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NUCLEAR REGULATORY COMMISSION

Title: Advisory Committee on Reactor Safeguards
Materials, Metallurgy and Reactor Fuels
Subcommittee Meeting: Open Session

Docket Number: (n/a)

Location: Rockville, Maryland

Date: Tuesday, June 4, 2013

Work Order No.: NRC-4279 Pages 1-155

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1 UNITED STATES OF AMERICA

2 NUCLEAR REGULATORY COMMISSION

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4 ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

5 (ACRS)

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7 MATERIALS, METALLURGY, AND REACTOR FUELS SUBCOMMITTEE

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9 TUESDAY

10 JUNE 4, 2013

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12 ROCKVILLE, MARYLAND

13 + + + + +

14 The Subcommittee met at the Nuclear

15 Regulatory Commission, Two White Flint North,

16 Room T2B1, 11545 Rockville Pike, at 8:30 a.m., J. Sam

17 Armijo, Chairman, presiding.

18 COMMITTEE MEMBERS:

19 J. SAM ARMIJO, Chairman

20 DENNIS C. BLEY, Member

21 CHARLES H. BROWN, JR., Member

22 JOY REMPE, Member

23 STEPHEN P. SCHULTZ, Member

24 WILLIAM J. SHACK, Member

25 DESIGNATED FEDERAL OFFICIAL:

1 CHRIS BROWN, ACRS Staff

2

3 ALSO PRESENT:

4 K. AHLAWALIA, EPRI

5 MICHAEL BENSON, RES

6 MIKE CASE, RES

7 JAY COLLINS, NRR

8 ANNE DEMMA, EPRI

9 DARRELL DUNN, RES

10 STEVE FYFITCH, AREVA

11 MIRELA GAVRILAS, RES

12 JEFF GORMAN, DEI

13 ROBERT HARDIES, NRR

14 CRAIG HARRINGTON, EPRI

15 JOSH KUSNICK, RES

16 SHAH MALIK, RES

17 JACK RILEY, RES

18 DAVID RUDLAND, RES

19 KYLE SCHMITT, DEI

20 ROBERT TREGONING, RES

21 GLENN WHITE, DEI

22

23

24

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

2 (8:30 a.m.)

3 CHAIRMAN ARMIJO: Good morning. The
4 meeting will now come to order. This is a meeting of
5 the Materials, Metallurgy, and Reactor Fuels
6 Subcommittee.
7 I am Sam Armijo, Chairman of the
8 Subcommittee. Members in attendance are Dennis Bley,
9 Stephen Schultz, Bill Shack, Charles Brown, and Joy
10 Rempe.
11 Christopher Brown of the ACRS Staff is the
12 Designated Federal Official for this meeting.
13 The purpose of this briefing is for the
14 staff to discuss the crack initiation module of the
15 extremely low probability of rupture, xLPR, project.
16 We will hear presentations from
17 representatives from the Office of Nuclear Regulatory
18 Research and industry. The Subcommittee will gather
19 information, analyze relevant issues and facts, and
20 formulate a proposed position and action as appropriate
21 for deliberation by the full Committee.
22 The rules for participation in today's
23 meeting were announced as part of the notice of this
24 meeting, previously published in the Federal Register
25 on May 28, 2013.

1 The meeting will be open to the public
2 attendance with the exception of portions of it may be
3 closed to protect information that is proprietary
4 pursuant to 5 USC 552(b), Section C4.
5 We have received no written comments or
6 requests for time to make oral statements from members
7 of the public regarding today's meeting.
8 A transcript of the meeting is being kept
9 and will be made available as stated in the Federal
10 Register notice. Therefore, we request that the
11 participants in this meeting use the microphones located
12 throughout the meeting room when addressing the
13 Subcommittee. Participants should first identify
14 themselves and speak with sufficient clarity and volume
15 so that they can readily heard.
16 I'd like everyone to please check your
17 phones and silence them.
18 We will now proceed with the meeting, and
19 I call upon David Rudland of the Office of Nuclear
20 Reactor Regulation to make introductory remarks.
21 David?
22 MR. RUDLAND: Hi. Good morning, everyone.
23 My name is David --
24 CHAIRMAN ARMIJO: RES.
25 MR. RUDLAND: Yes.

1 CHAIRMAN ARMIJO: Well, my goodness. I
2 apologize.
3 MR. RUDLAND: My name is Dave Rudland, and
4 I'm a Senior Materials Engineer with the Office of
5 Nuclear Regulatory Research, Division of Engineering,
6 Component Integrity Branch. And I'm going to be talking
7 today about the stress corrosion cracking models that
8 are currently in the xLPR code.
9 The reason why we're meeting today is by
10 request from this Committee that when we made a briefing
11 on the overall structure of the xLPR code, one of the
12 items of interest to the Committee was crack initiation
13 and how we go ahead and model that as well as calibrate
14 those models. So we're going to spend some time talking
15 about that this morning.
16 There are going to be several of us that
17 want to make presentations, so I want to introduce them
18 before we get started. Again, my name is Dave Rudland.
19 I'm going to be talking a little bit about the Version
20 1 models that we had in xLPR.
21 Before that, Jeff Gorman and Glenn White
22 will be talking a little bit about background, some of
23 the initiation background mechanisms, modeling
24 difficulties, and the selections that we made in the
25 process of determining what models to use in xLPR. They

1 are from Dominion Engineering.

2 After that, Steve Fyfitch will be making

3 some presentations about an expert panel that we put

4 together. After our experiences in Version 1, we

5 decided we needed to take a little closer look at the

6 models, and so we convened an expert panel to question

7 them on what we did in Version 1 and get their

8 recommendations for Version 2.

9 And then, after that Kyle Schmitt, also from

10 Dominion Engineering, will be talking about what we did

11 in Version 2. And, finally, Darrell Dunn from the

12 Office of Research also will be talking about some

13 thoughts that we have about continuing or starting up

14 ongoing initiation testing patterns within the NRC.

15 And, again, the purpose of this meeting is

16 to go ahead and brief you on what we are doing in xLPR

17 in terms of crack initiation. As I mentioned, this was

18 by request from you guys. We also talked about weld

19 residual stress earlier this year, which was another

20 very important topic that the Committee wanted to be

21 briefed on.

22 And a reminder, the xLPR program is a

23 cooperative effort that is being conducted between the

24 Office of Research and EPRI through a memorandum of

25 understanding, and so we are doing that so that we can

1 gain benefit from both sides and doing it in a parallel
2 fashion, instead of in a serial fashion, as we develop
3 this type of technology.
4 And, again, the objective is just to have
5 an understanding of what we are doing in xLPR to
6 understand the models that we have chosen, why we chose
7 them, and how we are going to be using those models to
8 make predictions of probability of crack initiation.
9 CHAIRMAN ARMIJO: Dave, I'd just like to
10 make a couple of comments. When the Subcommittee and
11 the full Committee first reviewed xLPR, we were
12 impressed with the challenge that you took on to put
13 in a cracked nucleation module into the program.
14 And if I remember right, our letter said,
15 "If it turns out to be intractable or impossible, you
16 know, just go ahead, because the rest of the thing is
17 worth doing." I think it is a real challenge, but I've
18 been reading the background material that you have and
19 I am very impressed with where you are going.
20 MR. RUDLAND: Thank you.
21 CHAIRMAN ARMIJO: So I think not everyone
22 here is a materials person, so it wouldn't hurt to just
23 explain a little -- some terms that you may use that
24 are not common knowledge, stacking fault energies, and
25 things like that --

1 MR. RUDLAND: Okay.

2 CHAIRMAN ARMIJO: -- if you come across it.

3 MR. RUDLAND: Okay. So as Glenn is making

4 the presentation on background, if there are some things

5 that we think may be a little bit confusing, please stop

6 them. He'll do a great job in explaining those kinds

7 of things.

8 And what we'd like out of this is, of course,

9 your review and advice on where we're going and what

10 we're doing.

11 Just a point that Sam made, you know, we

12 are striving to have a very good set of options in xLPR

13 for crack initiation, but we realize the difficulty of

14 the problem, and so of course within xLPR we are also

15 developing the code such that it can be run without these

16 models, so they can be run conditional on crack

17 initiation.

18 So you can still get the benefit of what

19 you are looking for in terms of risk of piping rupture,

20 but it would all be conditioned on crack initiation if

21 we can't get to an agreement on what is the best thing

22 to use from a regulatory standpoint.

23 MEMBER SHACK: Somehow with all of your

24 calibration studies I was never clear how you were going

25 to be able to sort out the effects of residual stress

1 versus initiation.

2 MR. RUDLAND: Yeah.

3 MEMBER SHACK: They seem so closely

4 coupled.

5 MR. RUDLAND: Yeah, they are. They are.

6 And, again, you know, we look at studies that have been

7 done on how the surface stress affects initiation, and

8 we try to calibrate to that way. I mean, there is -- as

9 Glenn will point out, there are several models there

10 that take into account stress. And, you know, the

11 typical models relate to time to stress to the fourth

12 power. And he looked at that kind of information.

13 And the reason why -- how we try to take

14 advantage of that is try to be as flexible as possible

15 in the models that we have, so that sensitivity studies

16 could be done. Again, the data that we have is limited

17 to calibrate to. Operational data is limited. So we've

18 got to try to use all of that data and be --

19 MEMBER SHACK: Well, I was thinking more

20 in the sense of as you try to balance whether you are

21 getting leaks and cracks of the right depth.

