooling rates. Controlled movement of the sample into and out of the furnace achieves faster heating and cooling rates. Benchmark tests should be performed to determine the heating and cooling rates. With proper thermal benchmarking, resistance-heating furnaces are acceptable for generating PQD specimens for ductility determination.

5.4 *Induction Heating*

Induction heating has the advantage of rapid sample heating and cooling rates. The CINOG program in France (EP-Ref. 8) has used it to generate weight-gain kinetics data for Zry-4, M5, and developmental alloys. Although the data from these tests appear reliable, reported weight gains for Zry-4 are about 10–12% lower than those predicted using the CP correlation and are in better agreement with the weight-gain correlation (LS) derived by Leistikow and Schanz (EP-Ref. 9) using data from resistance heating. However, this should not be an important factor in determining the embrittlement oxidation level as calculated with the CP weight-gain correlation as long as the oxidation temperatures are accurate. These temperatures are determined using optical pyrometry. With proper thermal benchmarking, induction-heating furnaces might be acceptable for generating PQD samples. However, as it is not clear how to do the benchmarking, the use of induction heating is not recommended for preparing PQD samples.

5.5 *Direct Electrical Heating*

Direct electrical heating of cladding has been used in the past for studies relevant to LOCAs. Because resistance and heating rate change with temperature, direct electrical heating of cladding is not recommended for preparing PQD samples. However, “indirect” electrical heating may be an acceptable method for internal heating of another material inside the cladding to generate a heat flux simulating heating of the cladding by means of decay heat from the fuel.

6. **Temperature Control and Monitoring**

6.1 *Thermocouples*

For oxidation temperatures $\leq 1,200$ °C, Type S (Pt/10%Rh-Pt) TCs should be used to record temperature and control furnace power. The TCs should be calibrated using instrumentation and standards that are traceable to NIST. Generally, this service is provided by the TC vendor, who, for an extra fee, provides a certificate of calibration. Every TC used to measure sample temperature either directly or indirectly should have a certificate of calibration showing the results of the calibration at three

temperatures: 1,200 °C, 1,100 °C, and 1,000 °C. Copies of these certificates should accompany the data report. Verification should be provided demonstrating that the vendor actually did the calibration according to the standards in internationally recognized standards organizations, such as the International Organization for Standardization (ISO), and American National Standards Institute/National Conference of Standards Laboratories (ANSI/NCSL).

6.2 Thermal Benchmarks

For short (e.g., 25–30 mm) two-sided oxidation samples, direct welding of TCs onto the sample outer surface is not recommended for data-generating tests. The interaction between the TC and the cladding metal causes a local flaw. Also, it is difficult to get an accurate posttest weight measurement after removing the welded TCs. Although measured weight gain is not used to determine the oxidation level (CP-ECR), it is used to check that the target temperature and hold time at that temperature are achieved.

For longer two-sided and one-sided oxidation samples, TCs may be welded near the sample ends for data-generating tests. For one-sided samples, in particular, the TC may be welded to the cladding outer surface in the heat-affected zone.

In most cases, the control TC will be welded onto the sample holder or as close to the sample as possible without contacting the sample. This requires thermal benchmarks to be performed to establish the relationship between the control TC that will be used during data-generating tests and the temperature of the sample outer surface. Generally, the control TC will experience slower heating and cooling rates than the sample. The thermal benchmarking should be performed at three sample temperatures: 1,200 °C, 1,100 °C, and 1,000 °C. An important phase of the benchmarking is to determine the control TC temperature at which quench water should be introduced to rapidly cool the sample at the prescribed temperature. For the work reported in EP-Ref. 1, two to three TCs (120° apart) were welded directly onto the benchmark sample outer surface. These readings were compared to the readings of three TCs welded onto the sample holder at a location just above the sample. For radiant heating and large-diameter (≈11-mm) cladding, three TCs were welded directly to the cladding outer surface to better define the average and one-standard-deviation cladding temperature. For smaller diameter cladding (9.50 mm), only two TCs welded directly to the cladding surface were needed. It is important that the thermal benchmark tests be conducted under the same flowing steam conditions as used in the data-generating tests.

For resistance-heating furnaces, thermal-benchmarking methods similar to the ones described for radiant-heating furnaces can be used. However, other methods commonly used (e.g., suspended and movable TC) may not be adequate for characterizing the heating rate of the sample. Samples with low thermal mass and high initial heats of oxidation, exposed to low steamflow rates, may heat up much faster than more massive sample holders. The results of the thermal benchmark tests should be documented and included in the data report.

For irradiated high-burnup material which has developed a corrosion layer, it is expected that pretest cladding corrosion would slow the initial oxidation rate and the heating rate associated with the exothermic oxidation reaction. The presence of the corrosion layer could affect the peak temperature reached during the very rapid heating ramp. The work reported in EP-Ref. 1 with out-of-cell tests confirmed this effect. The following procedure was used in the work reported in EP-Ref. 1 and could be used to validate a thermal benchmark for irradiated material which has developed a corrosion layer:

- a. With TCs welded onto bare as-fabricated cladding, conduct the thermal benchmark test for a hold time selected to grow an oxide layer relevant to the irradiated material to be tested.

- b. Cool to 300 °C and repeat the thermal benchmark test using the same controller parameters as were used in (a); compare the two sets of results with emphasis on the maximum temperature at the end of the rapid temperature rise (first peak), the time to reach the hold temperature, and the hold temperature.
- c. If necessary, increase the holder control temperature to achieve the desired hold temperature for cladding with pretransient oxide layers.

6.3 *Weight-Gain Benchmarks*

Following thermal benchmarking, samples should be tested without TCs welded onto the sample to determine the weight gain. These tests should be conducted at 1,200 °C, 1,100 °C, and 1,000 °C for a test time corresponding to 10% CP-ECR. For all cladding materials tested in the ANL program (EP-Ref. 1), weight gains were comparable to each other and to the CP-correlation predictions at oxidation temperatures of 1,200 °C and 1,100 °C. If the measured weight gain for these oxidation temperatures differed from the CP-predicted weight gain by $\geq 10\%$, then data-generating tests were not initiated until the root cause of the problem was found and corrected (EP-Ref. 1). Generally, this occurred only when the TCs used for the thermal benchmarking read 15 to 20 °C higher or lower than the actual sample temperature, even though the vendor had certified the TCs. As weight gain may depend somewhat on heating method, the weight gain for a particular cladding material should deviate by less than 10% from the vendor-established database for that material before the start of data-generating tests. For Zr-lined Zry-2 and alloys of Zr-1 and niobium, the measured weight gain at 1,000 °C is considerably lower than the CP-predicted weight gain.⁴ For these materials, the results of the weight-gain benchmark should be compared to the published or vendor-proprietary, material-specific databases.

The weight-gain benchmarks are designed as a supplement to the thermal benchmarks to ensure adequate TC readings and adequate steamflow. The results of the weight-gain benchmark tests should be documented and included in the data report.

For irradiated high-burn material that has developed a corrosion layer, the corrosion layer may affect the oxidation kinetics, and it should be confirmed that the weight gain of the irradiated material is comparable to the CP correlation. For the testing reported in EP-Ref. 1, which included oxidation tests with high-burnup cladding, the measured oxide layer thickness and the weight gain determined from layer thicknesses agreed quite well with CP-predicted values for as-fabricated and high-burnup cladding. To validate that, for irradiated material which has developed a corrosion layer, the CP correlation accurately predicts weight gain, mass and metallographic examination can be used to determine that the measured weight gain and the measured oxide layer thicknesses are in good agreement with CP-predicted values. A test with the hold time chosen to give a weight gain equivalent to 10% CP-ECR is recommended. If the out-of-cell and in-cell weight gains and converted ECR values are in good agreement, then the use of the test train in the in-cell furnace can be considered validated, and the weight gain can be used as a supplement to the thermal benchmarks to ensure adequate TC readings and adequate steamflow.

⁴ Even when the measured weight gain at 1,000 °C was considerably lower than the CP-predicted weight gain for a particular alloy, the CP correlation accurately predicted the embrittlement of cladding alloys tested. It is important to clarify that the loss of cladding ductility is the result of oxygen diffusion into the base metal and is not directly related to the growth of a Zr dioxide layer on the outside cladding diameter (i.e., weight gain). A limit correlated with peak local oxidation, as calculated by the CP correlation, is used as a surrogate to limit time at elevated temperature and associated oxygen diffusion. This surrogate approach is possible because both CP-calculated oxidation and diffusion share similar temperature dependences.

7. Water Quality, Steamflow Rate, and Steam Pressure

7.1 Water Quality

Purified water should be used for generating steam. Grade A water with ≤ 45 parts per billion (ppb) oxygen should be used for corrosion tests in pressurized water and steam (EP-Ref. 7). Laboratory-grade Type I (distilled and/or deionized) water is also of sufficient purity for oxidation tests at $\geq 1,000$ °C. ASTM, the National Committee for Clinical Laboratory Standards (now Clinical and Laboratory Standards Institute), and ISO 3696, “Water for Analytical Laboratory Use—Specification and Test Methods,” have similar definitions for Type I purified water.

7.2 Steamflow Rate

The average steamflow rate used to oxidize PQD samples should be determined (and reported) from the mass of condensed water collected during the test, or by the mass of water that is input to the steam chamber, divided by the test time, and normalized to the net cross-sectional area of the steam chamber. The average steamflow rate should be in the range of 0.8 to 30 mg/square centimeter ($\text{cm}^2 \text{ s}$). Justification for this range is provided in the following.

Leistikow and Schanz (EP-Ref. 9) and Uetsuka (EP-Ref. 10) studied the effects of low steamflow rates on the oxidation kinetics of Zry-4 at 1,000 °C. Figure 9 of EP-Ref. 9 summarizes their results. In terms of flow rate normalized to the cross-sectional area of the steam chamber, the oxidation kinetics began to decrease due to steam starvation for flow rates $< 0.05 \text{ mg}/(\text{cm}^2 \text{ s})$. For the EP-Ref. 9 work, the sample length was 30 mm and oxidation was two-sided. Aomi, et al. (EP-Ref. 11) studied the relationship between weight gain and steamflow rate for oxidation temperatures up to 1,200 °C. They found that the weight gain for fixed test times and temperatures was independent of steamflow rates in the range of 0.8 to 7.8 $\text{mg}/(\text{cm}^2 \text{ s})$. Kawasaki, et al. (EP-Ref. 12) also performed high-temperature oxidation tests to determine the range of steamflow rates for which the weight gain for a given test time was independent of steamflow rate. They report this range as 3 to 28 $\text{mg}/(\text{cm}^2 \text{ s})$.

Although EP-Ref. 11 and EP-Ref. 12 give maximum steamflow rates of 7.8 $\text{mg}/(\text{cm}^2 \text{ s})$ and 28 $\text{mg}/(\text{cm}^2 \text{ s})$, it is not clear why higher steamflow rates would have an effect on weight gain and oxidation kinetics. It is desirable to have a steamflow rate higher than 0.8 $\text{mg}/(\text{cm}^2 \text{ s})$ to reduce temperature overshoot during the heating phase for bare cladding. Although the maximum steamflow rate may not be as critical as the minimum steamflow rate, it should be limited to $\leq 30 \text{ mg}/(\text{cm}^2 \text{ s})$. The use of steamflow rates $> 30 \text{ mg}/(\text{cm}^2 \text{ s})$ should be justified.

7.3 Steam Pressure

Oxidation tests for preparation of PQD samples should be conducted at a steam pressure at or slightly above atmospheric pressure. This is consistent with steam pressures used in previous studies (e.g., EP-Refs. 1–3).

8. Procedure for Oxidation and Quench Tests

The specific details of the test procedure depend on the heating furnace used. Listed below are the steps used in EP-Ref. 1, along with some generalizations that would apply to other heating and cooling methods (e.g., those used in EP-Ref. 3).

8.1 *Test Train and Steam Chamber*

The test train or sample holder and the steam chamber form a unit that should be designed to contain the steamflow and to prevent impurities, especially nitrogen, from entering the chamber. By using steam that has a pressure slightly greater than the surrounding atmosphere, the test train/steam chamber does not have to be highly “leaktight” to provide a pathway for steamflow and protect the sample from gas-phase impurities.

In choosing the material for the test train or sample holder, it is desirable to have a nonoxidizing or limited-oxidizing material such as stainless steels or nickel (Ni) alloys (e.g., Inconel 600). Particular attention should be given to direct contact of the sample with materials such as iron (Fe) and Ni alloys, because of the low-temperature eutectics for Zr and these elements. Eutectic reactions between Zr-based alloys and test train materials must be prevented. Hofmann and Markiewicz (EP-Ref. 13) studied the reaction rates and eutectics of Zry-4 and Inconel-718. They also present binary phase diagrams for Zr-Fe and Zr-Ni, which have eutectic temperatures as low as ≈ 930 °C and 980 °C, respectively. In EP-Ref. 1, alumina inserts and zirconia washers were used between the Inconel holder and the sample to prevent such reactions from occurring. Testing laboratories may institute controls other than those used in EP-Ref. 1 to prevent eutectic reactions between Zr-based alloys and the test train materials.

8.2 *Purging Steam Chamber and Stabilizing Steamflow*

Before heating and steamflow initiation, the steam chamber is filled with gas representative of the environment of the test facility (usually air). The test chamber may be purged with a high-purity inert gas (e.g., argon) before the start of steamflow, or it may be purged with low-temperature steam before the temperature ramp. If steam is used to purge the steam chamber, then steamflow should be maintained for 500 seconds before the temperature ramp.

Steamflow should be initiated at a test chamber temperature of ≈ 30 °C. Following introduction of steam into the chamber, furnace heating should commence for a pretest hold temperature of 300 °C. Stabilization of steamflow and 300 °C sample temperature should occur within 500 seconds.

Deviations from this procedure may be pursued but should be justified. Deviations that may have a significant effect on test results include heating the sample to the target temperature in an inert gas before the introduction of steamflow. Impurities in the inert gas will result in an oxide or oxide-nitride film on the cladding that is not relevant to the LOCA. Also, the heat of oxidation would be very high for such a scenario, leading to significant temperature overshoot.

8.3 *Ramping Temperature and Holding Temperature at Target Value*

The target test temperature is predetermined. It should be based on the average sample temperature. Depending on the heating method used, axial and circumferential variations could be significant. For a single sample, the axial temperature variation should be ≤ 10 °C, and the circumferential temperature variation should be ≤ 20 °C.

For resistance furnaces, the sample heating rate is controlled by the rate of movement of the sample into the furnace heating zone. For radiant-heating furnaces, the heating rate is controlled through feedback from a TC welded onto the holder to the furnace power. For the radiant heating used in EP-Ref. 1, the temperature ramp rate for as-fabricated cladding materials was programmed to be very fast (> 50 °C/s) from 300 °C to within 50–100 °C of the target temperature and slow (2 to 3 °C/s) from that temperature to the target temperature. This programmed ramp was designed to eliminate temperature

overshoot. In later studies with prehydrided cladding and high-burnup cladding, the 1,200 °C tests were conducted with rapid heating to 1,000 °C followed by slower heating (2 to 3 °C/s) to 1,200 °C.

8.4 *End of Heating Phase and Cooldown*

After the target test time has been reached, furnace power should be turned off or decreased in a controlled manner while steamflow is maintained. The rate of temperature decrease will depend on the heating method used and the method of removing the sample from the furnace. For in situ cooling, the steamflow should be maintained until the sample temperature reaches 800 °C. For the EP-Ref. 1 work, this corresponded to a holder temperature of 700–720 °C. Following this step, there was ample moisture in the steam chamber during the very brief period between steamflow and quench-water flow.

8.5 *Determination of Equivalent Cladding Reacted*

The CP-ECR is calculated to determine test time. It should be calculated by integration of the CP weight-gain rate correlation with respect to test time. Equations 5 and 6 from EP-Ref. 1 are repeated below for conversion of CP weight gain (W_g in grams (g)/cm²) to oxidation level (ECR in percent):

$$\text{One-sided oxidation} \quad \text{ECR} = 43.9 [(W_g/h)/(1 - h/D_o)], \quad (1)$$

$$\text{Two-sided oxidation} \quad \text{ECR} = 87.8 W_g/h, \quad (2)$$

where h is cladding thickness in cm, and D_o is the cladding outer diameter in cm.

9. **Post-Oxidation-Quench Measurements and Characterization**

9.1 *Sample Drying Time*

To determine an accurate posttest sample weight, it is important that the sample be free of moisture. For drying in stagnant air, the drying time should be 2 hours or more. This time can be reduced significantly by the use of forced-air drying. The sample weight will continue to decrease during the drying process until it reaches a minimum and holds at that minimum. Whatever drying method is used, the drying time should be verified by weight measurements.

9.2 *Weight Measurement and Use of Weight Gain To Verify Oxidation Temperature*

The posttest sample weight should be measured to the nearest 0.1 mg as specified in 7.1.3 of EP-Ref. 7. The weight gain (in mg) is determined by subtracting the pretest weight from the posttest weight and normalizing this value to the steam-exposed surface area of the sample. Although this normalized weight gain is not used to determine the oxidation level, it is used to validate temperature control and monitoring, as well as adequacy of steamflow and test procedures throughout the data-generating phase of testing.

9.3 *Hydrogen Content Measurement*

If it has been demonstrated and documented that prehydrided samples have very little axial variation in hydrogen content, then posttest hydrogen analysis would not be needed. Significant axial variation is defined as >30 wppm along the test sample length. For such samples, posttest hydrogen analyses could be performed using rings 2–3 mm in length, sectioned from both sides of the 8-mm-long ring-compression sample. Alternatively, posttest hydrogen analysis could be performed using the

8-mm-long rings after RCT. In either case, posttest hydrogen values should be corrected for weight gain so that the reference weight for hydrogen content is the pretest weight. Hydrogen pickup during the oxidation-quench phase is expected to be small (<20 wppm), based on the results presented in EP-Ref. 1, as long as breakaway oxidation does not occur.

10. Matrix for Oxidation and Quench Tests

10.1 *As-Fabricated Cladding*

Based on the results presented in EP-Ref. 1, embrittlement of as-fabricated cladding with very low hydrogen content (e.g., 5–15 wppm) is not expected to occur at oxidation temperatures of 1,100 °C and 1,000 °C for oxidation levels up to 20% CP-ECR. The reason for this is the relatively low oxygen solubility limit in Zr-based cladding alloys at these temperatures. Even after the beta layer is saturated with oxygen, it remains ductile. Further oxidation simply increases the oxide and oxygen-stabilized alpha layer thickness values and reduces the beta layer thickness. Strength (i.e., maximum load at failure) continues to decrease, but ductility remains essentially constant until significant beta-layer thinning occurs at >20% CP-ECR.