22 MR. RUDLAND: Right.

23 MEMBER SHACK: Those are as much controlled

24 by the residual stress patterns that you --

25 MR. RUDLAND: That's right.

1 MEMBER SHACK: -- pick as they are by the
2 initiation models.
3 MR. RUDLAND: Sure. Sure.
4 MEMBER SHACK: And so when you don't match,
5 it's not clear which dial you tweak.
6 MR. RUDLAND: Yeah. That's right.
7 That's right. Yeah. And all we can do is try to
8 validate to whatever operating experience that we have.
9 You know, and so a lot of these models, at least for
10 initiation, a lot of these models are calibrated to the
11 operating experience. So you are going to get what
12 happened, right, out of it.
13 So here is the -- on this slide is the
14 presentations that we will be making. I already went
15 through who is going to make them, so I'm not going to
16 spend any more time on that.
17 Okay. All right. So now Glenn is going
18 to be talking about the background initiation.
19 Glenn, would you like me to run it? Or
20 would you like to sit here and control the presentation?
21 MR. WHITE: Why don't I sit there.
22 MR. RUDLAND: Okay.
23 MR. WHITE: Very good. Thanks, Dave.
24 Just as a preface here, I'd like to, you know, really
25 say what a good experience I think this project has been.

1 I've been working on materials issues since I came out
2 of school in 1993, so it will be 20 years this summer.
3
4 And so I've seen how things have developed
5 over the last 20 years in this area, and this has I think
6 been a great technical exchange and effort within the
7 xLPR framework between the industry and NRC.
8 So I'm going to cover these slides that were
9 prepared by Jeff Gorman and myself, and we wanted to
10 kickoff the day by just going over briefly the history
11 of PWSCC and the PWRs, the understanding of the
12 mechanisms, the state of the art research, and then what
13 models are available for modeling initiation and why
14 xLPR is focused on the three different models. And
15 we'll hear later about those particular models.
16 So let's just wrap up or summarize here the
17 history starting with 1959 and the French research by
18 Coriou, who identified Alloy 600 as being susceptible
19 to pure water stress corrosion cracking. So a steady
20 load stress -- steady stress on Alloy 600 material in
21 pure water reported that in fact it was susceptible to
22 cracking.
23 That viewpoint was not accepted in the U.S.
24 at that point. It was believed that there must have
25 been contamination of the stress resulting in the

1 cracking. But there was a realization that began to
2 develop that in fact pure water could be -- cause
3 cracking and, for example, the Germans in the late '60s
4 moved to Alloy 800 based on that concern.
5 Then, of course, we had the second
6 generation -- first and second generations of commercial
7 PWRs in the U.S., and then began to see cracking started
8 to occur in the secondary site of steam generators with
9 a more aggressive environment. But then, in the late
10 1970s, we started with the primary water stress
11 corrosion cracking experience in steam generators with
12 the all volatile treatment water chemistry.
13 Then, about 1980, the picture was that PWSCC
14 is aggravated by high stresses, cold water, high
15 temperature, and microstructural conditions. So that
16 basic picture was known by then. But then we also knew
17 that PWSCC and caustic SCC both decreased by thermal
18 treatment and precipitation of carbides and grain
19 boundaries. So grain boundary decoration was
20 recognized as a significant material factor.
21 And then, so that was the impetus for
22 additional research in the '80s and '90s based on the
23 additional operating experience with cracking, of
24 course, the IGSCC and stainless steels, but also
25 Alloy 600 cracking in the BWRs, and the 182 welds in

1 the BWR piping, then, additional experience in the PWR
2 steam generators.
3 And then, starting with '82, we started to
4 see PWSCC of the thicker wall materials starting at the
5 pressurizer temperatures. And then, by about 2000, the
6 mechanism of PWSCC was not firmly identified, but the
7 general trends were well identified in terms of stress,
8 thermal treatment, and microstructure, and so on. So
9 the basic trends were understood, but the fundamental
10 physics were not identified in detail.
11 And then, the movement since about 2000 has
12 been towards more fundamental research at national labs
13 and at universities in the U.S., Europe, and in Asia.
14 And that work has concentrated in the role of oxides
15 forming on the surface and penetrating grain boundaries.
16 It has concentrated on the role of complex drain
17 history, and the influence of hydrogen. So there has
18 been detailed work there.
19 But the basic picture here again is shown
20 here in these bullets, that the general qualitative
21 trends are -- there is good consensus that these are
22 the qualitative trends that apply to cracking.
23 This timeline here illustrates the
24 experience of PWSCC starting with the Coriou report in
25 1959 at the left end there. And then the first group

1 here, what we see here is the progression of PWSCC and
2 SCC from more susceptible locations towards less
3 susceptible locations.
4 So initially -- and the pattern really fits
5 what you -- in retrospect, what you might expect based
6 on those trends on the previous slide. So it started
7 with the more aggressive environments in the secondary
8 side of steam generators -- that's not PWSCC --but in
9 the early 1970s. And then, again, that first PWSCC
10 experience in 1977 in steam generators.
11 Then, we moved to the pressurizer
12 temperatures for the ANO 2 heater sleeve, and the -- but
13 that case was kind of a special case because the swelling
14 caused high stresses. So especially high loading there
15 due to the swelling that occurred in the heater sleeve.
16 And so that was kind of an anomalous condition, which
17 led to early -- relatively early cracking.
18 And then, by 1986 we had the first report
19 of a j-groove nozzle weld PWSCC at one plant, and a
20 pressurizer instrumentation nozzle. And at that point,
21 then we reached 1991, now the cracking has progressed
22 towards the hot leg temperature.
23 So first reported in France, and the French
24 material was found to cause cracking somewhat more
25 aggressively than in the U.S., and we think we understand

1 the basic material differences between the French plants
2 had a lower temperature forging material, and so the
3 microstructure tended to be, on average, I think a poor
4 microstructure from a PWSCC perspective. Also, the
5 French nozzles had --
6 CHAIRMAN ARMIJO: Glenn?
7 MR. WHITE: Yes.
8 CHAIRMAN ARMIJO: What did you mean by
9 "poor microstructure"?
10 MR. WHITE: Poor carbide decoration.
11 CHAIRMAN ARMIJO: Less.
12 MR. WHITE: Yeah.
13 CHAIRMAN ARMIJO: Okay.
14 MR. WHITE: Less carbide decoration.
15 CHAIRMAN ARMIJO: Grain size is about the
16 same? Other mechanical property --
17 MR. WHITE: I can't -- I don't remember.
18 MR. FYFITCH: Not necessarily.
19 CHAIRMAN ARMIJO: Not necessarily?
20 MEMBER SHACK: I mean, they weren't aiming
21 to decorate the grain boundaries with carbides and these
22 components.
23 MR. GORMAN: No, no. At the time those
24 were built, that wasn't --
25 MEMBER SHACK: Yeah. I mean, that

1 wasn't -- so that's just sort of an accident --

2 MR. GORMAN: An accidental result.

3 MR. WHITE: What we do know is the forging

4 material is different than the extruded and bar stock

5 materials in the U.S. So different class of materials.

6 The other big difference is they

7 have -- typically have a counter bore on the inside of

8 the nozzle, too, whereas in the USPWRs that is -- I think

9 only two units have that -- had that configuration.

10 And that leads to stress concentration at that corner

11 of the counter bore.

12 So the French CRDM nozzle crack started to

13 be reported in the early '90s, and then we had a

14 circumferential crack in the Alloy 600 safe end at the

15 one CE plant. So that was an unusual case in that there

16 are relatively few Alloy 600 safe ends used on the

17 piping, but that was a series of six discrete throughwall

18 flaws that were linked up to cause leakage. The

19 cracking was almost exclusively in the safe end itself,

20 again, but at pressurizer temperature.

21 Now, when we reach 2000, we have had the

22 V.C. Summer experience with the throughwall cracking

23 in the reactor vessel outlet nozzle, and then also

24 reports of leakage and circumferential cracking in CRDM

25 nozzles. And so the cracking was extended to hot leg

1 temperature at that point in the U.S.

2 Then, we have the Davis-Besse case, of

3 course, again, with the wastage following the cracking,

4 and also the case of five circumferential indications

5 at one plant that were presumed to be PWSCC in the absence

6 of destructive examinations, and that led to work in

7 the 2006/2007 timeframe to look at the effect of the

8 concern of circumferential cracking that possibly could

9 lead to a rupture concern.

10 And so there was an effort in EPRI and in

11 the industry to evaluate that through a natural flaw

12 growth type approach using finite element fracture

13 mechanics calculations. And what came out of -- a big

14 conclusion of that work was that weld residual stress,

15 as Bill has already said, is paramount kind of to

16 the -- it's the number one factor that can drive

17 cracking, including the length of the flaws, as they

18 begin to become of engineering significance.

19 So then a validation program not shown here

20 that industry and the NRC had a memorandum of

21 understanding and worked on validation for weld residual

22 stress, and then the xLPR program has been using that

23 work and is intended, first, to look at the butt welds

24 but to address these concerns on a probabilistic basis.

25 Then, towards the right end here we have

1 starting in 2007 we have seen PWSCC flaws at cold leg
2 temperatures. Well, first, back in 2003, at the
3 bottom-mounted nozzle, at one plant we had two leaking
4 nozzles. They were -- at least one of them was linked
5 to weld defects, a lack of fusion-type defect, possibly
6 with inclusions that contribute to a chemical
7 environment there.
8 And then, in 2007, one PWR top head had
9 indications of PWSCC, again, linked to a subsurface weld
10 defect that appeared to have been wetted at some point
11 and then promoted cracking. So began to see in the 2000s
12 PWSCC at cold leg temperatures, but typically was linked
13 to the presence of relatively large and sharp
14 fabrication weld defects.
15 But, and then as we've gotten to more recent
16 times, the last few years we began to see some
17 indications and top heads that were not linked to weld
18 defects. They appeared to be exclusively in the base
19 metal on the OD but below the toe of the weld. And so
20 what we are seeing again is things spreading out from
21 more aggressive conditions to less aggressive
22 conditions.
23 So not necessarily the highest stresses,
24 not necessarily the highest temperatures, not
25 necessarily weld defects, so things have been spreading

1 towards more mundane conditions is what we're seeing.
2 But overall, as we'll talk about, you know,
3 the industry experience in terms of the piping butt
4 welds, the frequency of cracking has been reasonably
5 low as we will see later.
6 So as we said, things are slowly spreading
7 to lower temperatures, less aggressive conditions, and
8 inspection programs are successfully identifying flaws
9 at relatively early stages. I gave a presentation at
10 the EPRI conference last year on the top head experience,
11 and since the -- after the first inspection of a complete
12 100 percent exam of the top heads, we have not seen any
13 leaking or significant circumferential flaws.
14 So the repeat -- once you are into a program
15 of repeat inspections, for the top heads, for example,
16 they have been quite successful in catching the cracking
17 before leaks or circumferential cracks are produced.
18 CHAIRMAN ARMIJO: The comment -- the
19 locations are slowly spreading to lower temperatures,
20 lower stresses, do you attribute that just simply to
21 time?
22 MR. WHITE: Yes. Yes. So it's really
23 more a question of when than if, you know, so we have
24 these various factors and there can be a range of two
25 orders of magnitude in time to cracking. We have seen

one year in the most aggressive steam generator conditions, albeit on the secondary side cracking, the primary --

MR. GORMAN: You're talking the dual, too. Many --

MR. WHITE: Okay.