At an oxidation temperature of 1,200 °C, the oxygen solubility limit (e.g., 0.6 wt. % for Zry-4) in Zr-based cladding alloys is close to the embrittlement limit at a ring-compression test temperature of 135 °C. Cladding materials experience a significant decrease in ductility (from >40% to <10%) in the oxidation range of 10% to 17% CP-ECR, following oxidation at 1,200 °C. Thus, it is recommended that scoping tests be performed at oxidation levels of 10%, 13%, 17%, and 20% CP-ECR. For each oxidation sample ≥ 30 mm long, at least three ring-compression samples can be sectioned. Based on these results, additional tests can be performed in a narrow CP-ECR range. If the cladding is ductile at 17% and brittle at 20%, then multiple tests should be performed at 18% and 19% CP-ECR to determine the ductile-to-brittle transition CP-ECR. Three oxidation-quench tests are recommended at each intermediate CP-ECR values to give nine PQD data points at each oxidation level. This would be sufficient to determine the ductile-to-brittle transition to the nearest percent CP-ECR.

10.2 *Prehydrided Cladding*

For tests with prehydrided cladding, the hydrogen contents selected should be in a range relevant to the cladding material. It has been a common practice to rely on data concerning the thickness of the corrosion layer, for which there is much data as a function of axial position and burnup, and a hydrogen pickup fraction to determine hydrogen content in the cladding. However, this approach is not reliable because cladding hydrogen absorption and distribution vary with alloy composition, cladding heat treatment, cladding temperature distribution, proximity of cladding to dissimilar metal (shadow corrosion under non-Zr grid cage components), corrosion layer thickness, axial location, burnup, and plant chemistry. Also, the hydrogen measured in hot cells for defueled cladding samples includes the hydrogen in the corrosion layer and the hydrogen in the cladding metal. In expressing it in units of wppm, the total weight of the sample (corrosion layer, metal, fuel-cladding bond, and both fission products and actinides within and adherent to the bond) is used. This practice may be relatively accurate for low-burnup cladding with thin corrosion layers and no fuel-cladding bond. However, the hydrogen in the cladding metal may be lower or higher than what is reported for intermediate- and high-burnup cladding. Only the hydrogen in the metal contributes to embrittlement. Hydrogen levels used in PQD testing with prehydrided cladding materials should cover the anticipated range of hydrogen in the metal of irradiated cladding.

For samples to be oxidized at $\leq 1,200$ °C (i.e., >2 °C/s heating rate from 1,000 °C to the 1,200 °C hold temperature), the ductile-to-brittle transition oxidation level is highly dependent on the hydrogen

content. For this oxidation temperature, the embrittlement threshold provided in DG-1263 (Ref. 6) as a function of hydrogen content may be used as a guide in selecting the range of oxidation levels to be included in the test matrix. Table 1 below provides the embrittlement threshold in DG-1263 in tabular form for clarity. For low hydrogen contents (<150 wppm) typical of those measured for high-burnup M5, the results presented in EP-Ref. 3 may be used as a guide. EP-Ref. 3 also presents PQD data for prehydrided M5 and Zry-4 oxidized at lower test temperatures. For a specific hydrogen content (e.g., 300 wppm), the first test should be conducted at the CP-ECR determined from EP-Ref. 1 embrittlement data (e.g., 9% CP-ECR for 300 wppm hydrogen). Depending on the results, the second test should be conducted at a CP-ECR 2% higher (if ductile at 9%) or lower (if brittle at 9%). Assuming that ductile and brittle oxidation levels have been found, then three tests should be conducted at the intermediate CP-ECR to confirm the embrittlement threshold.

Table 1. Embrittlement Threshold

Hydrogen Content (wppm)	Embrittlement ECR
10	18%
100	15%
200	12%
300	9%
400	6%
500	5%
600	4%

Unlike as-fabricated cladding, prehydrided cladding oxidized at 1,100 °C and 1,000 °C will embrittle at ECR values significantly below 17%. This is because of the hydrogen-induced increase in oxygen diffusion rate and in oxygen solubility in the beta phase, as well as some intrinsic hydrogen embrittlement. Testing prehydrided cladding at temperatures lower than 1,204 °C is important if an applicant can demonstrate that calculated LOCA temperatures are significantly lower than 1,204 °C.

11. Procedure for Conducting Ring-Compression Postquench Ductility Tests

11.1 Pretest Activities

The materials test system (MTS) used to conduct ring-compression tests should be subjected to an annual verification of calibration with regard to measurement of compressive loads by the load cell, the determination of crosshead displacement, and the determination of crosshead speed. The calibration should be performed to NIST-traceable standards. This service is offered by the vendor (e.g., Instron), who provides documentation of calibration verification.

The TC or TCs used to control furnace or oven power corresponding to a ring test temperature of 135 °C should be calibrated to an NIST-traceable standard. The TC vendor provides this service for a fee and supplies a certificate of calibration along with the TC. The calibration should be performed at 135 °C. A variety of TCs could be used at this low temperature. Type K (chromel-alumel) TCs are recommended. The standard deviation between the TC reading and the NIST-traceable standard is quite low (e.g., ±0.3 °C for room temperature (RT) to 200 °C).

In addition to the annual verification of calibration, it is recommended that six ring-compression tests be performed using as-fabricated cladding to determine the relationship between offset and permanent displacements: three tests at RT and three tests at 135 °C. Appendix A gives the results of six

tests conducted with as-fabricated ZIRLO™. This specific verification of calibration is also used to determine if the measured loads are reasonable.

Rings sectioned from LOCA oxidation-quench samples should be in the range of 7–10 mm long and should not include oxidized ends (two-sided samples) or weld-heat-affected zones (one-sided samples). The reference length for ANL tests was 8 mm. For two-sided oxidation samples, it is sufficient to cut off 1–2 mm from the ends of the oxidation samples. The ends of the sectioned rings should be deburred, and the samples should be cleaned in a chemical detergent or organic solvent following deburring.

Following sectioning, the length of the rings should be measured to one decimal place (e.g., 7.9 mm), and the minimum and maximum diameter of the oxidized rings should be measured to two decimal places (e.g., 9.51 mm). As the ring should be positioned such that the minimum diameter aligns with the loading direction, only the minimum diameter is used in the calculation of permanent displacement and strain. Micrometers used to measure length and diameter should be calibrated to an NIST-traceable standard.

11.2 Test Temperature and Crosshead Displacement Rate

It is recommended that an oven, rather than a furnace, be used to heat the test ring to 135 °C. For such uniform heating, it is sufficient to use a single TC in contact with the inner surface of the sample at the bottom support position. The spring-loading of the TC also serves to fix the location of the ring relative to the top loading rod. Tests in such a heating device should be conducted at a test temperature of 135 ±1 °C. The PQD test results in EP-Ref. 1 for as-fabricated and prehydrided LOCA samples used oven heating for the tabletop Instron Model 5566 MTS, along with a single TC strapped to the bottom inner surface of the ring.

It is more common that the MTS would be equipped with a clamshell radiant-heating furnace provided by the vendor. Such furnaces are known to result in circumferential temperature gradients for rings because of the relationship between the ring location and the focal point of the furnace. For such furnaces, the bottom TC, which is in intimate contact with the sample, should be used to control furnace power to achieve a steady temperature of 135 °C. Additional TCs at the 3 and 9 o'clock positions, which initially contact the sample through spring loading, should be used to determine the circumferential variation in temperature. These TCs, which contact the sample outer surface with mild spring loading, are less accurate than the bottom TC. Tests should be initiated when the average deviation of the side TC readings is ≤5 °C relative to the 135 °C control TC reading. The use of test temperatures higher than 135 °C requires justification, while test temperatures lower than 135 °C do not require justification.

This heating and temperature monitoring method, along with an Instron Model 8511 servohydraulic MTS, was used to generate the EP-Ref. 1 results for high-burnup cladding LOCA samples. The results presented in Appendix A were generated with the Instron 8511.

The crosshead displacement rate for ring-compression samples should be in the range of 0.083 to 0.033 mm/s (0.5 to 2 mm/minute). These rates are consistent with those used in past research (EP-Ref. 1, 3), and they are slow enough to allow test termination after the first significant load drop.

11.3 Test Conduct

The test should be conducted in the “displacement-controlled mode” rather than the “force-controlled mode.” Software inputs include the constant displacement rate and the maximum displacement. The maximum displacement (i.e., crosshead travel) is important to protect the control TC

and the MTS itself. Because of the “bow-tie” shape of a highly deformed ring, the maximum displacement should be less than the inner diameter of the cladding minus the TC diameter. For standard 17×17 cladding with an inner diameter of about 8.3 mm, the maximum displacement should be <6 mm.

Test conduct is standard with regard to setup and operation. EP-Ref. 14 gives details for ring-compression tests conducted with the screw-type Instron Model 5566 used to generate data reported in EP-Ref. 1 for as-fabricated and prehydrided cladding.

11.4 Test Termination

The preferred method for ending the test is to release the compressive load as soon as there is a sharp load drop >30%. This is achieved by simply pushing the reset button. Given the slow displacement rate, there is ample time to terminate the test very shortly after the load drop is observed. Based on the experience reported in EP-Ref. 1, load drops in the range of 30–50% indicate a single through-wall crack, which may be very tight or loose because of recoil following test termination. For tight cracks, an accurate posttest diameter can be measured in the loading direction. For a single loose crack, the posttest diameter reading is not very accurate. For load drops of about 70–80%, the sample should have two cracks. For load drops of 80–100%, it is likely that the sample cracked into three or four pieces.

The more common method used in RCT (e.g., EP-Ref. 3) is to run the test for a fixed displacement. As multiple cracks are likely to occur, no useful posttest diameter can be measured. Although this method is acceptable, it is not recommended, as the only data that can be obtained are the offset displacement and strain.

11.5 Posttest Measurements

After removing the compressed ring from the oven or furnace, cooling to RT occurs rather quickly. The sample should be examined visually to determine if cracking has occurred, the number of cracks, and the location of the cracks. For samples that are likely to have a single tight crack, the visual examination should include one at about 4X magnification to verify that the crack is through-wall (from examination of ring ends) and extends along the whole length of the sample (from examination of outer and inner surfaces).

If the test was terminated following a steep 30–40% load drop and visual examination indicates a single tight crack, then the outer diameter in the loading direction should be measured.

The offset displacement should be determined from the load-displacement curve using methods illustrated in Appendices B and C. In general, this means mathematically unloading the sample at the load just before the steep load drop. The linearized slope (i.e., ring stiffness in kilo Newton/mm) of the initial loading curve is used to do the mathematical unloading. For ductile rings that exhibit a gradual load drop with increasing displacement, the offset strain determination is dependent on the visual examination of the posttest ring. If the posttest sample has a through-wall crack, then the offset strain should be determined based on the location on the curve where the load has decreased by 50%. For samples that have no posttest cracks, the full load-displacement curve may be used to determine the offset displacement. These cases are not important in the determination of the ductile-to-brittle transition oxidation level, as they represent samples with very high ductility.

To convert offset and permanent displacement to strain, it is recommended that the outer diameter of the as-fabricated cladding be used to normalize these displacements. Prehydriding samples will result in a small increase in the outer diameter and the wall thickness. Oxidation will result in additional increases in diameter and wall thickness. However, these increases have only a small effect on the

calculated normalized displacements. It is recommended that strain be reported in percent as displacement divided by the diameter of the as-fabricated cladding used for oxidation or for prehydrogenating and oxidation. Based on measurement error and data scatter, these strains should be reported to one significant decimal place. If the postoxidation diameter in the loading direction is used to calculate permanent strain, it should be reported along with the displacements and the converted strains.

After determination of the offset and permanent strains, the compressed ring should be used to measure the postoxidation hydrogen content in the ring. This hydrogen content should be corrected for weight gain. The measurement should be performed if oxidation samples are expected to have >10% axial and circumferential variation in hydrogen content relative to the average hydrogen content.

12. Data Reporting and Assessment

12.1 Hydrogen Level, Test Temperature, Test Time, CP-ECR, Offset Strain, and Permanent Strain

Tabular results should include hydrogen level, test temperature, test time (from 300 °C to the quench time), CP-ECR, offset strain, and permanent strain. A footnote should clarify which diameter was used to determine strain from displacement.

Graphical results should include the load-displacement curves (including determination of offset strain) and summary graphs of offset strain versus CP-ECR and permanent strain versus CP-ECR.

12.2 Determination of Ductile-to-Brittle Transition CP-ECR

Rings that exhibit $\geq 1.0\%$ permanent strain are classified as ductile. The 1.0% is based on uncertainties in diameter readings, in recoil (or spring-back) of cracked rings versus intact rings, and in diameter reduction due to flaking off of oxide. It is also based on trend curves of permanent strain versus CP-ECR. For samples that are clearly brittle, measured permanent strains are generally in the range of 0.2–0.8%, which for cladding with an outer diameter of 9.50 mm corresponds to permanent displacement of 0.2–0.8 mm. These displacements and strains are considered to be in the “noise” of uncertainty. The ductile-to-brittle transition CP-ECR is defined as the CP-ECR corresponding to 1.0% permanent strain (i.e., the maximum CP-ECR for which ductility is retained). For multiple data points at the same sample and test conditions, the average permanent strain should be calculated. The ductile-to-brittle CP-ECR should be based on average permanent strain $\geq 1.0\%$. As it is unlikely to measure exactly 1.0% permanent strain, the CP-ECR may be determined from interpolation between an oxidation level for which the permanent strain is $>1.0\%$ (ductile) and an oxidation level for which the permanent strain is $<1.0\%$. These CP-ECR values should differ by no more than 2%. In this case, the transition should be identified to occur at the highest CP-ECR at which the permanent strain is $\geq 1.0\%$. The ductile-to-brittle transition oxidation level should be reported to the nearest percent. For example, if the sample is ductile at 8% CP-ECR and brittle at 10% CP-ECR and no further testing is conducted, the transition CP-ECR would be reported as 8%. However, it is recommended that three confirmation tests be conducted at 9% CP-ECR. Figure 2 shows an example from the work reported in EP-Ref. 1 for as-fabricated HBR-type 15×15 Zry-4. Based on multiple oxidation tests in a narrow range and multiple ring-compression samples, the permanent strains were $1.5 \pm 0.4\%$ at 15.2% CP-ECR and $1.1 \pm 0.3\%$ at 16% CP-ECR, where the \pm values represent one standard deviation caused by data scatter from repeat tests. Based on linear extrapolation, the transition CP-ECR is calculated to be 16%.

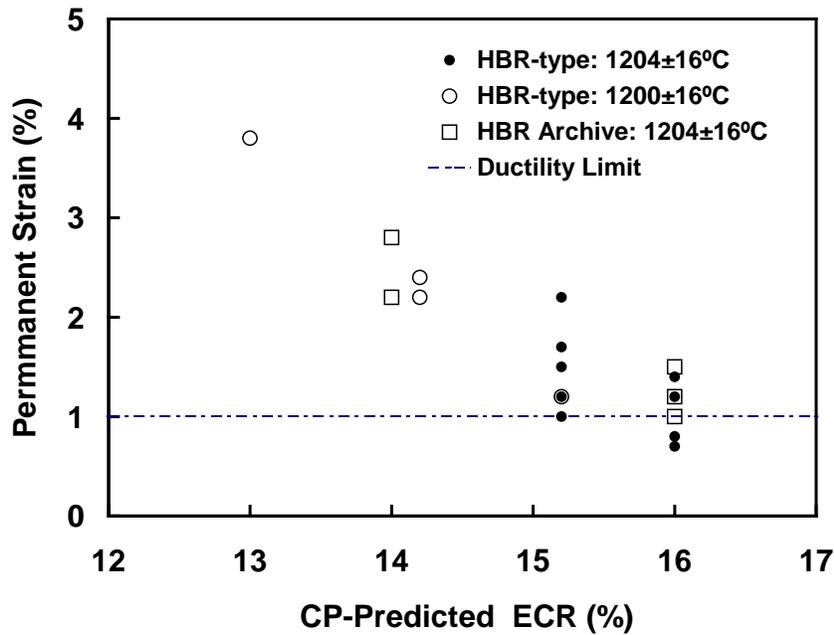


Figure 2. Determination of ductile-to-brittle transition CP-ECR based on the permanent strain criterion ($\geq 1.0\%$ implies ductility) for as-fabricated HBR-type 15×15 Zry-4 oxidized at $\approx 1,200$ °C and quenched at 800 °C. Ring-compression tests were conducted at 2 mm/minute displacement rate and 135 °C ring temperature. The ductile-to-brittle transition oxidation level is 16% CP-ECR based on average permanent strain $\geq 1.0\%$.

If ring-compression tests are not interrupted at the first significant load drop, then the ring will crack into pieces, which renders measurement of posttest diameter impractical and unreliable. One must rely on offset displacement and strain to assess whether a ring is ductile or brittle. The method for determining the offset displacement has an inherent error because the unknown unloading slope will always be less than the loading slope. Appendix C summarizes the data reported in EP-Refs. 1 and 15, along with the HBR data presented in Figure 2, for rings sectioned from cladding alloys oxidized at 1,200 °C. The trend curve shown in Figure C1 indicates that the error associated with offset strain displacement increases with calculated oxidation level (CP-ECR). This leads to the following ductility criterion based on offset strain:

$$\text{Average Measured Offset Strain} \geq 1.41 + 0.1082 \text{ CP-ECR} \quad (3)$$

Equation 3 gives $\geq 2.0\%$ at 5% CP-ECR and $\geq 3.6\%$ at 20% CP-ECR. However, because of the large data scatter in Figure C1, the offset strain criterion given on the right side of Equation 3 represents the one-sigma upper bound of the data. This method is illustrated in the following example.

The offset strains corresponding to the permanent strain data shown in Figure 2 are plotted in Figure 3.

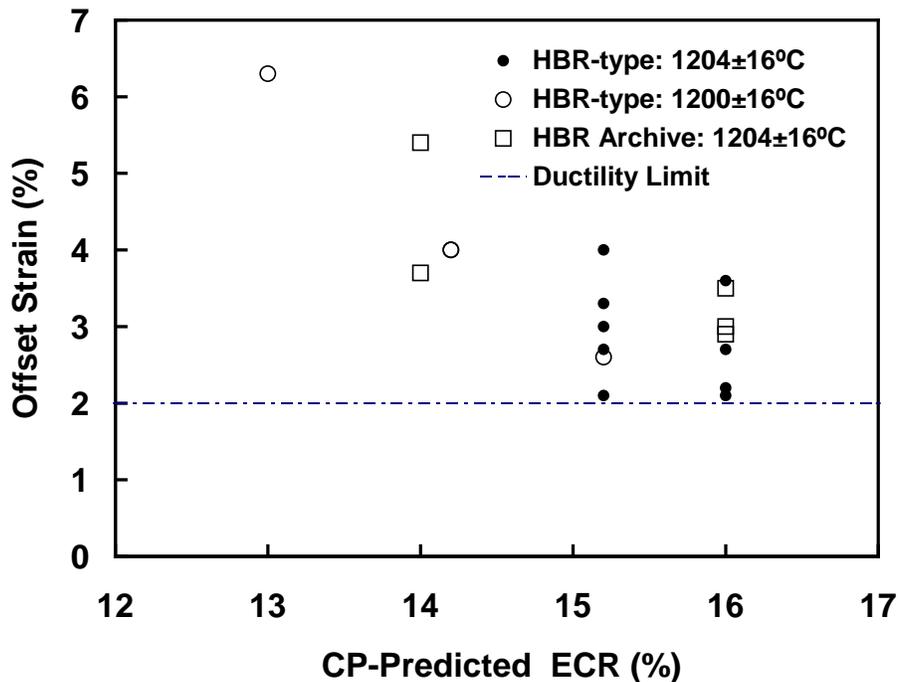


Figure 3. Offset strains determined for as-fabricated HBR-type 15×15 Zry-4 oxidized at ≈1,200 °C and quenched at 800 °C (see Figure 2 for corresponding permanent strains).