MR. GORMAN: -- sleeves that was three to four months after installation that they went throughwall. Yeah. That was primary side cracking.

MR. WHITE: Okay. So the most aggressive loading conditions can lead to very fast -- relatively fast cracking. Then, when you come back to cold leg temperatures and stresses, perhaps below yield, and depending on the surface condition, you know, then the times can be beyond the plant lifetimes. So you have a continuum between the two conditions.

CHAIRMAN ARMIJO: So is that -- the regime we're in now is one where it is dominated by crack initiation as a controlling -- as opposed to in the early failures, early life failures, might be crack growth? Easy to initiate but quick --

MR. WHITE: I think both. I think we're seeing both -- both issues. So when flaws initiate at cold leg temperature, they may be, you know, below -- however you define initiation. They may be

1 below detectability limits, and so by the time they will
2 be -- you can see them in a UT exam, they have to grow
3 some, and then they take significant time at cold leg
4 temperature.
5 CHAIRMAN ARMIJO: The reason I'm bringing
6 this up is in the BWR work that I was involved in, and
7 certainly Bill was involved in, the early failures were
8 partly due to easy initiation of cracking. We had
9 bypass, you know, four-inch diameter lines cracking,
10 and of course spray lines and 11-inch diameter lines
11 cracking, and one common feature in all of those things
12 was they were -- these were not furnished sensitized.
13 They were just plain old butt-welded pipes.
14 There was a fabrication technique that was
15 used extensively, and that was post-weld grinding of
16 the ID surface, maybe in a high residual stress on the
17 ID. And later we found out that we built a pipe test
18 laboratory at GE, and we found out that the best way
19 to initiate cracks quickly was to post-weld grind our
20 test samples.
21 And I'm just wondering if similar
22 fabrication practices were employed in the PWRs with
23 these nickel base alloys. And is there a prohibition
24 or advice to not do that anymore?
25 MR. GORMAN: Oh, let's see. Whether the

1 advice is getting to the people who actually do the work,
2 I don't know. But in the research community for the
3 last 10 years the drum beat is surface abuse you've got
4 to avoid.
5 I mean, careful -- and we struggled with,
6 how do you get that message so that it becomes
7 institutionalized to the people who are actually making
8 the weld. That's a tough, tough --
9 CHAIRMAN ARMIJO: The problem I had is in
10 the BWR material is that people like to pass their X-ray
11 inspection technique, and to avoid these corner edges
12 and things like that in the weld.
13 MR. GORMAN: Yeah. The undercuts and
14 stuff like that.
15 CHAIRMAN ARMIJO: The nice thing is to make
16 a nice, smooth ground surface and everything looks great
17 on X-ray. But you just leave a crack initiation
18 favorable situation. And, you're right, people don't
19 necessarily listen.
20 MR. GORMAN: Well, I think the locations
21 where these cold leg cracks have been occurring are not
22 susceptible to that kind of grinding, right? Like in
23 the drain nozzles on steam generator heads and the -- and
24 on the CRDMs.
25 MR. WHITE: Well, to the extent we have seen

lack of fusion kind of defects as a cause, then maybe the grinding wasn't --

MR. RUDLAND: I think they do work the CRDM welds.

MR. GORMAN: Yeah. They do polish them afterwards, yeah.

MR. FYFITCH: This is Steve Fyfitch. I know for the BNW units, the CRDM nozzles, the OD was a ground surface.

CHAIRMAN ARMIJO: Okay.

MR. FYFITCH: And that's where the cracking initiated in most of our units.

CHAIRMAN ARMIJO: It's a nice initiator. Yeah.

MEMBER BLEY: What is it -- I mean, traditionally, we thought making things smooth, and the like, is good for a lot of reasons. But it leaves -- it is cold work phenomena. Is that what we're talking about?

CHAIRMAN ARMIJO: Grinding -- you know, they use these grinding discs, you know, and literally it takes the metal up to very high temperature. You don't know. You may even have melted surface. But whatever it does, it leaves a very high residual tensile stress on the surface.

1 MEMBER BLEY: Right on the surface.

2 MR. RUDLAND: It is really

3 process-oriented, right, because, I mean, if they do

4 the grinding properly, it won't leave the high residual

5 stress. You've got to be using high-speed and pushing

6 hard, you know, to get enough heat there to do that.

7 CHAIRMAN ARMIJO: Well, that's a debate.

8 But, you know, you can polish it away, and they are -- I

9 think there is commercial offerings now of techniques

10 for very fine polishing to remove all of that. I wish

11 more people did that and less grinding or just leave

12 it alone.

13 MR. GORMAN: It not only increases the

14 residual stress, but also the hardness. I mean, like

15 hardness, Vickers will go from 180 to 350, for example,

16 within the last few microns on the surface, so -- which

17 increases susceptibility to crack initiation and crack

18 growth. So --

19 MEMBER BLEY: Could you -- this slowly

20 spreading idea, it is a time in service I guess, but

21 are you -- what kind of -- what is the lowest temperatures

22 where we are actually seeing this happen? Do you know?

23 MR. GORMAN: The lowest surface

24 temperature that I know of where we have had cracking,

25 but not on the OD, not of the type you are talking about

in steam generator tubes, is Conn Yankee cold leg. They had these skip rolls, and very high stress at the bottom, and those cracked quite widely, and that's 535 hot leg temperature, if I remember correctly. Do you know?

MR. WHITE: That's about right.

MR. GORMAN: That's about right, yeah.

MEMBER BLEY: Is there anything about this slowly spreading idea that as time in service extends that it is ramping up? I mean, you know, when we do extensions for licenses, what kind of trouble are we maybe getting into?

MR. WHITE: Well, as we will see, when you look at, for example, the piping butt welds, the Alloy 82/182 piping butt welds in PWRs, we see a slope that is -- a Weibull slope that is low. And so there is many factors at play here, the grinding, weld defects, fabrication factors, the material -- the welding practices. And because of all of those factors, it tends to spread out the time to cracking.

MEMBER BLEY: Do we have enough evidence to know if it's linear in time, or if it's maybe going faster than that?

MR. WHITE: Yeah. The evidence is that it is more linear, exponential kind of function.

MEMBER SHACK: Why did we try to fit things

1 to a Poisson rate in the calibration studies?

2 MR. RUDLAND: Why did we?

3 MEMBER SHACK: Yeah. I mean, somehow that

4 seems to me contradictory to all -- everything that we

5 have heard here.

6 MR. RUDLAND: But we only did that in the

7 first -- do you mean within xLPR? We only did that in

8 the first version of the code. We are not doing it in

9 the second version. You know, we were still

10 understanding --

11 MEMBER SHACK: That seemed like a good idea

12 at --

13 (Laughter.)

14 MR. RUDLAND: Yeah, that's right. And

15 I'll talk a little bit about that in B1, but we did that

16 just in the initial -- in the initial studies.

17 MR. WHITE: As a placeholder.

18 MR. RUDLAND: As a placeholder, right.

19 MEMBER SHACK: Are the inspections now

20 growing in scope? I mean, you know, if you can't just

21 look at welds anymore, where do you stop inspecting at

22 this point? You know, once it's in the base metal, do

23 you -- are you inspecting all of the Alloy 600?

24 MR. WHITE: So there are -- every plant is

25 required to have a, you know, comprehensive Alloy 600

program to look at all locations, and then we have the various regulatory requirements. So, yeah, the majority of locations are -- have either been replaced, you know, with the --

MEMBER SHACK: I am thinking more like these cold head situations now. You know, where do you expand the inspection to once you have decided that even the base metal is susceptible?

MR. WHITE: Well, those are 100 percent exams that are done --

MEMBER SHACK: Full circuits --

MR. WHITE: -- of the base metal.

MR. RUDLAND: Now, there's a range, right, that was dictated by the stress level, which they have to inspect.

MR. GORMAN: It's all associated with the weld metal -- weldment, but it goes beyond the edges of the weld.

MR. RUDLAND: It goes to ranges of about 20 ksi.

MEMBER SHACK: Oh, okay.

MR. RUDLAND: The stresses drop off to about 20 ksi.

MEMBER SHACK: So there's a stress limit on the thing. Okay.

1 MR. RUDLAND: Yeah.

2 MEMBER SHACK: Gotcha.

3 MR. WHITE: But, again, there isn't -- for
4 the weld metal itself, the approach is to look at
5 the -- if there is leakage and a leak path exam, to look
6 at a second exam to see if there is throughwall cracking
7 in the base metal and the weld metal.

8 A part-depth flaw in the weld metal is not
9 a direct safety concern, because it can't lead to nozzle
10 ejection directly. And if there were to be a leak that
11 was in a crack that was exclusively in the weld metal,
12 you would expect a rather small leak rate, which would
13 not lead to significant wastage.

14 And the experience is, again, when the flaws
15 are in the weld metal, if they become large they will
16 grow into the base metal and then be inspectable. So
17 that has been the approach.

18 MEMBER SCHULTZ: So is that what you would
19 attribute the success of the inspection program as it
20 grows, is it experience or scope or equipment
21 capability? What would you -- how would you rank order
22 the success factors of the inspection program?

23 MR. WHITE: That they are sufficient to
24 catch the cracking relatively early stage. So they are
25 aggressive in that, for example, in the top heads there

1 are 100 percent exams, meaning every nozzle is
2 inspected.
3 Bare metal visual exams that are performed,
4 you know, directly of the inner -- of the annuluses from
5 the top of the head are very sensitive. And, again,
6 they have not been finding leakage since the time
7 we -- during a periodic program of inspections, which
8 tells me the intervals, you know, were set appropriately
9 to catch the cracking at a relatively early stage.
10 MR. RUDLAND: And I think the inspection
11 programs have matured. As this cracking has occurred,
12 the inspection programs are maturing. And I think they
13 are still evolving also. I think it -- so they are
14 getting better at catching these things, but they are
15 still learning the capabilities of their technology.
16 MEMBER SCHULTZ: Thank you.
17 MR. WHITE: The materials reliability
18 program has a commitment to itself to continually look
19 at inspection results as they come in and continually
20 evaluate them versus the requirements in our technical
21 bases documents to ensure that we continue to be bounded
22 by our safety analyses.
23 MEMBER SCHULTZ: Thank you. Appreciate
24 it.
25 CHAIRMAN ARMIJO: All right.

1 MR. WHITE: Okay. So the development of
2 the understanding of the mechanism -- again, there was
3 initial skepticism about pure water, stress corrosion
4 cracking, and Alloy 600. But by 1970 it was concluded
5 that it could occur in the deoxygenated low potential
6 environment, and then a great deal of research in 1970
7 to 2000, which we have already touched on.
8 A note here that Roger Staehle introduced
9 the concept of the low potential stress corrosion
10 cracking in the mid-1990s, and his point was that we
11 shouldn't name mechanisms after a plant system, the
12 primary system. We should be naming it after the mode
13 of the mechanism. And he identifies -- looking at a
14 Porbay diagram of pH and electrochemical potential, he
15 identifies low potential stress corrosion cracking as
16 a mechanism distinct from the higher potential cracking
17 that can be seen in the oxidizing BWR environment.
18 So that is note there on that terminology
19 of low potential stress corrosion cracking. But as
20 we'll see, there still is no consensus on the mechanism.
21 But, again, the picture is largely the same as in the
22 previous slide in terms of the empirical understanding
23 of the effects. We have added a couple additional
24 bullets here in terms of stresses above about .8 times
25 the yield stress are required for PWSCC to occur.

1 So experimental data that shows in
2 practical kind of timeframes that are relevant to plants
3 this threshold of about .8 times the yield stress roughly
4 is practical limit.
5 Also, we have the effect -- more recently
6 the effect of electrochemical potential was discerned
7 in terms of the hydrogen concentration, so changing the
8 hydrogen concentration changes the electrochemical
9 potential, and there is a -- at a particular temperature
10 there is a hydrogen concentration in the water that puts
11 you at the nickel/nickel oxide phase transition.
12 And work by the national labs starting with
13 them, and then confirmed by others, showed that at this
14 transition point the crack growth rate tends to be a
15 maximum for these materials. So, again, these are
16 good -- very good consensus on these general trends are
17 now accepted.
18 So more recent work, as we have said, has
19 looked at oxide penetrations along grain boundaries,
20 slip lines. It has been realized that cracks can be
21 extremely tight, and that means you really don't have
22 a normal aqueous kind of water chemistry in the crack.
23 The properties of water are -- can be radically
24 different in a very tight crack. And so you have your
25 own type of chemistry processes that occur, and that

1 has been better understood in recent years.

2 Strain localization effects, the role of

3 complex strain path has been realized to be an important

4 factor, along with the effect of the surface condition

5 of the material. And so there are some ideas there in

6 terms of basic mechanisms.

7 So the terminology, internal oxidation, is

8 one way of -- one potential mechanism that oxidation

9 occurs along the grain boundaries, penetrates the

10 materials, and then leads to the grain boundaries

11 becoming susceptible to attack and to cracking.

12 But it also realizes that it appears the

13 role -- that there is a significant role of hydrogen,

14 both from the water itself, the dissolved hydrogen from

15 the hydrogen overpressure on the system, but also it

16 is realized that hydrogen can be produced through the

17 corrosion process. Electrons are produced at the

18 surface of the metal, and the water in those electrons

19 can produce hydrogen gas if they combine with the

20 hydrogen ions.

21 And we see right at fracture boundaries,

22 we see elevated levels of hydrogen. So there is a

23 thought that -- and we know about hydrogen embrittlement

24 being a concern in some materials, of course. So

25 putting these together, it is believed that hydrogen

1 may play a significant role.

2 So there is a couple of camps here about

3 oxidation versus hydrogen, and there is no ultimate

4 consensus among the whole community about the relative

5 importance of each. And then, the idea here of the

6 dialectrode constrictive stresses at the grain

7 boundaries also is a potential mechanism that can be

8 important.

9 So our conclusion here is given there is

10 no well understood, quantified mechanism for the entire

11 process, that pushes us more towards empirical,

12 semi-empirical approaches where we use plant data as

13 best we can to make predictions with adjustments to the

14 plant data based on laboratory research, for example,

15 the effective temperature and then strengths.

16 So I just have a few slides here to give

17 a flavor of that work that is going on in the last 10

18 years or so in the national labs and universities in

19 the U.S. and overseas.

20 And, first, with regard to the oxide

21 development at surfaces, grain boundaries, and in

22 cracks, the next slide here -- don't intend to go through

23 this slide, but we want to just -- this is a list of

24 the types of work that is going on in the research

25 community, so either advanced analytical equipment,

1 like transition electron microscopes looking at the very
2 detailed composition and cracked tips looking at the
3 different species and the role of inclusions and
4 particles, and so on, what is the composition of that
5 oxide inside the crack, and so on, various different
6 advanced tools, some simulation techniques using
7 atomistic modeling, and so on. So there is a whole list
8 here of advanced techniques and equipment in the leading
9 edge of material science that is looking at these issues.
10 MEMBER REMPE: So these are irradiated
11 materials that are like --
12 MR. GORMAN: In a few cases, there are
13 irradiated materials, but 99 percent of the cases, no.
14 No. This gets -- so these are on test materials that
15 have been in autoclave and tested.
16 MEMBER REMPE: Well, do you see much
17 difference in irradiated materials versus
18 non-irradiated?
19 MR. GORMAN: Let's see. I'll quote Peter
20 Andresen on this, that if it's hardened to the same level
21 it behaves pretty much the same, regardless of the way
22 it was hardened.
23 MEMBER REMPE: Okay.
24 MR. FYFITCH: Steve Fyfitch. Again, the
25 general answer to that, though, is Alloy 600 is typically

1 not used in highly irradiated areas --

2 MEMBER REMPE: Okay.

3 MR. FYFITCH: -- of plants.

4 MR. GORMAN: Yeah. Only in -- yeah, that's

5 right. Not even in where it's close -- it's on like

6 vessel supports. That is still pretty low radiation

7 level area, right.

8 MR. FYFITCH: There are only a couple of

9 instances, in the internals, for instance, where there

10 is Alloy 600.

11 MR. WHITE: So that is with regard -- that

12 slide, again, passage rates on oxide development, but

13 then we have investigations of the role of dislocations

14 at surfaces and grain boundaries, so there are material

15 science techniques that look at that area, including

16 atomistic modeling.

17 We have studies of the effects of stress,

18 strain, temperature, and cooling hydrogen

19 concentration, using tensile specimens instrumented

20 with potential drop measuring equipment, which is a

21 very -- can be a very sensitive technique that is being

22 developed to look at initiation.

23 We have short radiotracer studies that can

24 be used to look at how the hydrogen and oxygen has been

25 transported in the oxides. And, again, detailed

1 studies at this location of slip point interactions
2 using analytical micromechanical test methods.
3 So this is a list of the research that is
4 actively proceeding, and, you know, we have -- as an
5 industry, we follow that closely. Of course, EPRI has,
6 you know, corrosion research programs to follow this,
7 but we have to, you know, make practical predictions
8 with something like xLPR. And I'll talk about the
9 approaches that are practical to do that.
10 So what we have here are five modeling
11 approaches starting with what's termed the QMN approach,
12 which stands for quantitative micro nano. And so that
13 is the most rigorous kind of approach, the most detailed,
14 and it is a work in progress, but the approach there
15 is to try to model each stage of the stress corrosion
16 cracking process in as much detail as feasible based
17 on state-of-the-art knowledge and research of modeling.
18 And so that is -- you know, that is the future.
19 In 5.2, this is an effort spearheaded by
20 Mack Hall retired from Bettis, and he looked at a couple
21 ways of predicting initiation. And then we will get
22 to the last three methods become more practical methods
23 for practical life predictions like xLPR.
24 And we will start with the cold work SCC
25 model that Yogen Garud has designed and implemented for

1 EPRI, and then we will talk about a material index
2 approach, which has traditionally been used in France
3 by AREVA and others, and then we will talk about a
4 statistical approach using plant data.
5 And as you will see when Kyle Schmitt talks
6 about the models in Version 2 of xLPR, all three of these
7 approaches are implemented and were implemented in the
8 pilot study also.
9 And there really -- you know, the key thing
10 is in the detail, so these methods do have differences.
11 But depending on what data you use to set the inputs
12 for them, how you calibrate each model is really the
13 crux of how each model works.
14 If you use the same set of data to calibrate
15 the different models, we expect similar results. And
16 that is one of the things we are going to be, you know,
17 looking at now that we are -- we have code that is being
18 produced.
19 As we move forward in xLPR, we will be doing
20 calculations to compare these different models, see how
21 the results come out, how they do the predictions, and
22 then -- but, really, the key is the inputs, the data
23 set, either laboratory or plant data, or a combination
24 that you're using to set the inputs to these models.
25 But there are some differences.