Unlike permanent strains, offset strains level off to about 3% at 15.2 and 16.0 CP-ECR ($3.0 \pm 0.7\%$ at 15.2% CP-ECR and $2.9 \pm 0.5\%$ at 16.0% CP-ECR). Based on Equation 3, offset strains $\geq 3.1\%$ imply ductility at 15–16% CP-ECR. The average measured offset strains (3.0%) at 15.2% and 16% CP-ECR are slightly less than the ductility limit (3.1%). By interpolation between the data at 14.2% and 15.2% CP-ECR, the ductile-brittle-transition CP-ECR would be 15%. Thus, there is a penalty of 1% CP-ECR in using the less precise offset strain criterion as compared to the permanent strain criteria.

13. References for the Experimental Procedures

- EP-1. M. Billone, Y. Yan, T. Burtseva, and R. Daum, “Cladding Embrittlement during Postulated Loss-of-Coolant Accidents,” NUREG/CR-6967, July 2008 (ADAMS Accession No. ML082130389).
- EP-2. J. Cathcart, R. Pawel, R. McKee, R. Druschel, G. Yurek, J. Campbell, and S. Jury, “Zirconium Metal-Water Oxidation Kinetics IV. Reaction Rate Studies,” ORNL/NUREG-17, August 1977.
- EP-3. J. Mardon, J. Brachet, L. Portier, V. Maillot, T. Forgeron, A. Lesbros, and N. Waeckel, “Influence of Hydrogen Simulating Burn-Up Effects on the Metallurgical and Thermal-Mechanical Behavior of M5™ and Zircaloy-4 Alloys under LOCA Conditions,” *13th International Conference on Nuclear Engineering*, ICONE13-50457, pp. 1–9, Beijing, China, May 16–20, 2005.
- EP-4. F. Nagase and H. Uetsuka, “Hydrogen Morphology and Hydrogen Embrittlement of Zircaloy Fuel Cladding used in NSRR/HBO Experiment,” *Proceedings of the International Topical Meeting on Light Water Reactor Fuel Performance*, pp. 677–684, Portland, OR,

March 2–6, 1997, American Nuclear Society, La Grange Park, IL, 1997.

- EP-5. American Society for Testing and Materials, ASTM E1447-05, “Standard Test Method for Determination of Hydrogen in Titanium and Titanium Alloys by the Inert Gas Thermal Conductivity Method,” Book of Standards, Vol. 03.05, ASTM International, West Conshohocken, PA, 2005; also available online at <http://www.astm.org/standards/E1447.html>.
- EP-6. T. Burtseva, “Procedure for Hydrogen Analysis of Refractory Metals,” ANL Intra-Laboratory Memo, IPS-467-00-00, Argonne National Laboratory, Argonne, IL, November 25, 2005.
- EP-7. American Society for Testing and Materials, Designation G2/G2M-06, “Standard Test Method for Corrosion Testing of Products of Zirconium, Hafnium, and Their Alloys in Water at 680°F [360°C] or in Steam at 750°F [400°C],” pp. 1186–1193, ASTM International, West Conshohocken, PA, 2006.
- EP-8. Claude Grandjean and Georges Hache, “A State of the Art Review of Past Programmes Devoted to Fuel Behaviour under Loss-of-Coolant Conditions. Part 3. Cladding Oxidation. Resistance to Quench and Post-Quench Loads,” Institut de Radioprotection et de Sécurité (IRSN) Technical Report DPAM/SEMCA 2008-093, Saint Paul-lez-Durance Cedex, France, 2008.
- EP-9. S. Leistikow and G. Schanz, “Oxidation Kinetics and Related Phenomena of Zircaloy-4 Fuel Cladding Exposed to High Temperature Steam and Hydrogen-Steam Mixtures under PWR Accident Conditions,” *Nuclear Engineering and Design* 103, pp. 65–84, 1987.
- EP-10. H. Uetsuka, “Oxidation of Zircaloy-4 under Limited Steam Supply at 1000 and 1300°C,” Kernforschungszentrum Karlsruhe (KfK) 3848, Kernforschungszentrum Karlsruhe GmbH, Postfach 360, 76021 Karlsruhe, 1984.
- EP-11. M. Aomi, et al., “Behavior of BWR Fuel Cladding Tubes under Simulated LOCA Conditions,” *7th International Conference on Nuclear Engineering*, ICONE-7435, 1999.
- EP-12. S. Kawasaki, T. Furuta, and M. Suzuki, “Oxidation of Zircaloy-4 under High Temperature Steam Atmosphere and Its Effect on Ductility of Cladding,” *Journal of Nuclear Science and Technology*, Vol. 15, No. 8, pp. 589–596, 1978.
- EP-13. P. Hofmann and M. Markiewicz, “Chemical Interaction between As-Received and Pre-Oxidized Zircaloy-4 and Inconel-718 at High Temperatures,” Kernforschungszentrum Karlsruhe (KfK) 4729, Kernforschungszentrum Karlsruhe GmbH, Postfach 360, 76021 Karlsruhe, June 1994.
- EP-14. T.A. Burtseva, “Procedure for Conducting Ring-Compression Tests in Laboratory DL-102A,” ANL-IPS Memo, IPS-495-00-00, November 26, 2007.
- EP-15. Y. Yan, T.A. Burtseva, and M.C. Billone, “Post-quench Ductility Results for North Anna High-burnup 17×17 ZIRLO Cladding with Intermediate Hydrogen Content,” ANL letter report to NRC, April 17, 2009 (ADAMS Accession No. ML091200702).

D. IMPLEMENTATION

The purpose of this section is to provide information to applicants and licensees regarding the NRC's plans for using this regulatory guide.

This regulatory guide provides the NRC's first guidance on a new rule. When there is an issuance of a new rule, the agency backfitting considerations have been taken into account in the related rulemaking. The position of this guide is one methodology to meet the requirements of the rule. While an applicant or licensee is not required to use the methodology set forth in this guidance, they are required to comply with the rule. Should the applicant or licensee elect to use a different methodology, the NRC staff may require a demonstration of how the proposed methodology complies with rule. This regulatory guidance complies with backfit requirements set forth in 10 CFR 50.109.

GLOSSARY

alpha layer—For the purposes of this regulatory guide, refers to the zirconium phase which is characterized by a hexagonally close-packed crystal structure and is stable at room temperature. At high temperatures, the beta phase is stable; however, dissolved oxygen can stabilize the alpha phase at high temperature.

beta layer—For the purposes of this regulatory guide, refers to the zirconium phase which is characterized by a cubic crystal structure and is stable at elevated temperatures of $\approx 1,000$ °C.

breakaway oxidation—For the purposes of this regulatory guide, the fuel-cladding oxidation phenomenon in which weight-gain rate deviates from normal kinetics. This change occurs with a rapid increase of hydrogen pickup during prolonged exposure to a high-temperature steam environment, which promotes loss of cladding ductility

corrosion—For the purposes of this regulatory guide, the formation of a zirconium oxide layer resulting from the reaction of zirconium with coolant water during normal operation.

loss-of-coolant accident (LOCA)—A hypothetical accident that would result from the loss of reactor coolant, at a rate in excess of the capability of the reactor coolant makeup system, from breaks in pipes in the reactor coolant pressure boundary up to and including a break equivalent in size to the double-ended rupture of the largest pipe in the reactor coolant system.

offset strain—For the purposes of this regulatory guide, the value determined from a load-displacement curve by the following procedure: (1) linearize the initial loading curve, (2) use the slope of the initial loading curve to mathematically unload the sample at the peak load before a significant load drop (≈ 30 to 50%) indicating a through-wall crack along the length of the sample, and (3) determine the offset displacement (distance along the displacement axis between loading and unloading lines). This offset displacement is normalized to the outer diameter of the preoxidized cladding to determine a relative plastic strain.

oxidation—For the purposes of this regulatory guide, the formation of a zirconium oxide layer resulting from the reaction of zirconium with high-temperature steam during LOCA conditions.

permanent strain—For the purposes of this regulatory guide, the difference between the posttest outer diameter (after the sample is unloaded) and the pretest outer diameter of a cladding ring, normalized to the initial diameter of the cladding ring.

monoclinic oxide—For the purposes of this regulatory guide, the oxide phase that develops during normal operation and is neither fully dense nor protective. Although the oxide phase that typically develops under LOCA conditions is the tetragonal oxide phase, there are conditions that might occur during a small-break LOCA (such as extended time-at-temperature around 1,000 °C) which promote a transformation to the monoclinic phase.

tetragonal oxide—For the purposes of this regulatory guide, the oxide phase that develops under LOCA conditions which is dense, adherent, and observed to be protective with respect to hydrogen pickup.

REFERENCES⁵

1. 7X FR XXXXX, "Proposed Rule FRN," *Federal Register*, Volume 7X, Number XXX, p. XXXX, Washington, DC, June 31, 2011. (*insert FRN of proposed rule reference when available*)
2. NUREG/IA-0211, "Experimental Study of Embrittlement of Zr-1%Nb VVER Cladding under LOCA-Relevant Conditions," L. Yegorova, et al., March 2005 (ADAMS Accession No. ML051100343).
3. IFE/KR/E-2008/004, "LOCA Testing of High Burnup PWR Fuel in the HBWR. Additional PIE [Post Irradiation Examination] on the Cladding of the Segment 650-5," B.C. Oberlander, M. Espeland, H.K. Jenssen, April 11, 2008 (ADAMS Accession No. ML081750715).
4. NRC Research Information Letter 0801, "Technical Basis for Revision of Embrittlement Criteria in 10 CFR 50.46," May 30, 2008 (ADAMS Accession No. ML081350225).
5. NUREG/CR-6967, "Cladding Embrittlement during Postulated Loss-of-Coolant Accidents," M. Billone, et al., July 2008 (ADAMS Accession No. ML082130389).
6. Draft Regulatory Guide 1263, "Regulatory Guidance on Establishing Analytical Limits for Zirconium-Based Alloy Cladding," U.S. Nuclear Regulatory Commission, Washington, DC.

⁵ Publicly available NRC published documents are available electronically through the Electronic Reading Room on the NRC's public Web site at: <http://www.nrc.gov/reading-rm/doc-collections/>. The documents can also be viewed on-line or printed for a fee in the NRC's Public Document Room (PDR) at 11555 Rockville Pike, Rockville, MD; the mailing address is USNRC PDR, Washington, DC 20555; telephone (301) 415-4737 or (800) 397-4209; fax (301) 415-3548; and e-mail pdr.resource@nrc.gov.

APPENDIX A

RING-COMPRESSION RESULTS FOR ROOM TEMPERATURE AND 135 °C TESTS WITH AS-FABRICATED CLADDING SAMPLES

Document IPS-495-00-00 (Ref. 1) describes the procedure for verification of calibration, for test conduct, and for data interpretation for ring-compression tests (RCTs) conducted with the Instron Model 5566 Material Test System (MTS) used by Argonne National Laboratory to conduct RCTs with as-fabricated and prehydrided oxidized cladding samples. That document describes Phase 3 pre-data-generation tests to ensure that the Instron, as well as associated control and data acquisition systems, is performing within the expected range. It is recommended that these tests be conducted with any MTS before the generation of postquench ductility (PQD) data, particularly if the MTS has been used to conduct other tests (e.g., axial tensile tests) requiring modification to the load train, if the machine has been idle for more than a couple of months, or if testing is conducted beyond the due date for calibration verification. Three tests at room temperature (RT) and three tests at 135 degrees Celsius (°C) are to be conducted with as-fabricated cladding rings at 2 millimeters (mm)/minute (0.033 mm/second) to a maximum crosshead displacement of 2 mm. The data output (load displacement curves) is to be analyzed in terms of the measured loading stiffness K_m (linearized slope of the load versus displacement curve in kilo Newton/mm) and the measured offset displacement (δ_o , in mm). The measured loading stiffness K_m is compared to the calculated ring stiffness K_c according to the textbook formula:

$$K_c = (1/1.8) E L (h/R)^3, \quad (A1)$$

where E is Young's modulus in kN/mm², L is the actual length of the ring in mm, h is the wall thickness in mm, and R is the ring midwall radius in mm. Eq. A1 is applicable to the elastic behavior of a thin-wall ring of uniform length, outer diameter, and wall thickness.

The reference length for the test rings is 8 mm. However, as offset displacement should be independent of ring length and stiffness varies linearly with ring length, actual values of sectioned rings may be within the range 8.0±1.0 mm. The wall thickness (h) and the outer diameter (D_o) will vary somewhat along the length of cladding tubes. The pretest wall thickness for each sample should be measured at four circumferential orientations (0°, 90°, 180°, and 270°). The value of h used in Equation B1 is the average of the four readings. The pretest minimum [$(D_{oi})_{min}$] and maximum [$(D_{oi})_{max}$] outer diameters should be determined for each sample and averaged to give D_{oi} , where the "i" refers to initial or pretest value. The value of R used in Equation A1 is calculated from the relationship $R = (D_{oi} - h)/2$. Young's modulus, E, for cladding alloys is assumed to be the same as the isotropic modulus reported for Zircaloy (Zry)-4: $E = 92.4 \text{ kN/mm}^2$ (92,400 megapascals (MPa)) at RT, and $E = 86.5 \text{ kN/mm}^2$ (86,500 MPa) at 135 °C. For rings of uniform length, thickness, and outer diameter, the measured stiffness should be within about 10% of the calculated stiffness for machines with relatively high load-train stiffness. Because machine compliance tends to reduce the measured stiffness, the expectation is that the measured stiffness will be less than or equal to the calculated stiffness. Measured stiffness values ≥10% higher than the values predicted by Equation A1 indicate that the load cell and/or crosshead displacement indicator may be out of calibration.

The offset displacement (δ_o) is to be compared to the permanent displacement (d_p), which is determined from the difference in the pretest and posttest diameters in the loading direction. The ring is to be positioned in the Instron such that the loading direction is along the minimum pretest diameter. Based on the error introduced by assuming that the unloading stiffness is equal to the loading stiffness, the expectation is that $\delta_o < d_p$ and that the difference is $\delta_o - d_p \leq 0.2 \text{ mm}$, which is based on an extensive dataset for as-fabricated cladding displaced to 1.5–2.0 mm at RT and 2 mm/minute in the Instron 5566.

Two assessments are made using the measured stiffness and offset displacement values: one is precision (repeatability), and the other is adequacy of load and displacement measurements. The most important determination of the adequacy of the Instron MTS is the repeatability of offset and permanent displacements, as well as the difference of these two numbers. In making this assessment, the measured stiffness should be normalized to 8 mm by multiplying the measured stiffness by (8 mm/L): $K_{mn} = (8 \text{ mm/L}) K_m$. The calculated stiffness should also be normalized to 8 mm to give K_{cn} . Also, as the stiffness is highly dependent on the wall thickness, this factor should be considered in the data assessment.

The procedure described in IPS-495-00-00 Phase 3 should be used for any MTS, including the Argonne National Laboratory Instron 8511, which was used to perform RCTs with oxidized high-burnup cladding samples. This appendix presents the ring-compression verification test results for the Instron 8511 as an example of the procedure to follow and the methodology for interpreting the results.

The RT tests check the physical components, the data control software, and the data acquisition software. The elevated temperature tests check the physical and software components of the furnace system, as well as the performance of the Instron at 135 °C. Before conducting the elevated temperature tests with control and monitoring thermocouples, it should be demonstrated that the thermocouples have been calibrated to a National Institute of Standards and Technology (NIST)-traceable standard. The option is available to have the vendor do this calibration and supply a certificate for each thermocouple in a batch of thermocouples or one thermocouple in the batch. If only one thermocouple in a batch has a calibration certificate, then the thermocouples to be used to control and monitor ring temperature should be calibrated by comparison to the certified thermocouple. Generally, Type K thermocouples are used to monitor low temperatures such as 135 °C. The expected error for this type of thermocouple is ± 0.3 °C relative to an NIST-traceable standard.

As the Instron 8511 is a servo-hydraulic machine, some checks were made to ensure that all moving parts, all auxiliary equipment, and all data recorders functioned properly. Three RCTs were then conducted at RT. Based on the RT results (see Table A-1 and Figures A-1 through A-3), the average difference between the offset and permanent displacement was 0.19 mm, which is consistent with previous experience. Therefore, the Instron 8511 crosshead displacement indicator was determined to be accurate enough for ring-compression testing. The measured loading stiffness values were about 15% lower than the predicted values. The loading stiffness is expected to be less than or equal to the calculated stiffness because of the influence of machine compliance. Based on experience with the Instron Model 5566, the measured stiffness has been within 10% of the calculated stiffness. The Instron Model 8511 has a much longer load train, higher machine compliance, and lower machine stiffness. This may account for the difference between measured and calculated stiffness values. Although load is not an important parameter in ring-compression ductility tests, the stiffness results indicate that the load-cell output values are adequate for RCTs.

The results at 135 °C (see Table A-1 and Figures A-4 through A-6) proved to be more consistent than the RT results. For ductility determination, the most important parameter is the difference between offset displacement and permanent displacement, which was 0.20 mm on average. The measured stiffness values were about 8% lower than the calculated values, which suggests adequate load-cell performance at 135 °C.

The results of the six tests support the use of the Instron Model 8511 for performing RCT ductility tests using oxidized high-burnup cladding samples.

Table A-1. Results of Instron 8511 Checkout Tests to Verify Calibration for Conducting Ring- Compression Tests at a Displacement Rate of 0.0333 mm/s

K_c is calculated ring stiffness (i.e., spring constant), K_m is stiffness determined from linearized slope of load displacement curve, subscript “n” refers to stiffness normalized to 8 mm, δ_p is the offset displacement determined from the load-displacement curve, and d_p is the permanent displacement in the loading direction determined from pretest diameter minus posttest diameter.