1 CHAIRMAN ARMIJO: Glenn, the only approach
2 there that really takes into account the variability
3 of the environment, the chemistry, is the statistical
4 approach using plant data. You've got all of these
5 variables. How would you -- let's say whether it's a
6 material index approach or the cold work SCC approach,
7 how would you adjust your model to say, well, this is
8 for a particular type of water, but if you add a certain
9 amount of this or that, things get better or worse?
10 MR. WHITE: So, you know, fortunately, most
11 of our cases we have, you know, good refresh primary
12 water, which is a very controlled environment.
13 CHAIRMAN ARMIJO: Okay.
14 MR. WHITE: So there has also been some good
15 extensive laboratory testing looking at the effect of
16 pH and dissolved hydrogen.
17 CHAIRMAN ARMIJO: Okay.
18 MR. WHITE: So there are some effects
19 there, but they are relatively narrow effects compared
20 to the other things like stress, temperature, so --
21 CHAIRMAN ARMIJO: Okay.
22 MR. WHITE: -- in general, we don't need
23 to make corrections for the water chemistry. The
24 exceptions to that are if there are intrusions
25 of -- resin intrusions, for example, as seen in one plant

in Spain, which led to CRDM nozzle cracking. So that is -- plants have looked at that concern.

CHAIRMAN ARMIJO: I have seen some information notices where some cracking was attributed to oxygenated water that is retained during a startup or something like that, that it's a transient but --

MR. WHITE: There are locations in the plant where coming from an outage the oxygen may be retained for some time. So you have the welds and the canopy seal welds and the housing welds up in the top of the CRDM housing. And that is -- there has been some cracking seen there in the stainless steel material, and I think that is attributed to oxygen.

MR. GORMAN: And residual contaminants, sulphur and chloride, but oxygen primarily. Yes.

MR. WHITE: That's a difficult place to deoxygenate. It's right at the top of the system, and you are venting from lower than that point.

MR. GORMAN: Right.

MR. WHITE: So there are special locations that, yes, we have to be concerned of ox growths.

MEMBER BLEY: So is that outside of the code, the special areas? That's not something you are going to build into the code I guess. You know, if there are areas where you can get contaminants, or you can

1 get some complex chemistry because of that in small
2 areas, you are not trying to model that, or are you,
3 in this program?
4 MR. WHITE: Well, we are aware of that
5 experience.
6 MR. GORMAN: I don't think it's applicable
7 to the kind of locations that you are doing your xLPR
8 modeling. I mean, these are in -- KIPC is up in the
9 CRDMs, and the pressurizer heater sleeves, and sort of
10 special locations.
11 MEMBER BLEY: But you need -- some program
12 needs to keep a good eye on --
13 MR. GORMAN: Yeah.
14 MEMBER BLEY: -- but xLPR is not looking
15 at it. That's what I thought. Okay.
16 CHAIRMAN ARMIJO: But you -- with a
17 statistical approach, it's built in, that -- chemistry
18 variables.
19 MEMBER SHACK: It depends on which data you
20 put into the statistical approach.
21 CHAIRMAN ARMIJO: Well, assuming you put
22 in all the stuff.
23 MEMBER SHACK: And that's fairly unique
24 data.
25 CHAIRMAN ARMIJO: Okay. Thank you.

1 MR. WHITE: All right. So just a few
2 slides here on the QMN approach. So, again, as I said,
3 it develops models for each step in the process, and
4 the process looks like -- this is a figure here by Roger
5 Staehle from the first QMN conference in 2010.
6 But, you know, this is the nice way of
7 looking at it in terms of the Y-axis here is depth of
8 penetration, and so we have initial conditions is number
9 one, and then we have precursors. So before there is
10 any penetration at all, the precursors might be
11 important.
12 But then we really -- we get into -- the
13 PWSCC starts incubating in terms of these oxide
14 penetrations, and changes in the oxide film, and so on.
15 And then -- so that's a relatively slow stage of setting
16 the table for, then, actual cracks to start growing.
17 And these start off as micro cracks, and you can see
18 what is cited here as penetration of SCC up to 50 to
19 500 microns, up to early coalescence.
20 So when we reach this point here where we
21 are starting to approach propagation, meaning cracking
22 that is driven by linear elastic fracture mechanics kind
23 of a mechanism, then in this neighborhood the small short
24 cracks, they can be called, start to coalesce and to
25 form larger flaws of engineering significance.

1 And we use that term "engineering
2 significance" to mean flaws that are half a millimeter,
3 500 microns, up to about three millimeters deep. So
4 at that range they start to represent coalescence of
5 short cracks and start to grow by linear elastic fraction
6 mechanics, which may govern even down at the half a
7 millimeter or even somewhat shallower. But now they
8 coalescence to cracks that are -- that can have a range
9 of aspect ratios and to start to grow at a more rapid
10 rate.
11 So the idea, again, of QMN is to -- each
12 one of these stages to model in as much detail as possible
13 as practical.
14 All right. So QMN approach here. There
15 are conferences every year since 2010.
16 MR. GORMAN: "Conference" is the wrong
17 word. It's a limited meeting of 32 people.
18 (Laughter.)
19 MR. WHITE: It's an invite-only.
20 MR. GORMAN: Yeah. Invite-only. Yes,
21 right.
22 MR. WHITE: But the proceedings are
23 available.
24 MR. GORMAN: The proceedings are available
25 through Roger Staehle. They are free, but you have to

ask for them. It's not --

MR. WHITE: They are available. I don't think they are posted. If you put in the search for QMN 2, I don't think you will come up with it. You have to --

CHAIRMAN ARMIJO: Who is sponsoring or paying for QMN 2?

MR. GORMAN: That varies from time to time. This next one it seems to be mostly AECL. The first two were largely sponsored by INL, meaning -- so DOE money. But that funding dried up, and I don't really know who funded the third one. I think still some INL, Rolls-Royce has been supporting a good deal, as has AECL has, and Dominion Engineering has, too.

CHAIRMAN ARMIJO: And this is broader than just PWR.

MR. GORMAN: It is any SCC that affects lightwater -- I mean, water cooled, including CANDU water cooled reactors.

CHAIRMAN ARMIJO: Okay. So it -- okay. good. Thank you.

MEMBER SHACK: But PWSCC is a good common ground.

MR. FYFITCH: The proceedings are excellently written. In other words, I am the author.

1 Okay?

2 (Laughter.)

3 CHAIRMAN ARMIJO: Okay. Thank you, Jeff.

4 MR. WHITE: So QMN 4 is going to be in

5 Toronto, and that is in another week or so. And by QMN

6 6, the idea is to start talking about how to integrate

7 the various pieces.

8 All right. So this slide just, again,

9 talks about the various steps that are modeled.

10 So moving on to the hydrogen-assisted and

11 related strain energy density models -- so, again, Mack

12 Hall at Bettis published these approaches looking at

13 the role of hydrogen at the cracked head, looking at

14 different materials including X750 and other nickel base

15 alloy.

16 And, again, as we mentioned, there is

17 reasons for believing hydrogen is a main factor, and

18 this was published -- for example, QMN 1,

19 hydrogen-assisted creep rupture model, and -- but our

20 conclusion has not been developed to the point of making

21 quantitative predictions for plant components.

22 So we think additional work would need to

23 be done to be able to implement it in xLPR, and that's

24 the basic reason why it wasn't. So xLPR decided not

25 to try to implement these.

1 There was more data for X750, but not for
2 Alloy 600 -- enough for Alloy 600 that we thought that
3 we would devote resources to putting into xLPR.
4 There is a related model here, the SEDN
5 model, strain energy density, and there is a methodology
6 for calculating this parameter for both smooth specimens
7 and matched specimens. So it was a way of making
8 predictions for both types of specimens, kind of on a
9 common basis, but, again, difficult to apply at this
10 point to plant materials without significant kind of
11 work in that area.
12 Then, we had the model published by EPRI,
13 by Yogen Garud, and this assumes that SCC is dominated
14 by cracked tip strain rate that disrupts the protective
15 oxide film. And the model, as a function of
16 temperature, has -- all of these models are material
17 properties, specifically, the yield stress and ultimate
18 strength, and the total surface stress.
19 So the approach there is to look at the
20 mechanisms involved in cold working, how you relate the
21 level of cold work to the ratio of the ultimate strength
22 to the yield stress, for example, and to fit a series
23 of parameters to laboratory data to be able to develop
24 this effective stress, yield strength, and ultimate
25 strength.

1 So, and other models may just use the stress
2 to an exponent to model the effective stress. This work
3 shows that really there is good reasons -- there is data
4 to show that it is more complicated than that, and this
5 model was shown to give good results in terms of the
6 agreement versus the --
7 MEMBER SHACK: Well, I counted nine
8 parameters when I went through it, so that's --
9 MR. WHITE: Ten.
10 MEMBER SHACK: -- that's a lot of knobs
11 to --
12 MR. WHITE: You can adjust a lot of things.
13 MEMBER BLEY: I think we are getting to what
14 confused me a bunch of slides ago when you had five
15 different -- kind of five different physical models and
16 you said, Glenn, that we expect them all to give us the
17 same results. And I take it that is because it's got
18 enough knobs in it that you will fit the data. So it's
19 really an empirical result we are looking at.
20 MR. WHITE: Right. I agree. The key
21 thing is what model -- what data are you using to
22 implement that model. You're right.
23 So this slide here, again, says that this
24 was implemented in the pilot study. It continues in
25 Version 2, and, again, it adds in these strength

1 parameters, which is I think its main contribution.

2 And there is a validation of effort, and

3 we have separate slides on those. Should I talk about

4 them now?

5 CHAIRMAN ARMIJO: Yes. Are we going to be

6 getting into closed --

7 MR. WHITE: Yes. This is the closed

8 portion.

9 CHAIRMAN ARMIJO: Okay. We are getting

10 into closed session.

11 (Whereupon, the proceedings in the foregoing matter went

12 into Closed Session at 9:25 a.m. and

13 returned to Open Session at 9:34 a.m.)