Sample ID	Test T, °C	D_{oi} , mm	L, mm	h, mm	K_{cn} , kN/mm	K_m , kN/mm	K_{mn} , kN/mm	δ_p , mm	d_p , mm	$\delta_p - d_p$, mm
109B1	RT	9.49	7.67±0.06	0.587±0.003	0.94	0.77	0.80	1.24	1.07	0.17
109B2	RT	9.49±0.01	7.75±0.06	0.589±0.003	0.95	0.77	0.79	1.18	1.00	0.18
109B3	RT	9.49±0.01	8.03±0.02	0.589±0.003	0.95	0.85	0.85	1.31	1.08	0.23
RT Summary	RT	9.49	7.82	0.59	0.95		0.81	1.24	1.05	0.19
109B4	132±5	9.495±0.005	7.81±0.02	0.589±0.003	0.89	0.81	0.83	1.40	1.21	0.19
109B5	135±5	9.495±0.005	8.01±0.07	0.590±0.003	0.89	0.83	0.83	1.40	1.21	0.19
109B9	135±5	9.475±0.005	8.21±0.06	0.588±0.003	0.91	0.85	0.83	1.40	1.17	0.23
135 °C Summary		9.49	8.00	0.59	0.90		0.83	1.40	1.20	0.20

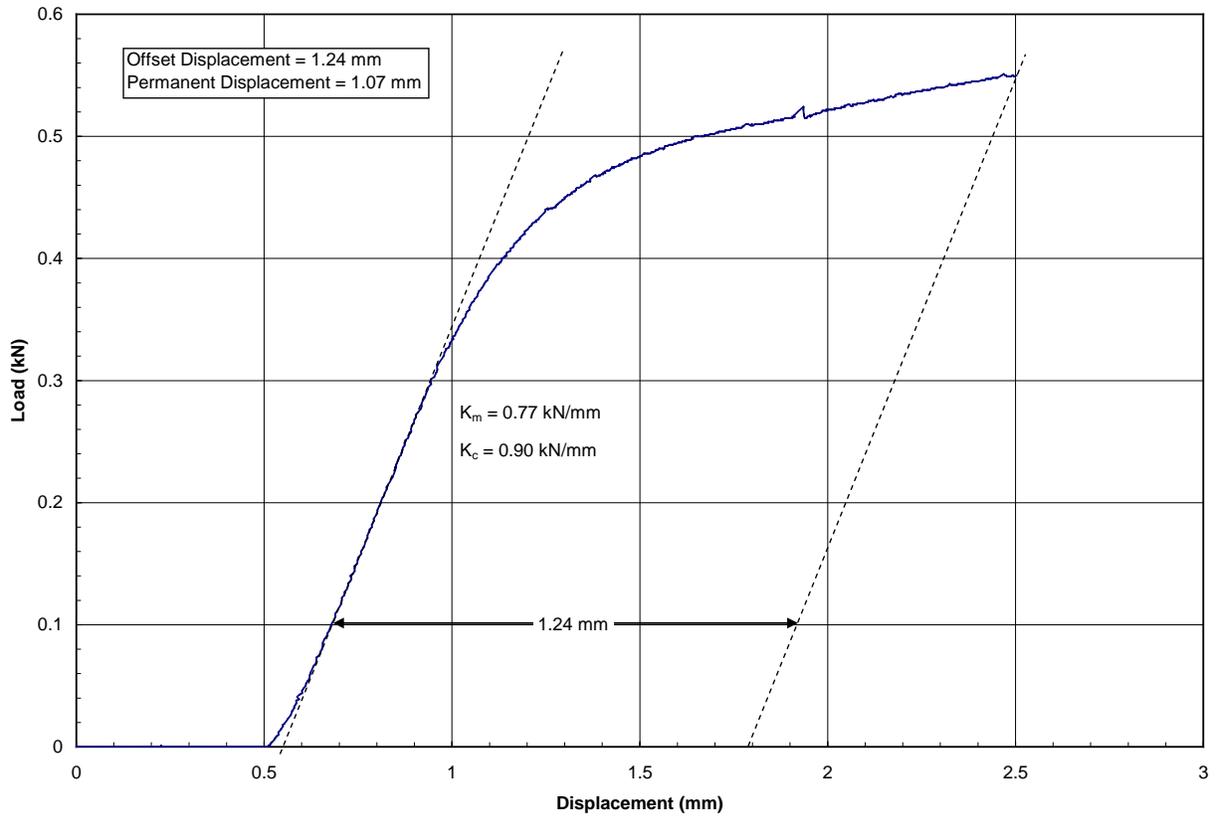


Figure A-1. Load-displacement curve for ZIRLO™ sample 109B1 compressed at RT and 2 mm/minute to 2-mm total displacement.

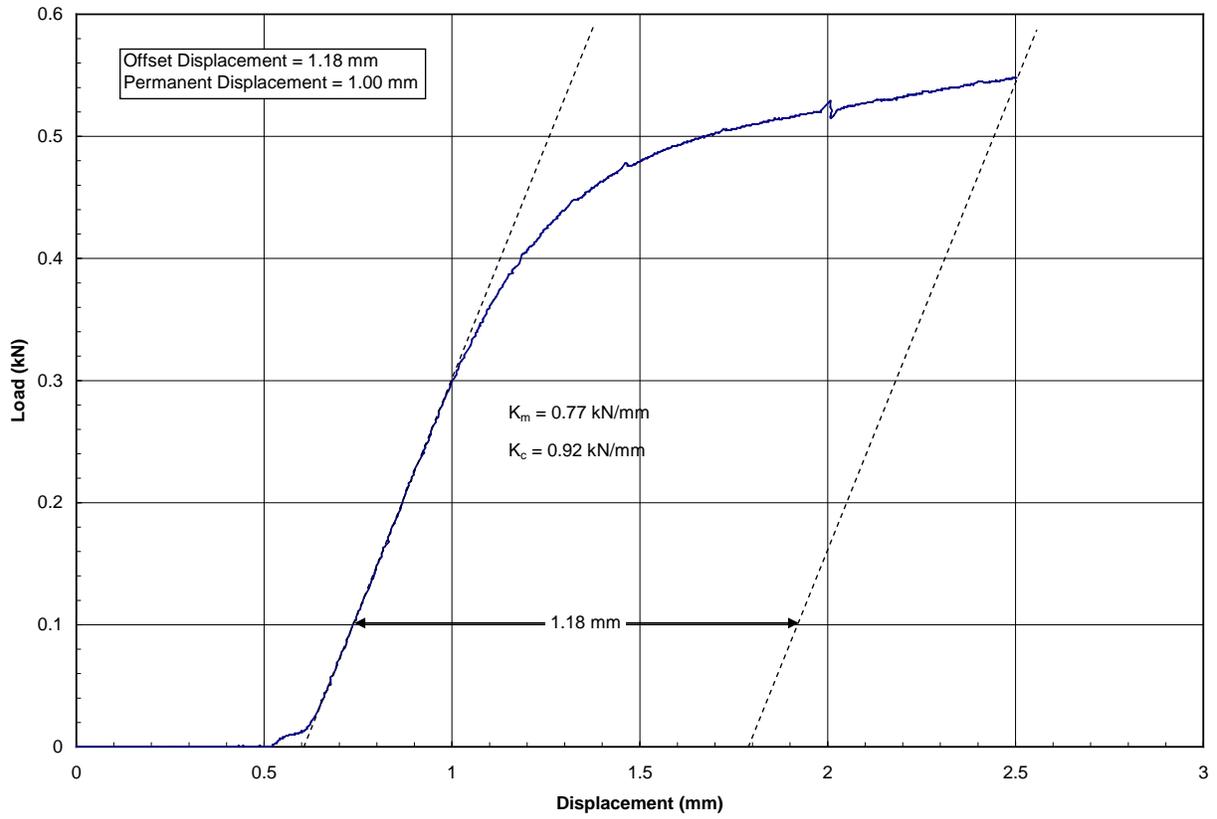


Figure A-2. Load-displacement curve for ZIRLO™ sample 109B2 compressed at RT and 2 mm/minute to 2-mm total displacement.

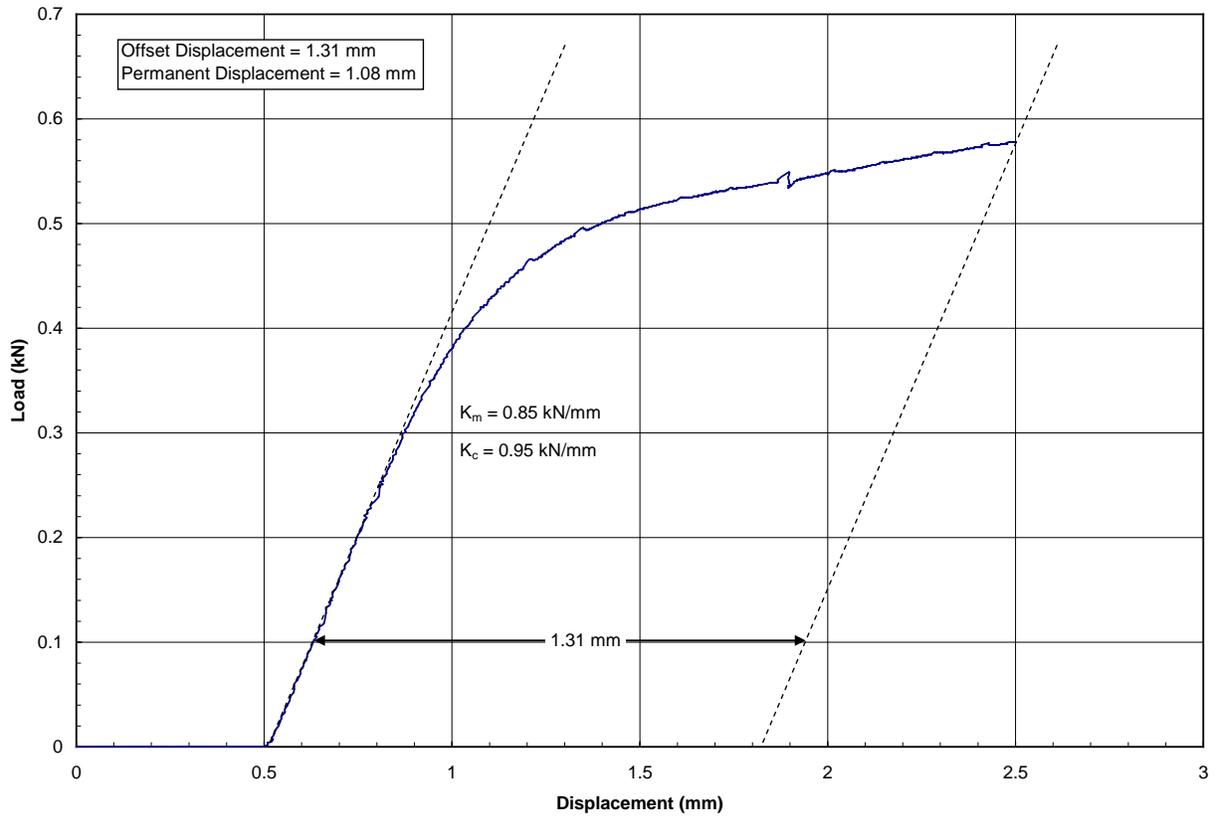


Figure A-3. Load-displacement curve for ZIRLO™ sample 109B3 compressed at RT and 2 mm/minute to 2-mm total displacement.

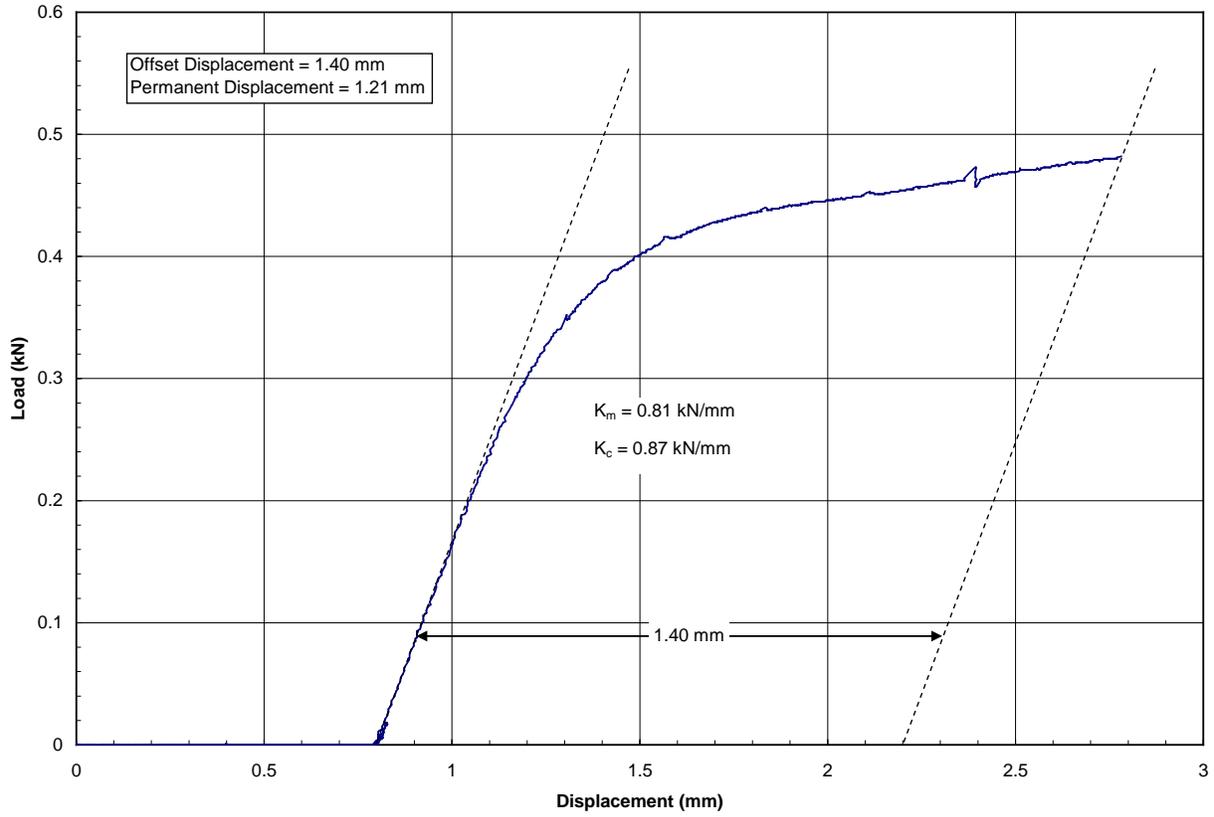


Figure A-4. Load-displacement curve for ZIRLO™ sample 109B4 compressed at 135 °C and 2 mm/minute to 2-mm total displacement.

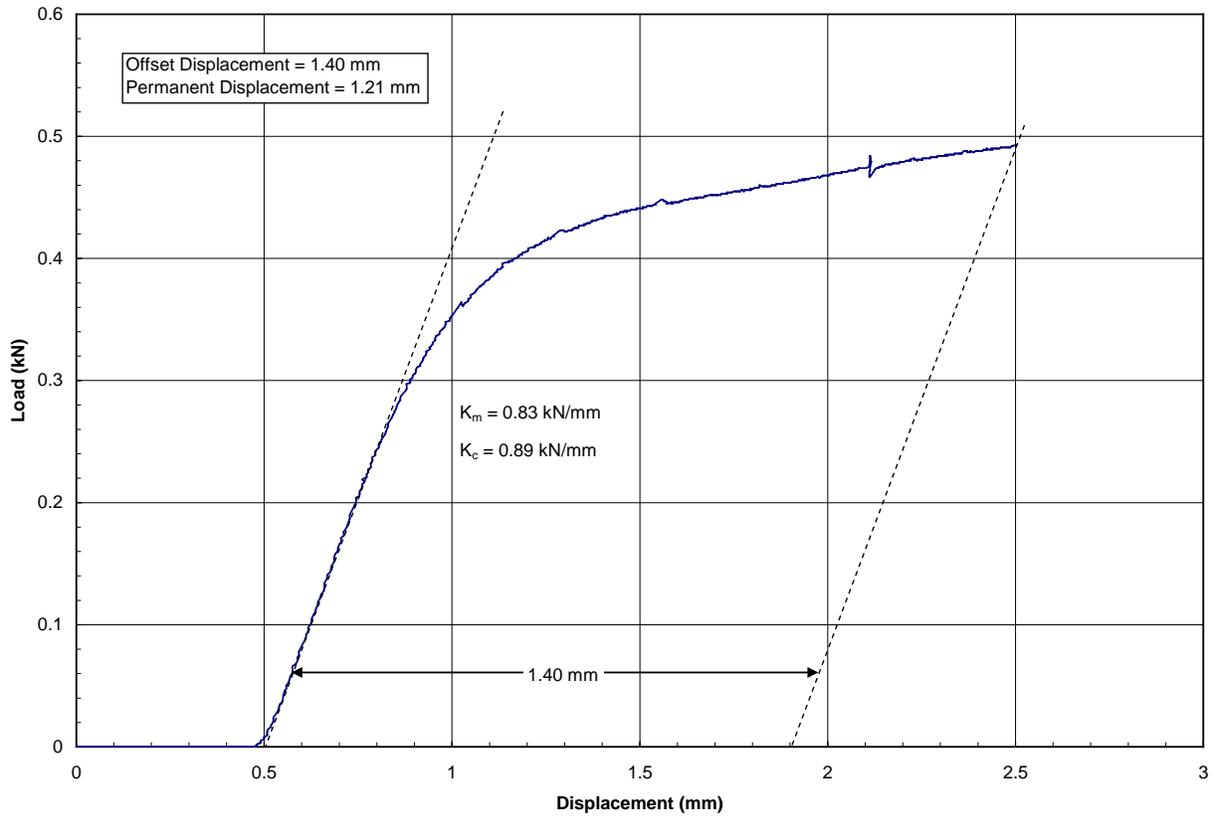


Figure A-5. Load-displacement curve for ZIRLO™ sample 109B5 compressed at 135 °C and 2 mm/minute to 2-mm total displacement.