14 MR. WHITE: The challenge here is that,

15 again, especially for the welds we don't necessarily

16 know that one butt weld has a different yield strength

17 and tensile strength than another butt weld. And the

18 stresses are more uncertain than, for example, CRDM

19 nozzles where we have CMTR data at least, which has the

20 yield strength for that particular heat, which gives

21 some indication of the starting yield strength.

22 For the butt welds, there may be weld

23 repairs that may have increased the stress. The details

24 of the weld fabrication, whether the root was machined

25 out or not is always not -- is not always known. So

1 some factors are -- there is more uncertainty in the
2 stress for the butt welds, and that is a main challenge
3 for us, as well as the strength values.
4 The material index approach, what this is
5 really referring to is the work done by AREVA and others
6 in France, first applied to CRDM nozzles to predict the
7 time to initiation, and it includes an activation energy
8 approach, stress raised to the fourth power in this case
9 to adjust for stress, and a material index factor which
10 can be related to the material microstructure.
11 So if you -- there were three iterations
12 of this work published by Tom Zologg and Peter Scott
13 and others. First, the deterministic approach, the
14 different deterministic material index numbers for
15 different microstructures. So the French researchers
16 came up with a framework for classifying different
17 levels of carbide decoration into different categories
18 and then assigned different index factors to each one,
19 and then made predictions for a lifetime
20 deterministically first.
21 And then that was -- was refined into a
22 Weibull kind of treatment, fitting a single Weibull
23 distribution to the data to describe the scatter. But
24 then they moved to what they call the Monte Carlo
25 approach, which they report to give the most realistic

1 predictions. And in that approach,
2 distributions -- statistical distributions are
3 developed for the stress, for the temperature, the
4 activation energy, and for material susceptibility
5 index.
6 So rather than just assigning it one number
7 to each category of material, they assigned a
8 distribution -- probabilistic distribution to each one,
9 but still had about four different levels of
10 susceptibility, so A, B, C, and D. And they were able
11 to assign certain heads into each category depending
12 on the microstructure expected for those different
13 categories of heads.
14 And then when they put this together along
15 and calibrated it using I think both lab and field data,
16 they were able to make useful predictions for
17 prioritizing their inspections of the top heads. And
18 they have -- I think by now they have replaced all of
19 their top heads, but this was a useful tool, you know,
20 for them as they managed that effort.
21 Now, the challenge for us in applying this
22 method is that for the butt welds we
23 cannot -- essentially we don't know that the material
24 is any different from one butt weld than another. So
25 with the raw material, you have some CMTR information.

1 You can research what the material processing was, what
2 the annealing temperature was, and so on, and you can
3 go back and you can -- or you can do replicas and get
4 information on microstructures. But for the butt welds
5 it's more challenging because it is really, you know,
6 a cast microstructure.
7 And so, in general, we can't say that if
8 this particular butt weld is a Category A
9 susceptibility, and this one is B, this becomes -- and,
10 again, as I mentioned, the stresses are very
11 challenging, to have a good distribution of stresses.
12 All right. Then, that brings us to the
13 statistical approach using plant data, and this is what
14 we call the Weibull model. And here this emphasizes
15 using plant data to calibrate the model, and this has
16 been very successful in the steam generator tube area
17 where you have lots of tubes and you can -- lots of
18 inspections and can make reasonably good predictions
19 going forward.
20 And the method, then, has also been applied
21 to CRDM nozzles in the industry and to the butt welds,
22 in terms of the materials reliability program -- is to
23 use this kind of approach concentrating on calibrating
24 the plant data for butt welds and CRDM nozzles in MRP-307
25 and 335R1.

1 307 looked at chemical mitigation, elevated
2 hydrogen content in the water to slow rate of crack
3 growth, looking at zinc addition to slow rate of
4 initiation, and looked at that on a probabilistic basis.
5 MRP-335R1 is a topical report that was just submitted
6 to the NRC formally this year, and there is a meeting
7 this Thursday to talk about the status of that between
8 industry and NRC.
9 Again, it is a probabilistic approach to
10 look at the benefit of peening mitigation of both CRDM
11 nozzles, top head nozzles, and the Alloy 82/182 piping
12 butt welds in PWRs, but uses an approach similar to what
13 is being implemented for Version 2 of xLPR.
14 The approach here is to rely on plant data
15 to the greatest extent possible, and then make
16 adjustments for temperature and stress. Temperature
17 is fairly straightforward although reactor vessel
18 outlet nozzles, because of streaming coming out of the
19 core, there is, you know, some uncertainty in the
20 temperature in any particular location on the
21 circumstances. We have to recognize that.
22 But the stress is the real challenge in
23 particular here, because when we apply the plant data
24 we don't have stress calculations for every nozzle that
25 has had indications. And it is not just the ones that

1 have had indications that are important; the ones that
2 haven't had indications also are used.
3 And so it's not practical to make
4 predictions for all hundreds of components, and so, you
5 know, there's a big assumption here about what is the
6 typical stress level that applies to this reference set
7 of data.
8 So the approach here, again, is to rely on
9 plant data, get as close to the -- and use the set of
10 components that are closest to, you know, your plant
11 data. So the balance there is you don't -- if you use
12 too small a data set your statistics are hampered by
13 small data set statistics. But if you try to use all
14 components that have Alloy 600 in the whole plant, there
15 is too great a dispersion in the experience.
16 You don't want to use -- CRDM nozzles are
17 significantly different than butt welds, and so we
18 really want to use the butt weld data to make predictions
19 for the -- for other butt welds. And then, again,
20 adjustments for temperature and stress as practical.
21 All right. Challenges here -- inspection
22 data works both ways. So there is -- we know that there
23 is 100 percent probability of detection for inspections.
24 So there are likely some flaws that haven't been
25 detected yet or possibly were missed, and so we are not

capturing those in our predictions or our fit to plan experience.

On the other hand, some of these indications may in fact have been fabrication defects, and they were conservatively interpreted as PWSCC. So it possibly could work either way, but just -- there's uncertainty in the approach. And the difficulty in characterizing a near surface stress is the main challenge.

CHAIRMAN ARMIJO: Just to go back a little bit, in your detection capability, are you able to detect the things that you define as an initiated crack, .2 to .4 millimeters on a butt weld?

MR. WHITE: No. And that's the reason that we tend to -- we are recommending to use a larger flaw that's an initiated flaw, more like one and a half --

CHAIRMAN ARMIJO: Bring it up to a detected --

MR. WHITE: -- one and a half millimeters deep, something that is closer to detectable.

CHAIRMAN ARMIJO: Okay.

MR. WHITE: Right.

MR. RUDLAND: It becomes another calibration parameter, right?

CHAIRMAN ARMIJO: Sure. Sure. But, you know, so you can't see them unless you --

1 MR. WHITE: When flaws are below a
2 millimeter, the case can be reasonably low and cracked
3 welds at the time become long. And so, yes, we can't
4 fool ourselves by starting -- picking starting flaw
5 sizes that give us extra time that's really not there
6 when we are calibrating the plant data based on what
7 was detected.
8 All right. Coalescence, short crack
9 initiation and coalescence. This is one of the
10 recommendations from the expert panel that Steve will
11 be talking about. So we did some work within xLPR to
12 review kind of work in this area.
13 The concept is is that these flaws really
14 initiate as they nucleate multiple flaws on the surface,
15 not just in one plane, and there is a certain rate of
16 nucleation of these short cracks, and that they grow
17 and then link up. They influence each other and
18 eventually become -- reach singly dominant flaws is the
19 terminology that Yogen Garud uses. They become linked
20 up into a dominant flaw that then grows and becomes the
21 largest flaw in that area.
22 And those large flaws can coalesce. So
23 when we talk about coalescence a little bit later this
24 morning, there is a later stage coalescence of
25 relatively large flaws. The coalescence we are talking

about here is coalescence of the early stages of growth before the cracks are likely detectable by UT.

So Parkins was a researcher working in the pipeline industry, and in the 1990 to 1995 timeframe developed this approach based on lab data and Monte Carlo modeling for both fatigue, crack growth, and SCC, not for our particular materials, Alloy 600, but this is a useful reference for this kind of approach.

So there is random nucleation. A crack can initiate anywhere in this area, susceptible area. It is not controlled by LEFM, initially on grain boundaries but also on shear bands. Then, these small cracks grow and there is a possible dormancy period, and they can coalesce and then their interactions, their coalescence, are governed by their sizes, but also their spacing, how close they are together.

So these models -- this approach requires a lot of information on these early stages of growth and coalescence. And that is the challenge here is developing experimental data to describe all of this.

Now, we just put in a couple of examples here. These are -- you know, these papers, you know, are available. So here is for SCC, and you see 10 different Monte Carlo realizations. So each one represents, you know, a prediction for a surface,

1 nucleating multiple flaws, and this is how the flaws
2 are linking up. And this is a maximum crack length that
3 is produced on that surface, given all of these
4 nucleating sites that are -- and you can see you have
5 growth occurring, but also more step changes which
6 represent coalescence.
7 CHAIRMAN ARMIJO: So this is pipeline
8 material. This is not --
9 MR. WHITE: Yes.
10 CHAIRMAN ARMIJO: -- Inconel.
11 MR. WHITE: That's right. And here is a
12 sensitivity case, just pulled out a couple plots from
13 his paper. In here he models the nucleation -- the
14 number of nucleation sites, nucleating small cracks,
15 as a constant M times time to the .4 power. And the
16 M is kind of this nucleation rate parameter, and you
17 can see that the higher the M, the shorter the time to
18 reaching a critical crack length.
19 So the more cracks are initiating, you know,
20 the less time there is before you produce that
21 coalescence flaw that is, you know, a structural
22 integrity concern. And he did sensitivity cases, so
23 the solid line is with dormancy and with coalescence.
24 He took out dormancy and that reduced the time, the
25 cracking. Does dormancy expose the process?