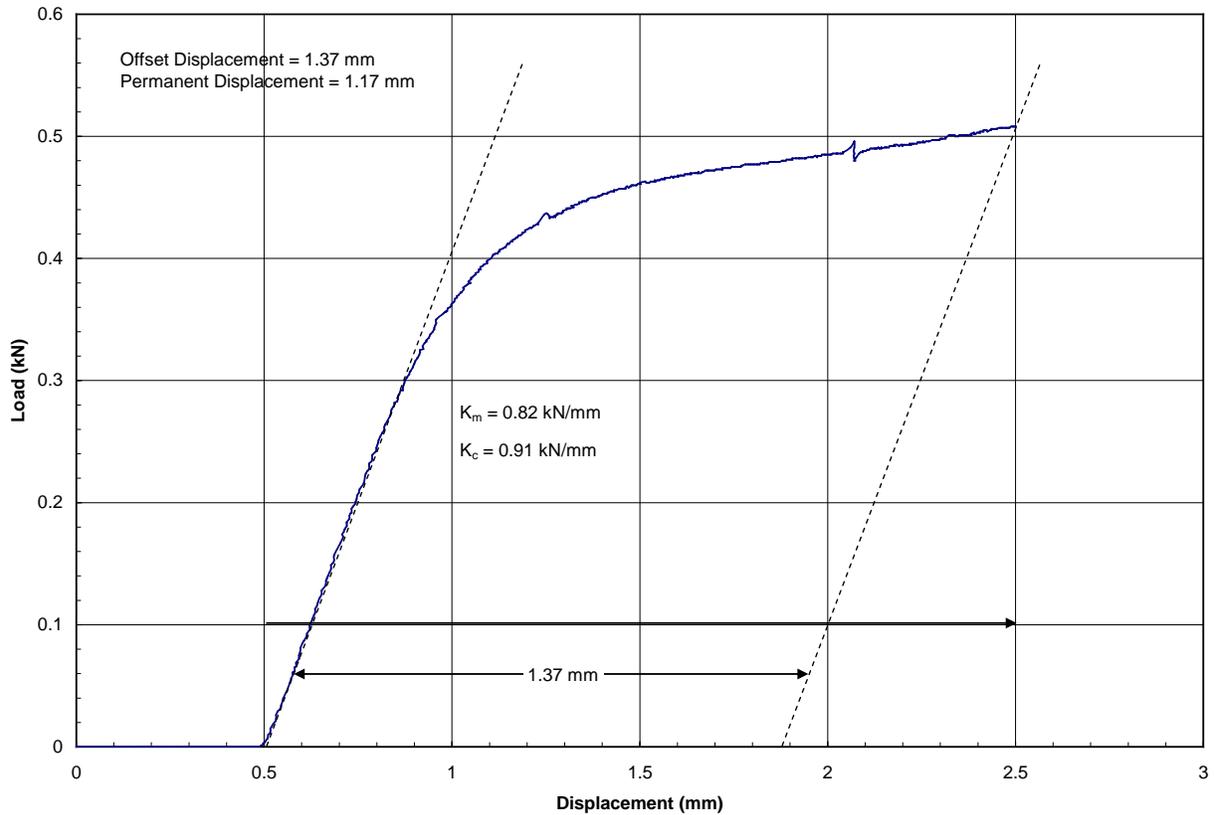


Figure A-6. Load-displacement curve for ZIRLO™ sample 109B9 compressed at 135 °C and 2 mm/minute to 2-mm total displacement.

References¹

1. T.A. Burtseva, "Procedure for Conducting Ring-Compression Tests in Laboratory DL-102A," ANL-IPS Memo, IPS-495-00-00, November 26, 2007.

¹ Publicly available NRC published documents are available electronically through the Electronic Reading Room on the NRC's public Web site at: <http://www.nrc.gov/reading-rm/doc-collections/>. The documents can also be viewed on-line or printed for a fee in the NRC's Public Document Room (PDR) at 11555 Rockville Pike, Rockville, MD; the mailing address is USNRC PDR, Washington, DC 20555; telephone 301-415-4737 or (800) 397-4209; fax (301) 415-3548; and e-mail pdr.resource@nrc.gov.

APPENDIX B

EXAMPLES OF LOAD-DISPLACEMENT CURVES, OFFSET STRAINS, AND PERMANENT STRAINS FOR OXIDIZED AND QUENCHED CLADDING SAMPLES

Figures B-1 through B-8 show examples of load-displacement curves and offset displacements determined from these curves. For this series of tests, prehydrided vintage 15×15 Zircaloy (Zry)-4 cladding samples, comparable to H.B. Robinson vintage cladding, were oxidized to 6% Cathcart-Pawel (CP) equivalent cladding reacted (ECR) at a maximum temperature of 1,200°degrees Celsius (°C). As shown in Table B-1 (Table 52 in NUREG/CR 6967, “Cladding Embrittlement during Postulated Loss-of-Coolant Accidents,” issued July 2008, Agencywide Documents Access and Management System Accession No. ML082130389), the quench temperature was varied from 800 °C to 700 °C to 600 °C to slow-cooling without quench. The load-displacement curves (see Figures B-1 through B-6) for the quenched samples indicate that all of these samples were brittle. Based on both offset strains and permanent strains, only the slow-cooled samples retained ductility (see Figures B-7 through B-8). For the samples that retained ductility, the difference between the offset strains and the permanent strains was only 0.9%. For prehydrided Zry-4, the ductility criteria used in EP-Ref. 1 is that ≥1.0% permanent strain implies ductility.

Table B-1. Postquench Ductility of Prehydrided HBR-type 15×15 Zry-4 Cladding Oxidized to 6% CP-ECR at 1,200 °C, Cooled at 13 °C/s to 800 °C, and Quenched at 800 °C, Cooled from 800 °C to 700 °C at 3 °C/s and Quenched at 700 °C, Cooled from 700 °C to 600 °C at 2 °C/s and Quenched at 600 °C, or Slow-cooled from 600 °C to RT at <2 °C/s

CP-ECR calculated from beginning of ramp to end of hold time; ring-compression tests performed on ≈8-mm-long samples at 135 °C and 0.0333 mm/s crosshead displacement rate

Sample and Test Conditions			ECR %		Plastic Displacement, mm		Plastic Strain, %	
Q-T, °C or SC	Test Time ^a s	H wppm	CP	Meas.	Offset	Permanent	Offset	Permanent
800	106	450	6.0	6.5	0.10	0.08	0.9	0.7
800	106	450	6.0	6.5	0.09	0.07	0.8	0.7
700	106	450	6.0	6.6	0.07	0.05	0.6	---
700	106	450	6.0	6.6	0.10	0.05	0.9	0.5
600	106	460	6.0	6.5	0.08	0.05	0.7	0.5
600	106	460	6.0	6.5	0.13	0.08	1.2	0.7
SC	106	470	6.0	6.4	0.22	0.18	2.1	1.7
SC	106	470	6.0	6.4	0.53	0.39	4.9	3.6

^a From beginning of ramp at 300 °C to end of hold time at ≈1,200 °C

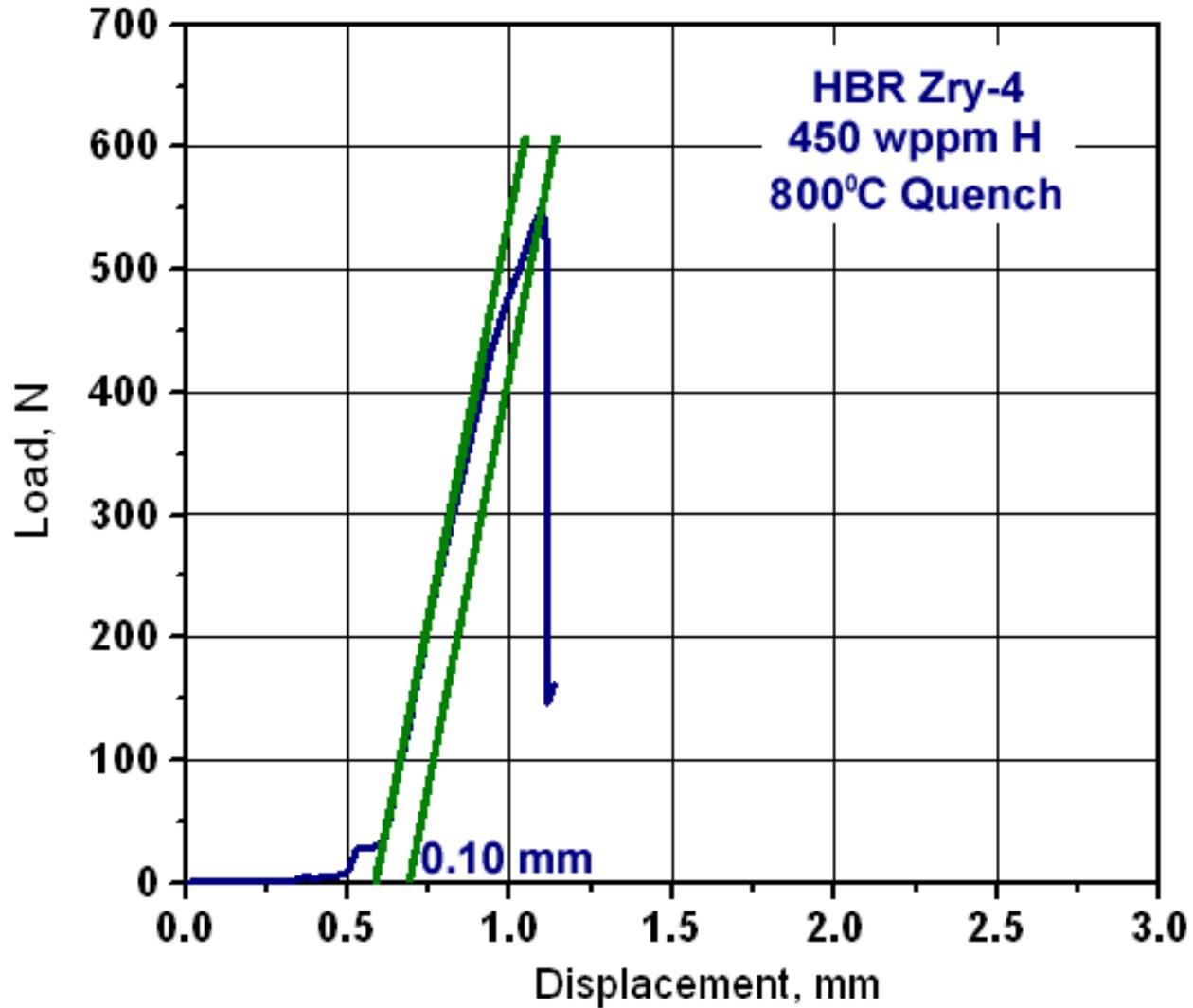


Figure B-1. Load-displacement results for ring #1 (8.12 mm long) of a prehydrided (450 wppm) HBR 15×15 Zry-4 sample oxidized to 6% CP-ECR at a maximum oxidation temperature of 1,200 °C and quenched at 800 °C. The posttest sample had tight through-wall cracks at load and support locations. Offset and permanent displacements were 0.10 mm and 0.08 mm, respectively.

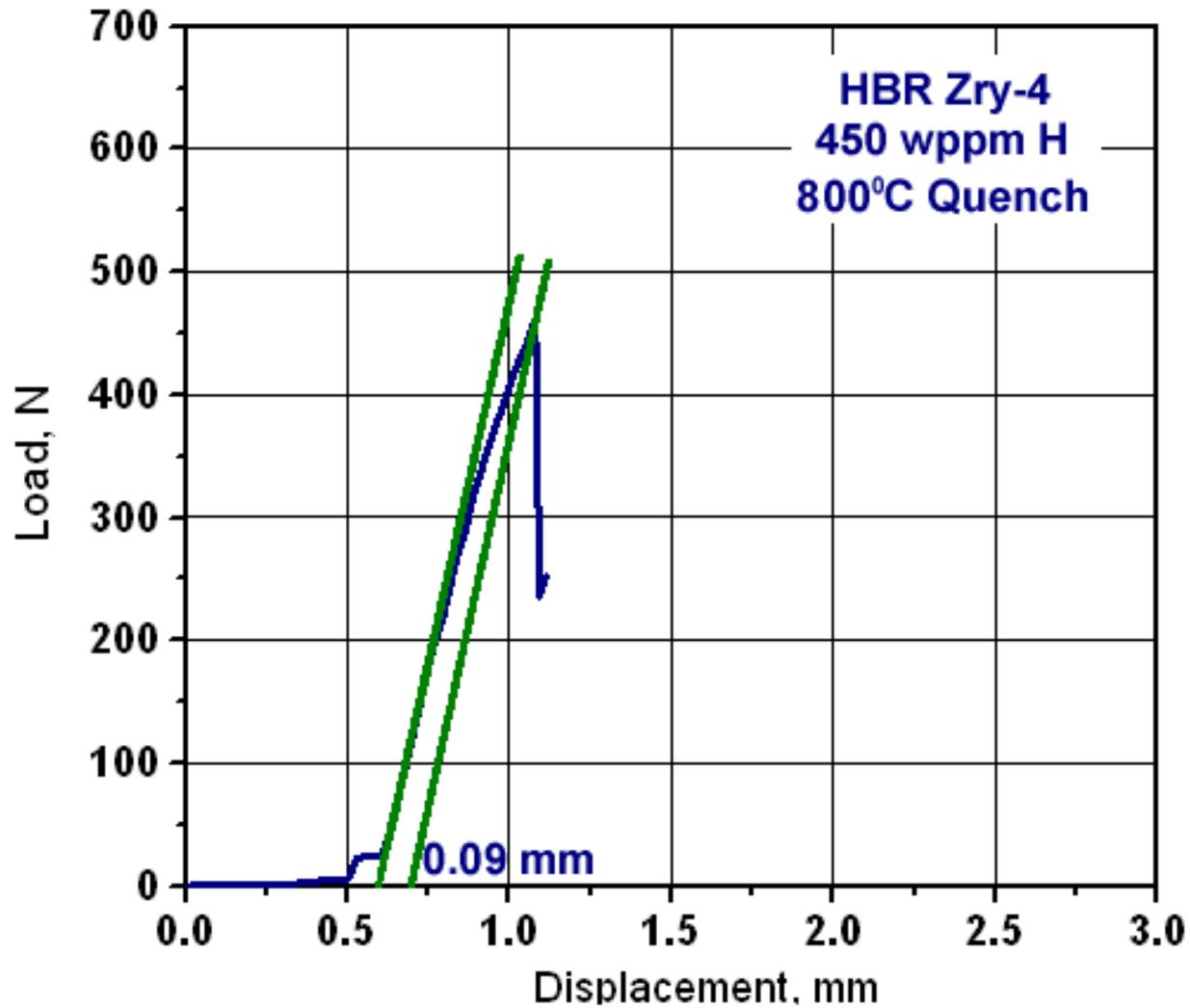


Figure B-2. Load-displacement results for ring #2 (6.84 mm long) of a prehydrided (450 wppm) HBR 15×15 Zry-4 sample oxidized to 6% CP-ECR at a maximum oxidation temperature of 1,200 °C and quenched at 800 °C. The posttest sample had a tight through-wall crack at the support locations. Offset and permanent displacements were 0.09 mm and 0.07 mm, respectively.

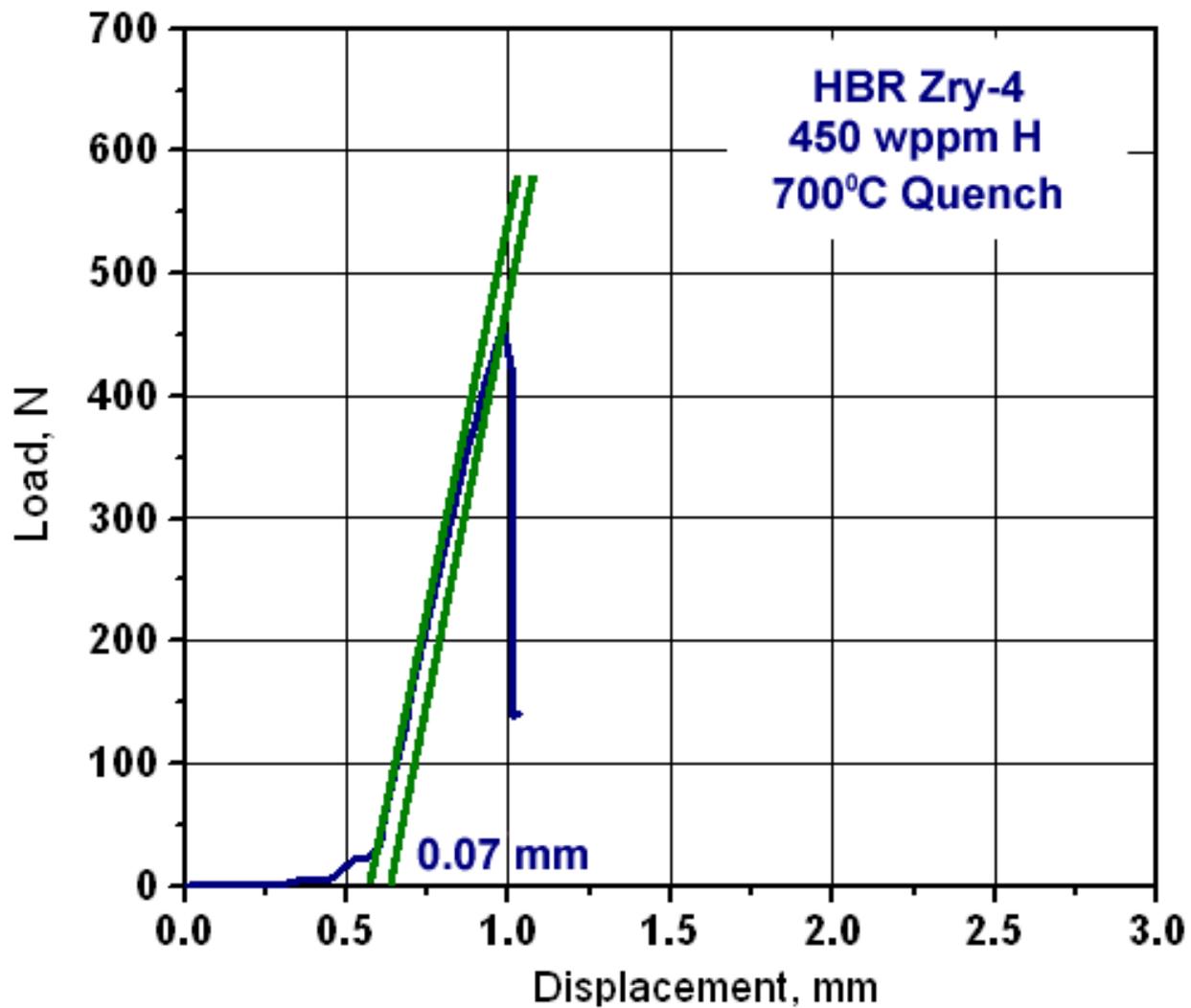


Figure B-3. Load-displacement results for ring #1 (8.08 mm long) of a prehydrided (450 wppm) HBR 15×15 Zry-4 sample oxidized to 6% CP-ECR at a maximum oxidation temperature of 1,200 °C and quenched at 700 °C. The posttest sample had through-wall cracks at load and support locations. Offset displacement was 0.07 mm.

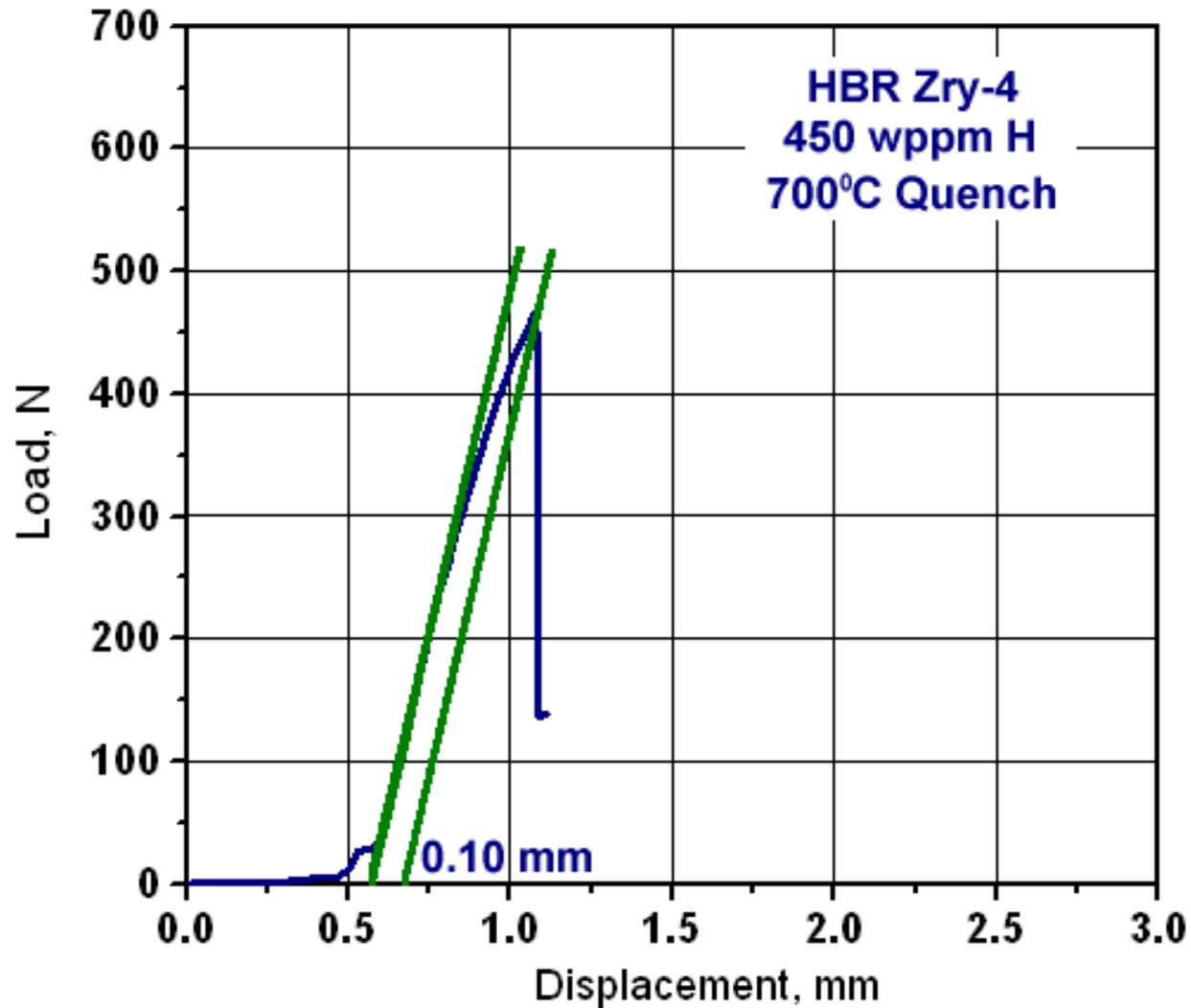


Figure B-4. Load-displacement results for ring #2 (7.30 mm long) of a prehydrided (450 wppm) HBR 15×15 Zry-4 sample oxidized to 6% CP-ECR at a maximum oxidation temperature of 1,200 °C and quenched at 700 °C. The posttest sample had tight through-wall cracks at load and support locations. Offset and permanent displacements were 0.10 mm and 0.05 mm, respectively.

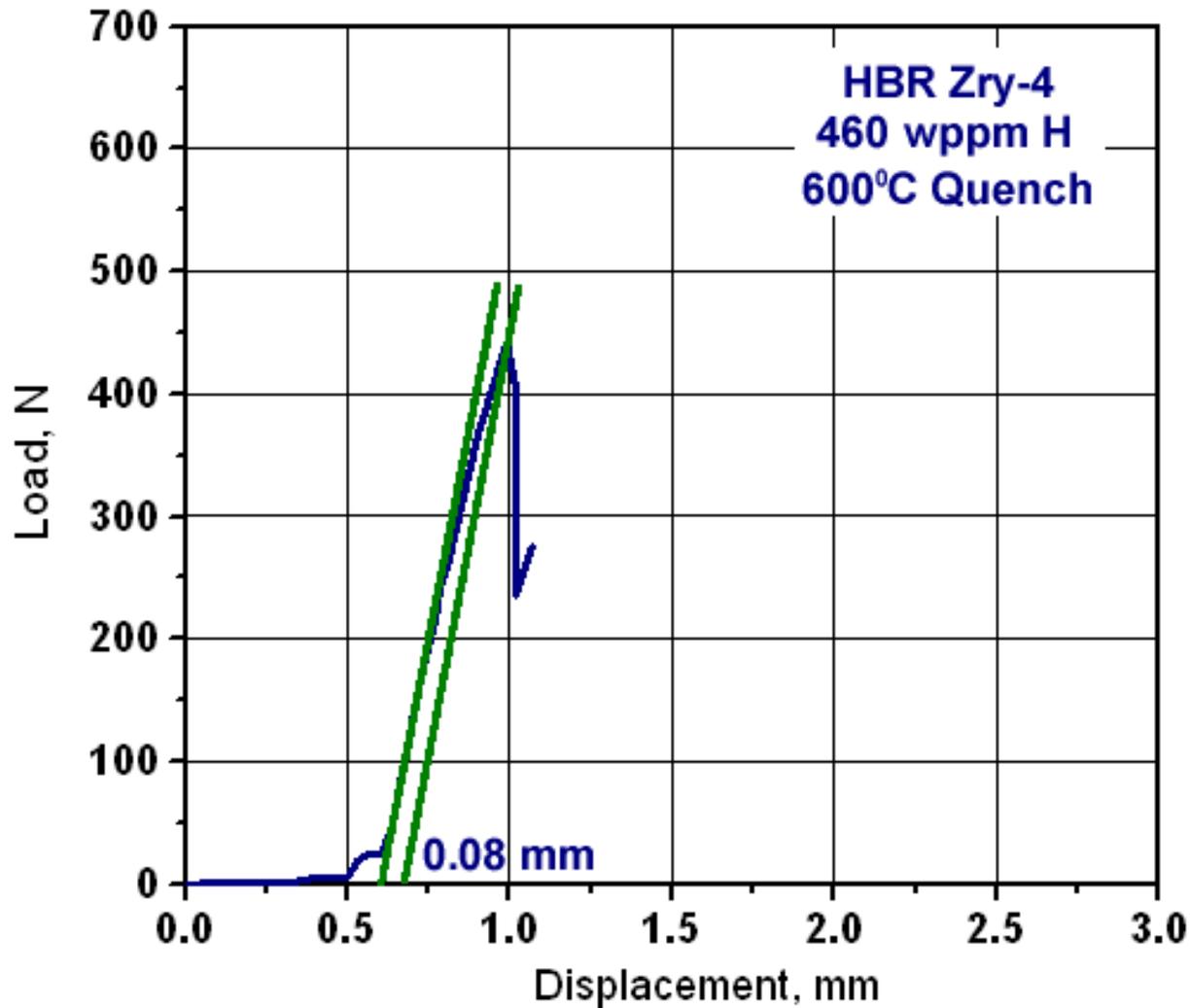


Figure B-5. Load-displacement results for ring #1 (7.93 mm long) of a prehydrided (460 ± 30 wppm) HBR 15×15 Zry-4 sample oxidized to 6% CP-ECR at a maximum oxidation temperature of 1,200 °C and quenched at 600 °C. The posttest sample had a tight through-wall crack at the support location. Offset and permanent displacements were 0.08 mm and 0.05 mm, respectively.

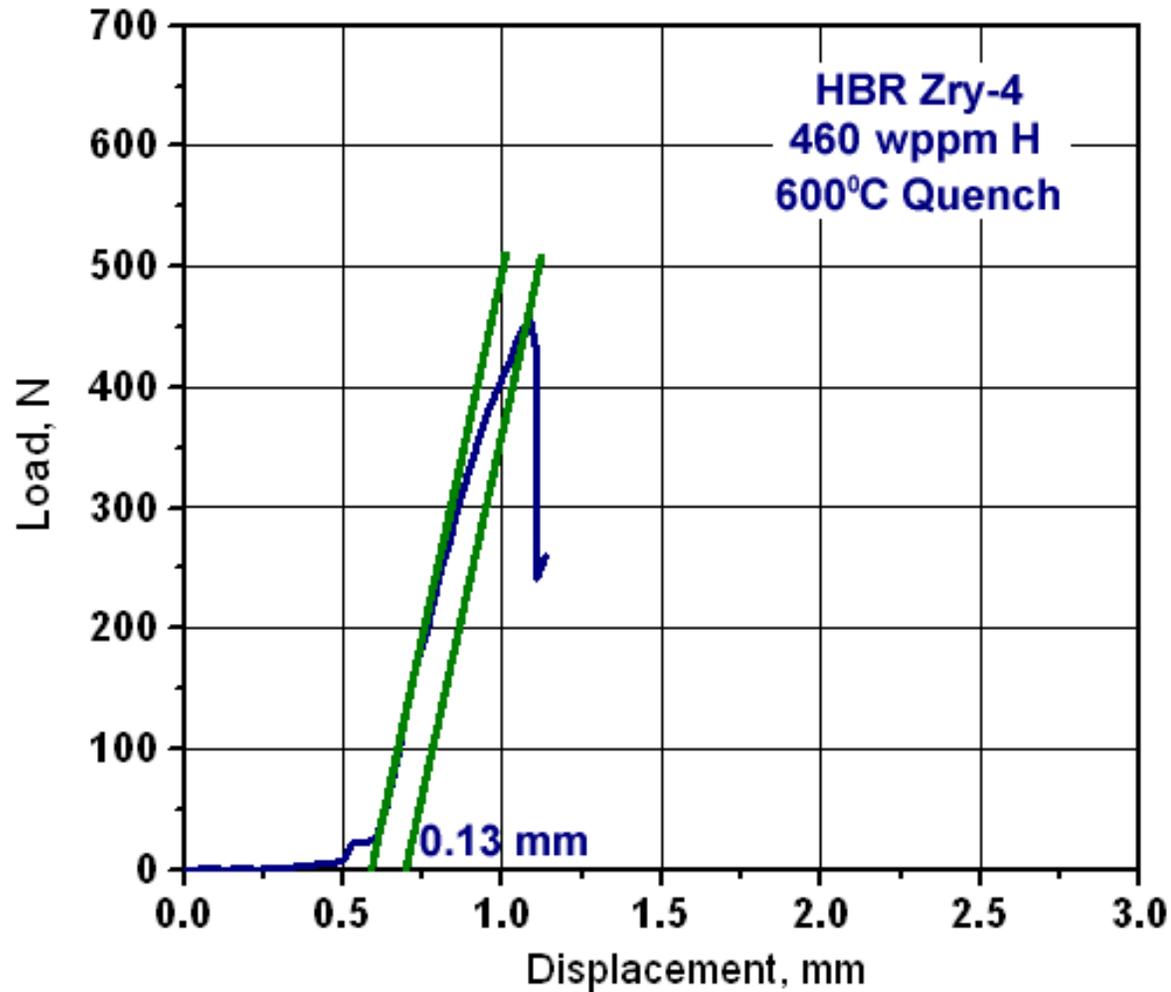


Figure B-6. Load-displacement results for ring #2 (7.05 mm long) of a prehydrided (460 ± 30 wppm) HBR 15×15 Zry-4 sample oxidized to 6% CP-ECR at a maximum oxidation temperature of 1,200 °C and quenched at 600 °C. The posttest sample had a through-wall crack at the loading location. Offset and permanent displacements were 0.13 mm and 0.08 mm, respectively.

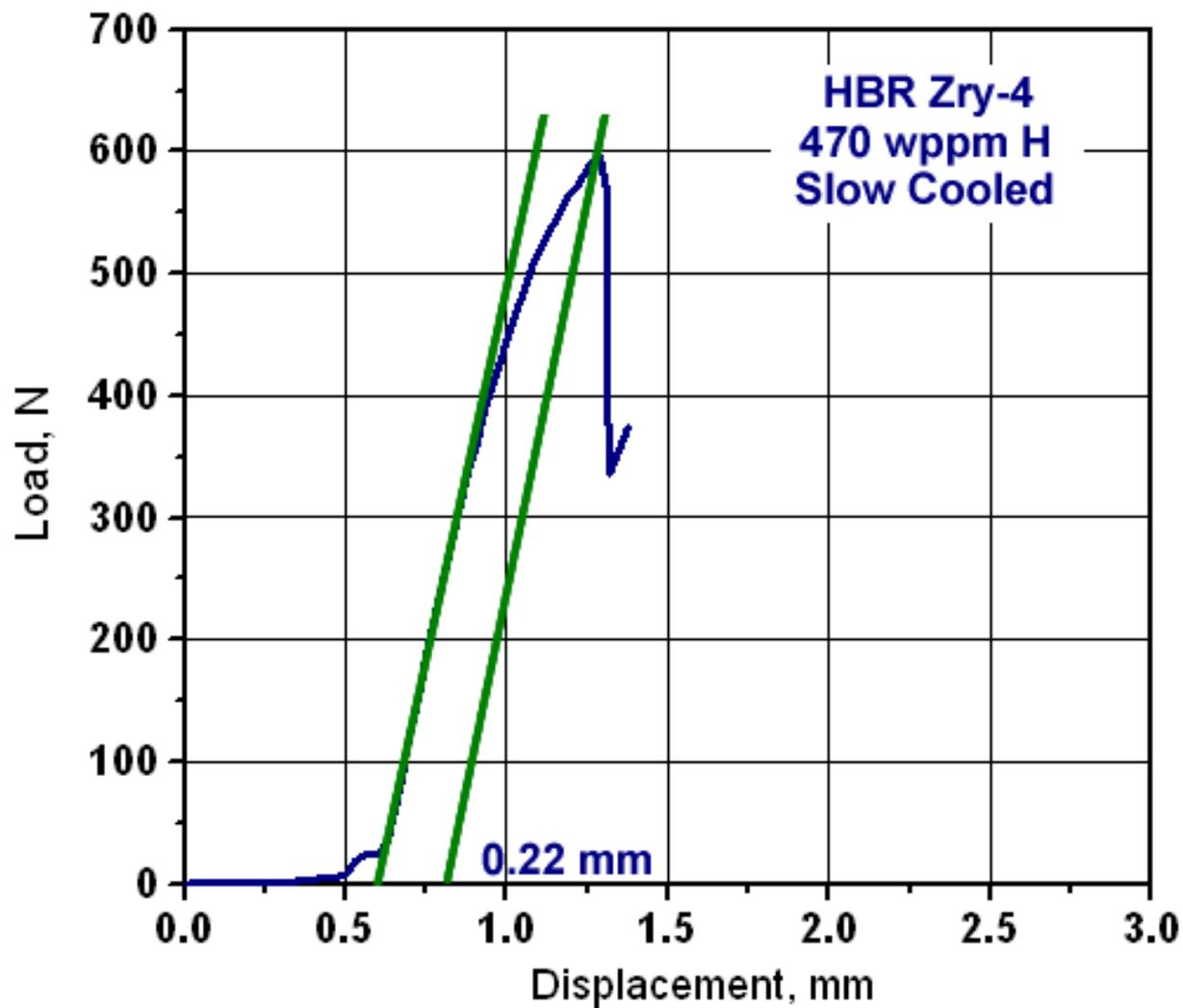


Figure B-7. Load-displacement results for ring #1 (8.04 mm long) of a prehydrided (470 ± 30 wppm) HBR 15×15 Zry-4 sample oxidized to 6% CP-ECR at a maximum oxidation temperature of 1,200 °C and cooled to room temperature without quench. The posttest sample had a tight through-wall crack at the support location. Offset and permanent displacements were 0.22 mm and 0.18 mm, respectively.

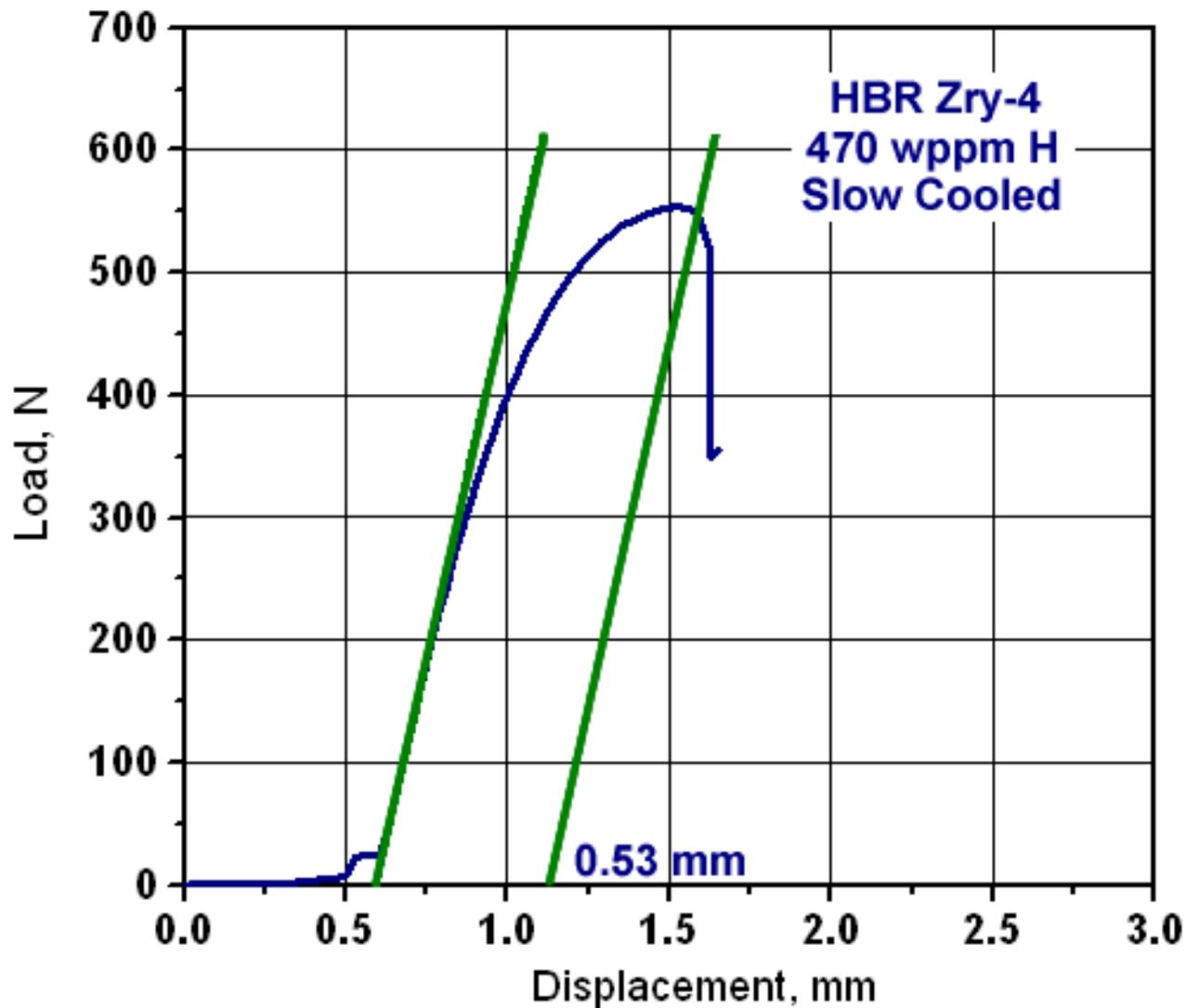


Figure B-8. Load-displacement results for ring #2 (7.05 mm long) of a prehydrided (470 ± 30 wppm) HBR 15×15 Zry-4 sample oxidized to 6% CP-ECR at a maximum oxidation temperature of 1,200 °C and cooled to room temperature without quench. The posttest sample had a tight through-wall crack at the loading location. Offset and permanent displacements were 0.53 mm and 0.39 mm, respectively.