1 And he also did a case without coalescence.
2 That also slows -- that slowed the process without
3 coalescence, but coalescence accelerates the effective
4 growth. So this is the type of work that he did.
5 The challenges to implementing this in xLPR
6 is having the data for our material stats to cover all
7 of these conditions. There is a practical challenge
8 that -- to model auto plane -- to model cracks growing
9 in multiple planes, becomes extremely complicated from
10 a point of view of structural integrity.
11 So how do you, you know, predict planes,
12 the effect of two parallel large cracks on the structural
13 integrity and the -- you know, the point you get rupture?
14 It complicates crack open displacement and leak rates,
15 and so the point we are with practical life predictions,
16 we use this -- we assume coplaner cracking.
17 And so to go in this direction, you know,
18 represents a real step change in the complexity of the
19 modeling. And the judgment was we weren't ready at this
20 point for xLPR 2.0 to go in this direction, but we agreed
21 that this is an area that is -- you know, a prime area
22 for additional work.
23 We did contact active -- Parkins has passed
24 away, but we contacted active investigators in the
25 pipeline industry, and we understand that this kind of

1 an approach is not being used for practical life
2 predictions of pipelines today.
3 But this really is the -- you know, that
4 occurs in our application also. The way that we address
5 this concern of coalescence of short cracks is that,
6 again, we bypass the states and we go to a deeper flaw,
7 say one and a half millimeters deep, and we assume a
8 range of aspect ratios.
9 So the flaws could be one and a half
10 millimeters deep and a couple millimeters long, or
11 significantly longer than that, and we used -- randomly
12 select what that aspect ratio distribution is, and in
13 that way we are indirectly trying to model the effect
14 of this coalescence.
15 So in some cases you may get a crack that
16 is this long, you know, or in some cases you may get
17 a longer crack. So, you see, at 150 hours you have some
18 cracks that are this long, four millimeters, some that
19 are 14 millimeters. So we're trying to use a
20 distribution to capture that empirically.
21 So we've gone through all of the data. We
22 have about 20 butt welds, Alloy 82/182 butt welds, where
23 inspection data has reported a length and a depth. The
24 ones for axial cracks are not too informative because
25 those cracks generally are the full width of the weld,

so their aspect ratio has been inhibited by the susceptible material length.

But the circumferential flaws in particular, we fit a distribution to that data to inform us about what kind of a distribution we could have for our situation. But, again, there's a lot of uncertainty there, and we have to use sensitivity studies to look at the effect of the aspect ratio of this engineering scale flaw.

But if we are able to use this Parkins kind of approach in the future, that can give us information on how long the flaws should be once they reach a depth that we can grow by the standard approaches we are using already in xLPR.

So I'd better wrap up here, move on to the next presentation. So we just have three conclusion slides. The first one here, again, we have seen all of these factors before. Again, there is very good consensus that these are the factors at play, but we have to look at which factors we have knowledge about specifically with the butt welds with the dissimilar metal piping butt welds.

So, as I have emphasized, total stress, we have limited knowledge. We know that things like a double V weld can lead to higher inside stresses. So

1 the V.C. Summer case was a double V design. In Japan,
2 we have had experience with steam generator inlet
3 nozzles, have shown some PWSCC experience. Again, that
4 is a double V design. We think that that is a more
5 susceptible configuration.
6 We know weld repairs can be important, are
7 important, if they are significantly large on the inside
8 to cause high stresses, surface grinding. But, in
9 general, we don't know enough to predict the stresses
10 for each location we want to model in xLPR. So that
11 is a big challenge.
12 So our local surface cold work and surface
13 damage, again, we know they are important, but we have
14 limited data on them. In terms of surface grinding,
15 I think the presumption is that all of the butt welds
16 are ground, and so they should all be in a roughly similar
17 state in terms of grinding. We carve on the inside
18 surface.
19 Microstructure -- again, these are cast
20 microstructures effectively as a weld. We don't have
21 information saying that one is any different from any
22 other. Similarly, for mechanical properties, we know,
23 you know, what the nominal yield strength and tensile
24 strength are for Alloy 82 and 182, but we can't say,
25 you know, for the particular weld configurations how

1 that varies. And it is not a uniform property, and not
2 necessarily the same in each direction. You know, and
3 so that is a big challenge.
4 But we do know our temperature generally,
5 water chemistry, chemical composition, duration of
6 exposure, and whether or not thermal treatment -- you
7 know, there was a post-Weibull treatment of the carbon
8 or low alloy steel after the weld metal was put there.
9 And so those things are known, and we can adjust for
10 those things.
11 Again, we have different approaches. It
12 is what data you use to implement those approaches is
13 the key -- the key thing we have to be concerned with.
14 CHAIRMAN ARMIJO: Okay. Very good.
15 Thank you very much.
16 I think now is a good time to take a
17 15-minute break, and let's be back at 10 after 10:00.
18 That's 15 minutes. Okay?
19 (Whereupon, the proceedings in the foregoing matter went
20 off the record at 9:53 a.m. and went back
21 on the record at 10:11 a.m.)
22 CHAIRMAN ARMIJO: We would like to come
23 back to order. We are back in open session, and, in
24 fact, we were in open session for part of the last bit,
25 and I think Chris corrected that. So now I'd like to

1 turn it over to David.

2 MR. RUDLAND: So we are a little bit -- if

3 you look at your schedule, a little behind schedule.

4 So in the next couple of presentations we are going

5 to try to catch up on some of that time. And there are

6 some topics that we talk about both in my presentation,

7 maybe in Steve's, as well as in Kyle's, where we touch

8 on some of the things that Glenn spent some time talking

9 about. So we will probably just skip over those details

10 since Glenn covered it pretty well in his presentation.

11 So I'm going to talk a little bit about

12 Version 1, the models that we use in Version 1, how we

13 calibrated those models as part of that feasibility

14 study, and what the results were that moved us on to

15 the next section.

16 Before we go into those models, I want to

17 talk a little bit about xLPR. We did come and brief

18 this Subcommittee I think in -- about a year ago on this

19 particular topic. But the goal of xLPR is to be a lot

20 more generic than just the issues that we are talking

21 about with leak before break.

22 We wanted to develop a modular code that

23 could be used for all pressure boundary integrity

24 issues, but we are currently focusing on those

25 particular lines that have been already approved for

1 LBB that have taken removal of equipment due to the GDC-4
2 criterion.
3 In that particular criterion, there was
4 certain large lines that were allowed to remove
5 equipment that was due to mitigate dynamic effects to
6 pipe ruptures. And in those particular cases, the
7 stipulation was that those lines were not susceptible
8 to any act of degradation.
9 Well, as we know through the conversations
10 that Glenn had, they are susceptible to this PWSCC.
11 And so we needed a way to directly assess those
12 locations, and so we are focusing xLPR Version 2 on those
13 particular locations.
14 As I mentioned earlier, this program is
15 being developed cooperatively between EPRI and the
16 Office of Nuclear Regulatory Research through an MOU
17 addendum. Unfortunately, I forgot to -- the first time
18 I mentioned this to introduce Craig Harrington who is
19 the EPRI representative on that particular program.
20 We will give him an opportunity, if he wants, later on
21 to make a couple of statements. But he is the program
22 manager from the EPRI side on this project.
23 When we first started this program in 2009,
24 we knew that it was going to be very difficult to do.
25 PWSCC aside, just the entire process was going to be

1 difficult, and so we kicked up a pilot study in 2009
2 to look at the effectiveness of the approach. And the
3 pilot study was meant to be a feasibility study, whether
4 or not we could actually do this process and make some
5 of these predictions and work cooperatively to do that.
6 And so we kicked that off in 2009. And,
7 again, it is -- when I talk about Version 1, that is
8 our pilot study code. And its objectives were to
9 develop and assess the management structure, the
10 cooperative structure between EPRI and RES, and
11 determine the appropriate framework in order to do these
12 kind of calculations, and to really assess whether or
13 not it was feasible to develop this kind of modular-based
14 code.
15 The pilot study focused on a particular
16 location, which was to pressurize a surge nozzle DM weld,
17 and only looked at PWSCC. We didn't look at any other
18 mechanisms. Within that pilot study, we developed
19 program plans, QA programs, budgets, deliverables, and
20 all of that important program-specific information for
21 Version 1.
22 We talked about this during our last, so,
23 again, I'll go through it quickly. The technical flow,
24 it's a Monte Carlo-based simulation technique where we
25 take inputs that are uncertain and we put them through

1 a series of modular-based fracture mechanics-type codes
2 where we can predict crack initiation, crack growth,
3 large crack coalescence, which Glenn alluded to.
4 This is large crack and not the small crack
5 coalescence that he mentioned earlier, inspections,
6 which are also random, mitigations, can we mitigate the
7 locations to help slow down or reduce the cracking,
8 analyses that determine leak rates as well as taking
9 into account leak detection capabilities, looking at
10 whether these flaws are stable or not, and whether they
11 rupture. And, if not, we continue that process through
12 the loop.
13 So, again, today we are only focusing just
14 on initiation. It's a very important but a relatively
15 small part of the overall structure of xLPR. In
16 Version 1, when we first started this back in 2009, we
17 put together a series of people to look into crack
18 initiation models. Glenn touched on that. These are
19 some of the people that we actually had on the panel
20 at the time.
21 The models that we looked at are listed
22 there. The red ones are what we chose. The darker ones
23 are some of the things that Glenn talked about earlier,
24 and reasons why we didn't choose those.
25 As Bill pointed out earlier, we did look

1 at an arrival rate model, and we did that mainly because
2 in Version 1 we wanted to have something that we knew
3 was consistent that we could use as a placeholder until
4 we developed some models that were a little better.
5 And actually we calibrated two arrival
6 rates as part of this version, but we took the Weibull
7 models that Glenn mentioned, the material index approach
8 as well as this cold work approach, and worked those
9 into Version 1 as part of the demonstration.
10 I'm not going to go through these, but,
11 again, the three models that Glenn talked about, the
12 direct model on the left, the cold worked model on the
13 right which has a lot more parameters. And keep in mind
14 the B1 parameter. I will talk about that, you know,
15 a little bit more, and the Weibull approach.
16 When we started -- when we were in
17 Version 1, again, it was in the midst of a lot of the
18 cracking that was going on in the pressurizer. So I
19 had a lot of the hot locations. The cracking was just
20 occurring. So we didn't have that much data at that
21 particular time. This plot here shows some of the data
22 that was there in mid-2007 from the cracks that were
23 found in the surge nozzle, safety relief, and spray
24 nozzles of the pressurizer.
25 So we didn't have a lot of data to work with.