APPENDIX C

RELATIONSHIP BETWEEN OFFSET STRAIN AND PERMANENT STRAIN

For as-fabricated cladding compressed at room temperature (RT) or at 135 degrees Celsius (°C) and at 0.033 millimeters/second (mm/s) to a total displacement of 2 mm, the difference between offset displacement and permanent displacement is ≤ 0.2 mm, which corresponds to a strain difference of $\approx 2\%$. As the applied displacement is decreased, the plastic deformation decreases, and the deviation between offset and permanent strain also decreases. This was demonstrated by conducting a set of ring-compression tests designed to result in low permanent strains of 1.0 to 2.3%. Table C-1 shows the results of these tests.

Table C-1. Results of Ring-Compression Tests Conducted with As-Fabricated Cladding Samples at RT and 2 mm/minute Displacement Rate

Total applied displacements were chosen to give low permanent strains (d_p/D_o) in the range of 1.0 to 2.3% and corresponding low offset strains.

Material (D_o , mm)	Sample ID IPS or AG No.	Offset Displacement δ_d , mm	Permanent Displacement d_d , mm	Permanent Strain d_d/D_o , %	Strain Difference $(\delta_d - d_d)/D_o$, %
15×15 Zry-4 (10.91 mm)	101B7	0.24	0.21	1.9	0.3
	101B8	0.20	0.17	1.6	0.3
	101B9	0.20	0.18	1.6	0.2
	101B10	0.16	0.14	1.3	0.2
17×17 ZIRLO™ (9.48 mm)	109D7	0.25	0.22	2.3	0.3
	109D8	0.17	0.16	1.7	0.1
	109D9	0.14	0.12	1.3	0.2
	109D10	0.14	0.12	1.3	0.2
17×17 M5 (9.48 mm)	636B2	0.18	0.19	2.0	0.0
	636B3	0.14	0.14	1.5	0.0
	636B4	0.15	0.15	1.6	0.0

For as-fabricated and prehydrided cladding oxidized at $\leq 1,200$ °C, the difference between offset and permanent displacement depends on both the oxidation level and the magnitude of the permanent displacement. For material with high ductility, the difference in displacements can be as high as 0.5 mm. For material with essentially no ductility, both the offset and permanent displacement values are in the “noise of uncertainty,” and their difference can be as low as 0.01 mm.

However, of relevance to the determination of the ductile-to-brittle transition oxidation level is the error in offset strain as determined by the difference between offset (δ_p/D_o in %) and permanent (d_p/D_o in %) strains for permanent strains in the range of 1.0 to 2.3%. Figure C-1 summarizes the data reported in EP-Refs. 1 and 2, in Figures 2 and 3 of DG-1262, and in Table C-1. The data are plotted as a function of Cathcart-Pawel equivalent cladding reacted (CP-ECR). Low values of permanent strain at low CP-ECR levels (e.g., 5–10%) are from prehydrided Zircaloy (Zry)-4 and high-burnup Zry-4 and ZIRLO™ samples. Low values of permanent strain at intermediate CP-ECR levels (10–18%) are from high-burnup ZIRLO™ and M5 samples. Low values of permanent strain at high ECR values (15–20%) are from as-fabricated cladding materials. The following equation gives the best linear fit to the data:

$$\delta_p/D_o - d_p/D_o = 0.25 + 0.0863 \text{ CP-ECR} \quad (\text{C1})$$

The one-sigma upper bound to the data is given by:

$$\delta_p/D_o - d_p/D_o = 0.41 + 0.1082 \text{ CP-ECR} \quad (\text{C2})$$

Because of the large data scatter in Figure C-1, the one-sigma upper bound is used to establish the offset-strain ductility criterion. It is derived by setting the permanent strain (d_p/D_o) in Equation C2 to 1.0%:

$$\delta_p/D_o \geq 1.41 + 0.1082 \text{ CP-ECR} \quad (\text{C3})$$

For multiple offset-strain data points at the same CP-ECR level, the average value for the dataset, rounded to the nearest tenth of a percent, should be used for δ_p/D_o in Equation C3. Similarly, the limit calculated from the right-hand side of Equation C3 should also be rounded to the nearest tenth of a percent.

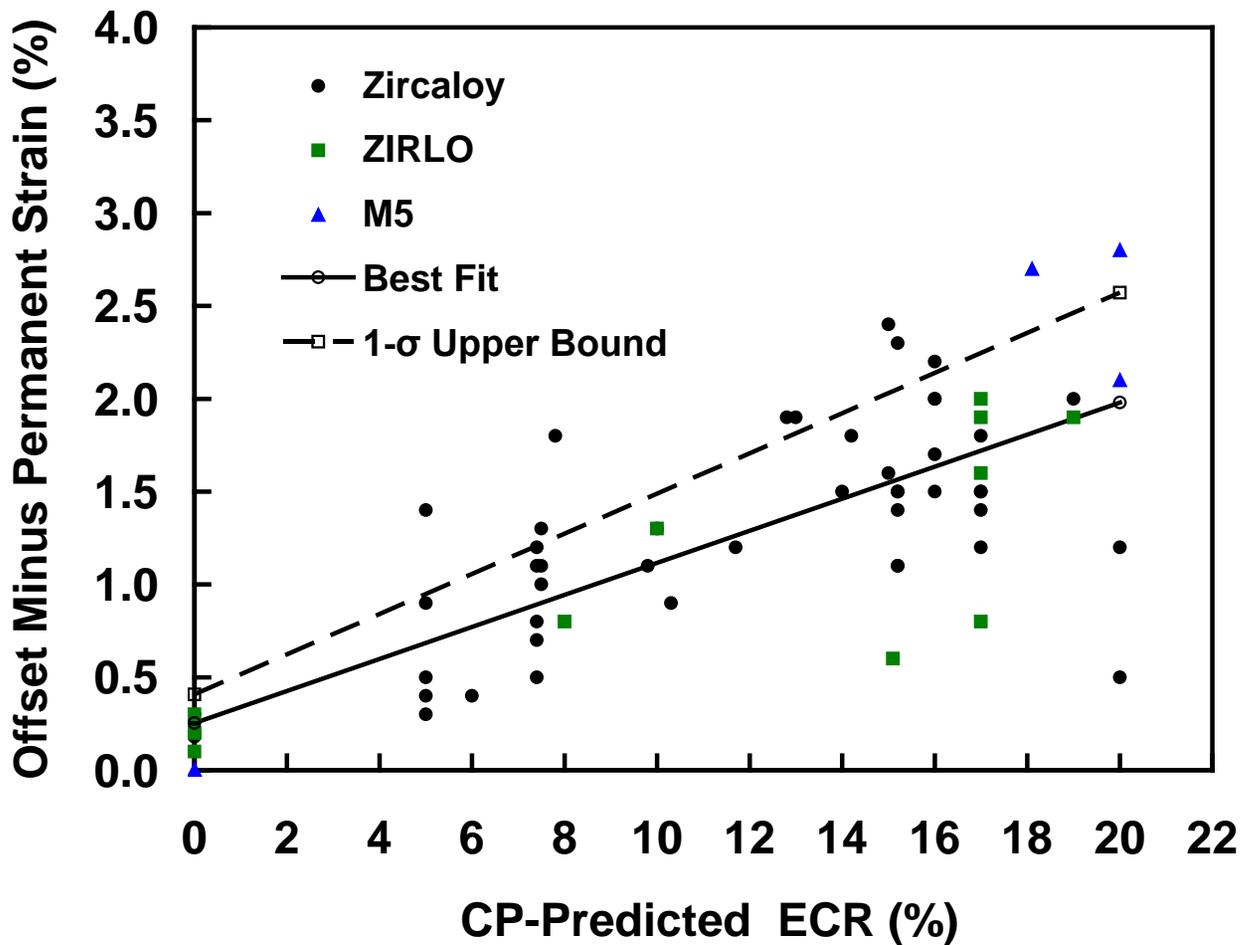


Figure C-1. Difference in offset strain and permanent strain as a function of calculated oxidation level (CP-ECR) for permanent strains near the embrittlement threshold (1.0 to 2.3%) for as-fabricated, prehydrided, and high-burnup cladding alloys oxidized at 1,200 °C and ring-compressed at room temperature and 135 °C and at 0.033 mm/s.

REFERENCES¹

1. M. Billone, Y. Yan, T. Burtseva, and R. Daum, "Cladding Embrittlement during Postulated Loss-of-Coolant Accidents," NUREG/CR-6967, July 2008 (ADAMS Accession No. ML082130389).
2. Y. Yan, T.A. Burtseva, and M.C. Billone, "Post-quench Ductility Results for North Anna High-burnup 17×17 ZIRLO Cladding with Intermediate Hydrogen Content," ANL letter report to NRC, April 17, 2009 (ADAMS Accession No. ML091200702).

¹ Publicly available NRC published documents are available electronically through the Electronic Reading Room on the NRC's public Web site at: <http://www.nrc.gov/reading-rm/doc-collections/>. The documents can also be viewed on-line or printed for a fee in the NRC's Public Document Room (PDR) at 11555 Rockville Pike, Rockville, MD; the mailing address is USNRC PDR, Washington, DC 20555; telephone 301-415-4737 or (800) 397-4209; fax (301) 415-3548; and e-mail pdresource@nrc.gov.

REGULATORY ANALYSIS

Draft Regulatory Guide, DG-1262, “Testing for Postquench Ductility” *(Proposed New Regulatory Guide 1.223)*

Statement of the Problem

In 1996, the U.S. Nuclear Regulatory Commission (NRC) initiated a fuel-cladding research program¹ intended to investigate the behavior of high-exposure fuel cladding under accident conditions. The research program identified new cladding embrittlement mechanisms and expanded NRC’s knowledge of previously identified mechanisms. The research results revealed that alloy composition has a minor effect on embrittlement, but cladding corrosion, which occurs as fuel burnup increases, has a substantial effect on embrittlement. One of the major findings of NRC’s research program was that hydrogen, which is absorbed in the cladding as a result of waterside corrosion under normal operation, has a significant influence on embrittlement during a hypothetical accident.

NRC initiated rulemaking activities (Ref. 1) to revise Emergency Core Cooling System (ECCS) acceptance criteria to reflect recent research findings on these new cladding embrittlement mechanisms. The revisions to the ECCS acceptance criteria were developed to enhance performance-based features of 10 CFR 50.46. Therefore, 10 CFR 50.46(c) calls for the establishment of analytical limits on peak cladding temperature and time at elevated temperature that correspond to the measured ductile-to-brittle transition for a specific zirconium-alloy cladding material. With this approach, the limits imposed on each zirconium-based alloy are consistent with the alloy’s particular behavior because they are based on measurements for that zirconium-based alloy.

This regulatory guidance makes it possible to revise 10 CFR 50.46(c) in a performance-based manner by providing a means of consistent, comparable generation of data to establish regulatory limits on peak cladding temperature and time at elevated temperature that correspond to the measured ductile-to-brittle transition for a specific zirconium-alloy cladding material. Development of this regulatory guidance captures the experimental technique used in NRC’s loss-of-coolant accident (LOCA) research program to measure the ductile-to-brittle transition of specific zirconium-based alloy cladding, thereby establishing an experimental technique acceptable to the NRC staff.

Objective

The objective of this regulatory action is to enable performance-based rule language in 10 CFR 50.46(c) 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.

¹ The research program included an extensive loss-of-coolant accident (LOCA) research and testing program at Argonne National Laboratory (ANL), as well as jointly funded programs at the Kurchatov Institute (Ref. 2) and the Halden Reactor (Ref. 3) project, to develop the body of technical information needed to evaluate LOCA regulations for high-exposure fuel. The research findings have been summarized in Research Information Letter (RIL) 0801, “Technical Basis for Revision of Embrittlement Criteria in 10 CFR 50.46,” dated May 30, 2008 (Ref. 4) and the detailed experimental results from the program at ANL are contained in NUREG/CR-6967, “Cladding Embrittlement During Postulated Loss-of-Coolant Accidents” (Ref. 5).

Alternative Approaches

The NRC staff considered the following alternative approaches:

Alternative 1: Do Not Create Draft Regulatory Guide-1262

Under this alternative, NRC would not create Draft Regulatory Guide (DG)-1262. If NRC does not take action, no changes would occur in costs or benefit to the public, licensees, or NRC. However, the “no-action” alternative would not provide a clear, acceptable approach for implementing the performance-based regulatory requirements proposed for 50.46(c). NRC would have to review the experimental techniques used to generate the data provided by licensees to support zirconium-based alloy limits related to the embrittlement behavior of zirconium-alloy claddings on a case-by-case basis.

The impact associated with not creating the regulatory guide is that NRC and its licensees and applicants may interpret differently the extent and details of experiential techniques acceptable to support a zirconium-based alloy analytical limit on peak cladding temperature and time at elevated temperature under LOCA conditions. In addition, the NRC resources required to review the experimental technique used to produce the data, which supports a licensee’s proposed zirconium-based alloy analytical limit on peak cladding temperature and time at elevated temperature, would be significant.

Alternative 2: Create Draft Regulatory Guide-1262

Under this alternative, NRC would create DG-1262. Creating DG-1262 will (1) enable implementation of the performance-based regulatory requirements proposed for 50.46(c) by providing a means of consistent, comparable generation of data to establish regulatory limits on peak cladding temperature and time at elevated temperature under LOCA conditions; (2) simplify the staff’s review process; and (3) reduce regulatory uncertainty and thereby help to minimize the costs associated with the implementation of the regulatory requirements proposed for 50.46(c). A benefit of this action is that it would enhance reactor safety by ensuring clear guidance is available for defining a zirconium-based alloy’s embrittlement behavior under LOCA conditions.

The impact to NRC would be the costs associated with preparing and creating the regulatory guide. The impact to the public would be the voluntary costs associated with reviewing and providing comments to NRC during the public comment period. The value to NRC and its applicants would be the benefits associated with enhanced efficiency and effectiveness in using common experimental techniques for generating data to establish regulatory limits on peak cladding temperature and time at elevated temperature under LOCA conditions.

Conclusions

Based on this regulatory analysis, the NRC staff recommends creating DG-1262. The staff concludes that the proposed action will enhance reactor safety ensuring clear guidance is available for defining a zirconium-based alloy’s embrittlement behavior under LOCA conditions. The creation of this guide also could reduce regulatory uncertainties and thereby minimize costs for the industry.

REFERENCES²

1. 7X FR XXXXX, "Proposed Rule FRN," *Federal Register*, Volume 7X, Number XXX, p. XXXX, Washington, DC, June 31, 2011. (*insert FRN of proposed rule reference when available*)
2. NUREG/IA 0211, "Experimental Study of Embrittlement of Zr 1%Nb VVER Cladding under LOCA-Relevant Conditions," U.S. Nuclear Regulatory Commission, Washington, DC, March 2005. (ADAMS Accession No. ML051100343)
3. IFE/KR/E 2008/004, "LOCA Testing of High Burnup PWR Fuel in the HBWR. Additional PIE on the Cladding of the Segment 650 5," Institute for Energy Technology, Kjeller, Norway, April 2008. (ADAMS Accession No. ML081750715)
4. Research Information Letter 0801, "Technical Basis for Revision of Embrittlement Criteria in 10 CFR 50.46," U.S. Nuclear Regulatory Commission, Washington, DC, May 30, 2008. (ADAMS Accession No. ML081350225)
5. NUREG/CR 6967, "Cladding Embrittlement during Postulated Loss-of-Coolant Accidents," U.S. Nuclear Regulatory Commission, Washington, DC, July 2008. (ADAMS Accession No. ML082130389)

²

Publicly available NRC-published documents are available electronically through the Electronic Reading Room on NRC's public Web site at: <http://www.nrc.gov/reading-rm/doc-collections/>. The documents can also be viewed online or printed for a fee in the NRC's Public Document Room (PDR) at 11555 Rockville Pike, Rockville, MD; the mailing address is USNRC PDR, Washington, DC 20555; telephone 301-415-4737 or 800-397-4209; fax 301-415-3548; and e-mail pdresource@nrc.gov.

NOTE: The availability of this draft rule language, as it exists in this document, is intended to inform stakeholders of the current status of the NRC's activities to revise the requirements for emergency core cooling systems to support an upcoming meeting with the Advisory Committee on Reactor Safeguards. The NRC staff is considering restructuring the current Section 50.46 regulation to distinguish ECCS performance requirements (i.e., criteria governing acceptable capability of ECCS to perform its cooling function during and after a design basis LOCA) from fuel/cladding performance requirements (i.e., criteria intended to ensure that the fuel and cladding do not result in prevention of successful cooling during and after a design basis LOCA, and any other effects with adverse impacts on the capability or other safety systems). Additionally, the NRC staff may add new paragraphs to address long standing issues and concerns with the current regulation. As such, this draft rule language may be incomplete or in error in one or more respects, and will be subject to further revisions during the rulemaking process. The NRC is not requesting formal public comments on this draft rule language. The NRC may post updated materials, including updated draft rule language, to this page. Interested stakeholders should periodically check this page for updates and added materials.

Draft Rule Language for 10 CFR 50.46c

§ 50.46c Requirements for emergency core cooling systems for light-water nuclear power reactors.

(a) *Applicability.* The requirements of this section apply to each holder of an operating license for any light water nuclear power reactor (LWR), regardless of fuel design or cladding material, except for a licensee who has submitted the certifications required under 10 CFR 50.82(a)(1) to the NRC.

(b) *Definitions.* As used in this section:

(1) *Loss-of-coolant accident (LOCA)* means a hypothetical accident that would result from the loss of reactor coolant, at a rate in excess of the capability of the reactor coolant makeup system, from breaks in pipes in the reactor coolant pressure boundary up to and including a break equivalent in size to the double-ended rupture of the largest pipe in the reactor coolant system.

(2) *Evaluation model* means the calculational framework for evaluating the behavior of the reactor system during a postulated loss-of-coolant accident (LOCA). It includes one or more computer programs and all other information necessary for application of the calculational framework to a specific LOCA, such as mathematical models used, assumptions included in the programs, procedure for treating the program input and output information, specification of those portions of analysis not included in computer programs, values of parameters, and all other information necessary to specify the calculational procedure.

(3) *Breakaway oxidation* means, for the purposes of this section, the fuel cladding oxidation phenomenon in which weight gain rate deviates from normal kinetics. This change occurs with a rapid increase of hydrogen pickup during prolonged exposure to a high temperature steam environment, which promotes loss of cladding ductility

(c) *General performance requirements for any fuel design or cladding material.* Each LWR must be provided with an emergency core cooling system (ECCS) designed so that, when fueled with an acceptable fuel design, the following performance requirements are satisfied in the event of a postulated loss-of-coolant accident (LOCA):

- (1) Core geometry remains amenable to cooling;
- (2) Generation of combustible gas is limited to the maximum extent practicable;
- (3) Core temperature is maintained at a value sufficient to ensure compliance with criteria in paragraphs (c)(1) and (c)(2) of this section;

NOTE: The availability of this draft rule language, as it exists in this document, is intended to inform stakeholders of the current status of the NRC's activities to revise the requirements for emergency core cooling systems to support an upcoming meeting with the Advisory Committee on Reactor Safeguards. The NRC staff is considering restructuring the current Section 50.46 regulation to distinguish ECCS performance requirements (i.e., criteria governing acceptable capability of ECCS to perform its cooling function during and after a design basis LOCA) from fuel/cladding performance requirements (i.e., criteria intended to ensure that the fuel and cladding do not result in prevention of successful cooling during and after a design basis LOCA, and any other effects with adverse impacts on the capability or other safety systems). Additionally, the NRC staff may add new paragraphs to address long standing issues and concerns with the current regulation. As such, this draft rule language may be incomplete or in error in one or more respects, and will be subject to further revisions during the rulemaking process. The NRC is not requesting formal public comments on this draft rule language. The NRC may post updated materials, including updated draft rule language, to this page. Interested stakeholders should periodically check this page for updates and added materials.

(4) Decay heat is removed for the extended period of time required by the long-lived radioactivity remaining in the core.

(5) ECCS cooling performance must be calculated in accordance with an acceptable evaluation model and must be calculated for a number of postulated loss-of-coolant accidents of different sizes, locations, and other properties sufficient to provide assurance that the most severe postulated loss-of-coolant accidents are calculated. The evaluation model must include sufficient supporting justification to show that the analytical technique realistically describes the behavior of the reactor system during a loss-of-coolant accident. Comparisons to applicable experimental data must be made and uncertainties in the analysis method and inputs must be identified and assessed so that the uncertainty in the calculated results can be estimated. This uncertainty must be accounted for, so that when the calculated ECCS cooling performance is compared to the applicable specified and acceptable analytical limits there is a high level of probability that the limits would not be exceeded. Appendix K, Part II Required Documentation, sets forth the documentation requirements for each evaluation model.

(d) *Specific requirements for fuel designs consisting of uranium oxide or mixed uranium-plutonium oxide pellets within zirconium-alloy cladding material.* Each LWR must be provided with an ECCS designed so that, when fueled with an acceptable fuel design consisting of uranium oxide or mixed uranium-plutonium oxide pellets within cylindrical zirconium-alloy cladding, the following performance requirements are satisfied in the event of a postulated LOCA:

(1) *Coolable geometry.* Calculated changes in core geometry shall be such that the core remains amenable to cooling.

(i) *Peak cladding temperature.* Except as provided in paragraph (d)(1)(ii) of this section, the calculated maximum fuel element cladding temperature shall not exceed 2200° F.

(ii) *Cladding embrittlement.* 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 2200° F limit specified in (d)(1)(i), then the lower temperature shall be used in place of the 2200° F limit.

iii) *Zirconium fuel cladding oxidation limits.* 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

NOTE: The availability of this draft rule language, as it exists in this document, is intended to inform stakeholders of the current status of the NRC's activities to revise the requirements for emergency core cooling systems to support an upcoming meeting with the Advisory Committee on Reactor Safeguards. The NRC staff is considering restructuring the current Section 50.46 regulation to distinguish ECCS performance requirements (i.e., criteria governing acceptable capability of ECCS to perform its cooling function during and after a design basis LOCA) from fuel/cladding performance requirements (i.e., criteria intended to ensure that the fuel and cladding do not result in prevention of successful cooling during and after a design basis LOCA, and any other effects with adverse impacts on the capability or other safety systems). Additionally, the NRC staff may add new paragraphs to address long standing issues and concerns with the current regulation. As such, this draft rule language may be incomplete or in error in one or more respects, and will be subject to further revisions during the rulemaking process. The NRC is not requesting formal public comments on this draft rule language. The NRC may post updated materials, including updated draft rule language, to this page. Interested stakeholders should periodically check this page for updates and added materials.

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.

(2) *Maximum hydrogen generation.* The calculated total amount of hydrogen generated from the chemical reaction of the cladding with water or steam shall not exceed 0.01 times the hypothetical amount that would be generated if all of the metal in the cladding cylinders surrounding the fuel, excluding the cladding surrounding the plenum volume, were to react.

(3) *Long-term cooling.* After any calculated successful initial operation of the ECCS, the calculated core temperature shall be maintained at an acceptably low value and decay heat shall be removed for the extended period of time required by the long-lived radioactivity remaining in the core.

(4) *Evaluation model.* ECCS cooling performance must be calculated in accordance with an acceptable evaluation model and must be calculated for a number of postulated loss-of-coolant accidents of different sizes, locations, and other properties sufficient to provide assurance that the most severe postulated loss-of-coolant accidents are calculated. Except as provided in paragraph (d)(4)(i) of this section, the evaluation model must include sufficient supporting justification to show that the analytical technique realistically describes the behavior of the reactor system during a loss-of-coolant accident. Comparisons to applicable experimental data must be made and uncertainties in the analysis method and inputs must be identified and assessed so that the uncertainty in the calculated results can be estimated. This uncertainty must be accounted for, so that when the calculated ECCS cooling performance is compared to the analytical limits established in accordance with paragraph (d)(1), (2), and (3) of this section, there is a high level of probability that the limits would not be exceeded. Appendix K, Part II Required Documentation, sets forth the documentation requirements for each evaluation model.

(i) Alternatively, an ECCS evaluation model may be developed in conformance with the required and acceptable features of appendix K ECCS Evaluation Models.

(ii) Oxygen diffusion from the cladding inside surfaces will reduce the allowable time at elevated temperature to embrittlement. If an oxygen source is present on the inside surfaces of the cladding at the onset of the LOCA, the effects of oxygen diffusion from the cladding inside surfaces shall be considered in the evaluation model.

- (e) [Reserved]
- (f) [Reserved]
- (g) [Reserved]
- (h) [Reserved]
- (i) [Reserved]

NOTE: The availability of this draft rule language, as it exists in this document, is intended to inform stakeholders of the current status of the NRC's activities to revise the requirements for emergency core cooling systems to support an upcoming meeting with the Advisory Committee on Reactor Safeguards. The NRC staff is considering restructuring the current Section 50.46 regulation to distinguish ECCS performance requirements (i.e., criteria governing acceptable capability of ECCS to perform its cooling function during and after a design basis LOCA) from fuel/cladding performance requirements (i.e., criteria intended to ensure that the fuel and cladding do not result in prevention of successful cooling during and after a design basis LOCA, and any other effects with adverse impacts on the capability or other safety systems). Additionally, the NRC staff may add new paragraphs to address long standing issues and concerns with the current regulation. As such, this draft rule language may be incomplete or in error in one or more respects, and will be subject to further revisions during the rulemaking process. The NRC is not requesting formal public comments on this draft rule language. The NRC may post updated materials, including updated draft rule language, to this page. Interested stakeholders should periodically check this page for updates and added materials.

(j) [Reserved]

(k) *Reporting.*

(1) Each applicant for or holder of an operating license or construction permit issued under this part, applicant for a standard design certification under part 52 of this chapter (including an applicant after the Commission has adopted a final design certification regulation), or an applicant for or holder of a standard design approval, a combined license or a manufacturing license issued under part 52 of this chapter, shall estimate the effect of any change to or error in an acceptable evaluation model or in the application of such a model to determine if the change or error is significant. For this purpose, a significant change or error is one which results in a calculated peak fuel cladding temperature different by more than 50 °F from the temperature calculated for the limiting transient using the last acceptable model, or is a cumulation of changes and errors such that the sum of the absolute magnitudes of the respective temperature changes is greater than 50 °F.

(2) For each change to or error discovered in an acceptable evaluation model or in the application of such a model that affects the temperature calculation, the applicant or holder of a construction permit, operating license, combined license, or manufacturing license shall report the nature of the change or error and its estimated effect on the limiting ECCS analysis to the Commission at least annually as specified in § 50.4 or § 52.3 of this chapter, as applicable. If the change or error is significant, the applicant or licensee shall provide this report within 30 days and include with the report a proposed schedule for providing a reanalysis or taking other action as may be needed to show compliance with § 50.46 requirements. This schedule may be developed using an integrated scheduling system previously approved for the facility by the NRC. For those facilities not using an NRC approved integrated scheduling system, a schedule will be established by the NRC staff within 60 days of receipt of the proposed schedule. Any change or error correction that results in a calculated ECCS performance that does not conform **to the analytical limits established in accordance with this section, as applicable**, is a reportable event as described in §§ 50.55(e), 50.72, and 50.73. The affected applicant or licensee shall propose immediate steps to demonstrate compliance or bring plant design or operation into compliance with § 50.46 requirements.

(3) For each change to or error discovered in an acceptable evaluation model or in the application of such a model that affects the temperature calculation, the applicant or holder of a standard design approval or the applicant for a standard design certification (including an applicant after the Commission has adopted a final design certification rule) shall report the nature of the change or error and its estimated effect on the limiting ECCS analysis to the Commission and to any applicant or licensee referencing the design approval or design certification at least annually as specified in § 52.3 of this chapter. If the change or error is significant, the applicant or holder of the design approval or the applicant for the design certification shall provide this report within 30 days and include with the report a proposed schedule for providing a reanalysis or taking other action as may be needed to show

NOTE: The availability of this draft rule language, as it exists in this document, is intended to inform stakeholders of the current status of the NRC's activities to revise the requirements for emergency core cooling systems to support an upcoming meeting with the Advisory Committee on Reactor Safeguards. The NRC staff is considering restructuring the current Section 50.46 regulation to distinguish ECCS performance requirements (i.e., criteria governing acceptable capability of ECCS to perform its cooling function during and after a design basis LOCA) from fuel/cladding performance requirements (i.e., criteria intended to ensure that the fuel and cladding do not result in prevention of successful cooling during and after a design basis LOCA, and any other effects with adverse impacts on the capability or other safety systems). Additionally, the NRC staff may add new paragraphs to address long standing issues and concerns with the current regulation. As such, this draft rule language may be incomplete or in error in one or more respects, and will be subject to further revisions during the rulemaking process. The NRC is not requesting formal public comments on this draft rule language. The NRC may post updated materials, including updated draft rule language, to this page. Interested stakeholders should periodically check this page for updates and added materials.

compliance with § 50.46 requirements. The affected applicant or holder shall propose immediate steps to demonstrate compliance or bring plant design into compliance with § 50.46 requirements.

(l) Authority to impose restrictions on operation. The Director of the Office of Nuclear Reactor Regulation (for licenses issued under 10 CFR 50) or the Director of the Office of New Reactors (for licenses issued under 10 CFR 52) may impose restrictions on reactor operation if it is found that the evaluations of ECCS cooling performance submitted are not consistent with the requirements of this section.

(m) Relationship to other NRC regulations. The requirements of this section are in addition to any other requirements applicable to ECCS set forth in this part. The analytical limits established in accordance with this section, with cooling performance calculated in accordance with an acceptable evaluation model, are in implementation of the general requirements with respect to ECCS cooling performance design set forth in this part, including in particular Criterion 35 of appendix A of this part.

(n) Implementation.

- (1) Construction permits issued under Part 50 after [EFFECTIVE DATE OF RULE] must comply with the requirements of this section.
- (2) Operating licenses issued under Part 50 which are based upon construction permits in effect as of [EFFECTIVE DATE OF RULE] (including deferred and reinstated construction permits) must comply with the requirements of § 50.46c by no later than the applicable data set forth in Table 1. Until such compliance is achieved, the requirements of this section continue to apply.
- (3) Operating licenses issued under Part 50 after [EFFECTIVE DATE OF RULE] must comply with the requirements of this section.
- (4) Operating licenses issued under Part 50 as of [EFFECTIVE DATE OF RULE] must comply with the requirements § 50.46c by no later than the applicable date set forth in Table 1. Until such compliance is achieved, the requirements of this section continue to apply.
- (5) Standard design certifications under part 52 of this chapter, whose applications (including applications for amendment) are pending as of or docketed after [EFFECTIVE DATE OF RULE], and new branches of these certifications whose applications are pending as of or docketed after [EFFECTIVE DATE OF RULE] must be amended to reflect compliance with this section no later than 36 months after [EFFECTIVE DATE OF RULE]. For purposes of this paragraph, a "branch" represents an alternative to the

NOTE: The availability of this draft rule language, as it exists in this document, is intended to inform stakeholders of the current status of the NRC's activities to revise the requirements for emergency core cooling systems to support an upcoming meeting with the Advisory Committee on Reactor Safeguards. The NRC staff is considering restructuring the current Section 50.46 regulation to distinguish ECCS performance requirements (i.e., criteria governing acceptable capability of ECCS to perform its cooling function during and after a design basis LOCA) from fuel/cladding performance requirements (i.e., criteria intended to ensure that the fuel and cladding do not result in prevention of successful cooling during and after a design basis LOCA, and any other effects with adverse impacts on the capability or other safety systems). Additionally, the NRC staff may add new paragraphs to address long standing issues and concerns with the current regulation. As such, this draft rule language may be incomplete or in error in one or more respects, and will be subject to further revisions during the rulemaking process. The NRC is not requesting formal public comments on this draft rule language. The NRC may post updated materials, including updated draft rule language, to this page. Interested stakeholders should periodically check this page for updates and added materials.

certified design as approved in the original design certification rulemaking. Such amendments are not subject to either the issue finality provisions under 10 CFR 52.103(g) or the backfitting requirements under 10 CFR 50.109.

- (6) Standard design certifications under part 52 of this chapter, or branches of standard design certifications in effect on [EFFECTIVE DATE OF RULE] but not referenced in an application for combined license or in a combined license, must be amended to reflect compliance with this section 36 months after the design certification rule is referenced in a combined license application or upon renewal, whichever is later. Such amendments are not subject to either the issue finality provisions under 10 CFR 52.103(g) or the backfitting requirements under 10 CFR 50.109.
- (7) Combined licenses under part 52 of this chapter must comply with this section no later than completion of the first refueling outage after initial fuel load. Until such compliance is achieved, the requirements in § 50.46 continue to apply.
- (8) Standard design approvals under part 52 of this chapter issued before [EFFECTIVE DATE OF RULE] must comply with this section before the design approval may be referenced in a construction permit, operating license, design certification, combined license or manufacturing license issued by the NRC.
- (9) Applications for standard design approvals under part 52 of this chapter issued after [EFFECTIVE DATE OF RULE] must comply with this section.
- (10) Applications for manufacturing licenses under part 52 of this chapter submitted after [EFFECTIVE DATE OF RULE] must comply with this section.

NOTE: The availability of this draft rule language, as it exists in this document, is intended to inform stakeholders of the current status of the NRC’s activities to revise the requirements for emergency core cooling systems to support an upcoming meeting with the Advisory Committee on Reactor Safeguards. The NRC staff is considering restructuring the current Section 50.46 regulation to distinguish ECCS performance requirements (i.e., criteria governing acceptable capability of ECCS to perform its cooling function during and after a design basis LOCA) from fuel/cladding performance requirements (i.e., criteria intended to ensure that the fuel and cladding do not result in prevention of successful cooling during and after a design basis LOCA, and any other effects with adverse impacts on the capability or other safety systems). Additionally, the NRC staff may add new paragraphs to address long standing issues and concerns with the current regulation. As such, this draft rule language may be incomplete or in error in one or more respects, and will be subject to further revisions during the rulemaking process. The NRC is not requesting formal public comments on this draft rule language. The NRC may post updated materials, including updated draft rule language, to this page. Interested stakeholders should periodically check this page for updates and added materials.

Table 1: Implementation dates for Nuclear Power Plants with operating licenses as of [EFFECTIVE DATE OF RULE] or operating licenses which are based upon construction permits in effect as of [EFFECTIVE DATE OF RULE] (including deferred and reinstated construction permits).

Calculated Local Oxidation (ECR ¹) Reported in UFSAR	Latest Date for Demonstrating Compliance
$ECR \geq 10.0$	No later than 36 months from effective date of rule
$10.0 > ECR > 5.0$	No later than 48 months from effective date of rule
$ECR \leq 5.0$	No later than 60 months from effective date of rule

¹ Equivalent cladding reacted

NOTE: The availability of this draft rule language, as it exists in this document, is intended to inform stakeholders of the current status of the NRC's activities to revise the requirements for emergency core cooling systems to support an upcoming meeting with the Advisory Committee on Reactor Safeguards. The NRC staff is considering restructuring the current Section 50.46 regulation to distinguish ECCS performance requirements (i.e., criteria governing acceptable capability of ECCS to perform its cooling function during and after a design basis LOCA) from fuel/cladding performance requirements (i.e., criteria intended to ensure that the fuel and cladding do not result in prevention of successful cooling during and after a design basis LOCA, and any other effects with adverse impacts on the capability or other safety systems). Additionally, the NRC staff may add new paragraphs to address long standing issues and concerns with the current regulation. As such, this draft rule language may be incomplete or in error in one or more respects, and will be subject to further revisions during the rulemaking process. The NRC is not requesting formal public comments on this draft rule language. The NRC may post updated materials, including updated draft rule language, to this page. Interested stakeholders should periodically check this page for updates and added materials.

In Appendix K to 10 CFR Part 50: (I)(B)

(B). Swelling and Rupture of the Cladding and Fuel Rod Thermal Parameters

Each evaluation model shall include a provision for predicting cladding swelling and rupture from consideration of the axial temperature distribution of the cladding and from the difference in pressure between the inside and outside of the cladding, both as functions of time. To be acceptable the swelling and rupture calculations shall be based on applicable data in such a way that the degree of swelling and incidence of rupture are not underestimated. The degree of swelling and rupture shall be taken into account in calculations of gap conductance, cladding oxidation and embrittlement, and hydrogen generation.

The calculations of fuel and cladding temperatures as a function of time shall use values for gap conductance and other thermal parameters as functions of temperature and other applicable time-dependent variables. The gap conductance shall be varied in accordance with changes in gap dimensions and any other applicable variables. The thermal effects of crud and oxide layers that accumulate on the fuel cladding during plant operation must be evaluated.

In Appendix K to 10 CFR Part 50: (II)(5)

5. General Standards for Acceptability—Elements of evaluation models reviewed will include technical adequacy of the calculation methods, including: For models covered by §50.46c(d)(4)(i) compliance with required features of section I of this Appendix K; and, for models covered by § 50.46c(d)(4), assurance of a high level of probability that the performance criteria of § 50.46c(b) would not be exceeded.