1 But from that data, we developed an arrival rate of
2 about .01 cracks per year relative to the particular
3 time at which those cracks were found. And so we took
4 that data and we fit it several different ways to both
5 the direct models as well as the Weibull model.
6 We allowed multiple circumferential cracks
7 to initiate, and we did not allow axial cracks in Version
8 1. So the data that you see here was calibrated to only
9 circumferential locations, circumferential indications
10 that were found.
11 MEMBER SHACK: Dave, let me just try to make
12 sure I understand what you did. You know, you have the
13 segmentation model, so --
14 MR. RUDLAND: Right.
15 MEMBER SHACK: -- I got along and I initiate
16 in a segment, and then I assume some crack size.
17 MR. RUDLAND: Right.
18 MEMBER SHACK: But from there on, it just
19 grows under normal linear elastic fracture mechanics.
20 MR. RUDLAND: That's correct.
21 MEMBER SHACK: So when you say you get a
22 LOCA, I assume that means you get a break before leak.
23 I mean, you are violating leak before break.
24 MR. RUDLAND: That's correct.
25 MEMBER SHACK: But you were only getting

1 single initiations, from what I could gather, from most
2 of the discussion of Version 1. So you got one crack
3 initiated and it really grew around --
4 MR. RUDLAND: There were several -- I think
5 the most we ever had within all of the runs that we did
6 in Version 1 were five cracks around the circumference.
7 MEMBER SHACK: Oh, okay. So you did -- so
8 you actually did exercise the coalescence model
9 somewhere along the way, though.
10 MR. RUDLAND: Oh, yes. Oh, yeah, yeah.
11 Oh, yeah, definitely. You know, when we did the
12 calculations, of course, we did them with and without
13 inspections and leak detection. So in some cases the
14 LOCAs were -- the calculations were very high, because
15 we didn't take into account those kinds of mitigation
16 techniques, right?
17 And then, when we took into account leak
18 detection and inspection, the ones that actually drove
19 the probabilities were those cracks that were -- surface
20 cracks that were big enough that caused rupture before
21 penetrating the wall.
22 MEMBER SHACK: And did they grow as a single
23 crack, or those were really coalesced to --
24 MR. RUDLAND: Those were coalesced.
25 MEMBER SHACK: They were coalesced.

1 MR. RUDLAND: In some cases, they were
2 coalesced. It really depended on the problem that we
3 were running at the particular time. But in many cases,
4 they -- in many cases we had one or two cracks, most
5 cases probably one crack, a few cases five cracks.
6 MEMBER SHACK: But if you put 1.5 or
7 something like that --
8 MR. RUDLAND: Yeah. It was something not
9 very large, but --
10 MEMBER SHACK: It was not very large, but
11 you did get up to five in some cases.
12 MR. RUDLAND: Yeah, in some cases. That's
13 right. That's right.
14 And, again, the way that that -- the way
15 it was chosen was, you know, there were -- each
16 individual subunit, as you see here, where it says equal
17 like segments had a unique sample for that time to
18 initiation that came from these equations here. And
19 so they had just initiated whenever their time got to
20 that particular --
21 MEMBER SHACK: And the initiated crack was,
22 as Glenn described, you'd pick some random length and
23 depth of --
24 MR. RUDLAND: That's right. There was
25 some --

1 MEMBER SHACK: Aspect ratio.

2 MR. RUDLAND: -- some aspect ratio and some
3 depth distribution that we chose. And, again, in
4 Version 1 we chose those that were -- we took I think
5 it was a three millimeter depth was the median value,
6 because, again, we didn't have the data at the time to
7 really know. We took that experience from fatigue data
8 that we had, and usually they assume about a three
9 millimeter depth fatigue initiation data.

10 And as Kyle will talk on, I think we are
11 refining that a little bit more in Version 2.

12 So as I just pointed out, we did a whole
13 bunch of sensitivity studies, varying different things,
14 to try to figure out what were driving the -- what was
15 driving the probabilities of rupture. And, again, once
16 we took leak detection and inspection into account, the
17 ones that were driving it were those long surface cracks
18 that were either coalesced or they were actually growing
19 around the circumference due to the residual stress on
20 the ID surface that were causing the issues.

21 And through the sensitivity studies we
22 found two parameters that were really driving the
23 probability to rupture. And as you would expect, the
24 sigma naught residual stress, which is the ID residual
25 stress, if you look at the output, how much the output

1 variance is -- how much the output variance is explained
2 by that input, for 60 years, for probability of rupture,
3 it's 43 percent driven by the uncertainty in the residual
4 stresses on the ID surface.
5 This plot here shows kind of a contour of
6 the crack initiation parameter B1, which is from the
7 second cold work model, and that ID residual stress.
8 So a high ID residual stress and a low value of that
9 B1 drove us to the highest points of being able to get
10 probabilities of -- to get high probabilities of
11 rupture.
12 So it was those two parameters -- initiation
13 parameter had about 16 or 17 percent impact on the
14 probabilities of rupture were driving most of the
15 problems. So that together is 60 percent of the
16 uncertainty was driven by those two variables.
17 And so we knew that those two things were
18 going to be of most importance, which we presented to
19 you last year and you said, "Oh, yeah. Well, I want
20 to know more about those things."
21 I'm not going to touch on this all that much.
22 Again, we talked about this last time, but we struggled
23 on how to characterize initiation, and moving it around
24 between being a lack of knowledge type of uncertainty
25 or a general uncertainty made a big difference in the

1 results, especially when we talked about differences
2 in the percentiles.
3 The pilot study which ended in about 2011
4 demonstrated that it was feasible to do this. We were
5 able to develop this code. We were able to take some
6 models that we knew at the time and produce reasonable
7 predictions of probability, calibrate those using
8 different data. The initiation had a very large impact,
9 as we showed earlier, for Version 1.
10 And so we wanted to continue the flexibility
11 that we had in Version 1 with several different models.
12 Some of the results I showed here were only one model,
13 but when we calibrated the model to the same data we
14 got the same results out of the three models. So we
15 are very happy with that.
16 But because of how important initiation was
17 at the end of Version 1, we wanted to revisit this problem
18 again, and so we put together an expert panel, a PWSCC
19 expert panel, and Steve is going to be talking about
20 that here in a second. And I think, again, not only
21 through the team but also through our discussions with
22 the ACRS we wanted to focus the panel on looking at what
23 models we had in V1, were they reasonable, and what steps
24 should we take in V2 and beyond to improve those models.
25 MEMBER BLEY: Dave?

1 MR. RUDLAND: Yes.

2 MEMBER BLEY: I knew we are here to talk

3 about initiation today, but the one you didn't want to

4 talk about much, the uncertainty one, have you evolved

5 in your thinking about how to parse out this aleatory

6 versus epistemic uncertainty?

7 MR. RUDLAND: Yeah.

8 MEMBER BLEY: Because that has a dramatic

9 difference.

10 MR. RUDLAND: In a lot of the models, we

11 spent a lot of time determining how the different

12 parameters of the model should be characterized. You

13 know, the initiation is by nature an aleatory process.

14 But there may be some epistemic parameters that go into

15 that.

16 I'm not sure if Kyle is going to touch on

17 that, but we spent a lot of time talking about that within

18 our subgroup to try to make a logical and reasonable

19 engineering decision on those kinds of things. And we

20 have developed protocols and how better to take data

21 to characterize what type of distribution that data may

22 be beyond, you know, the aleatory and epistemic.

23 And so we're not going to really talk about

24 that today, but we have developed tools to be able to

25 use, so that the users of the code can take what data

1 that they have and it will recommend to them what type
2 of uncertainty should be chosen.
3 MEMBER SHACK: Okay. Thanks. Sometime
4 in the future I would be interested to learn more about
5 that. Thanks.
6 MR. RUDLAND: Okay, Steve.
7 MR. FYFITCH: All right. My name is Steve
8 Fyfitch. I'm from AREVA. As Dave mentioned, I'm part
9 of the xLPR team for crack initiation. So I will go
10 over some of the things that we have done for the expert
11 panel sessions.
12 All right. So basically we had two
13 different expert panel sessions. We had one in November
14 2011 and then we had a second one this year in January
15 of 2013. The first one was just a phone conference call
16 kind of a panel session, and the second one was actually
17 an in-depth in-person meeting.
18 We went over the different models that
19 should be considered for xLPR, discussed them in detail,
20 and then we came up with the conclusions and
21 recommendations for going forward with xLPR Version 2.
22 And we also came up with some recommendations for
23 continuing on the program for Version 3, different
24 places we need to go.
25 In November 2011, we had, you know, quite

1 a cast of characters on the phone call. You can see
2 here different names, but we covered everybody that has
3 been working in crack initiation, has some knowledge
4 about crack initiation, has been around for a number
5 of years, working on PWSCC, you know, like Rich Jacko,
6 Westinghouse, has done a multitude of tests. Tetsuo
7 Shoji at Tahoku University has done quite a number of
8 tests, you know, so -- and also we had KAPL, Dave Morton,
9 involved in it, who has published quite a few papers
10 mostly recently on PWSCC. So it is a good set of people
11 that we had on the team.
12 The next one?
13 The topics that we went over, we took a look
14 at, you know, the current models that we used in Version
15 1 of the code, did an assessment of those from the expert
16 panel standpoint to see if, you know, they had any
17 agreement or not as to whether those were the correct
18 models, whether we had better models to utilize.
19 We discussed some on the data sets used for
20 the benchmarking to be done in Version 2. We talked
21 about the material variability and the significance of
22 that on the models and the predictions. We discussed
23 an initiation threshold, and I put "threshold" in quotes
24 because I personally don't believe there are any
25 thresholds in any of this. But, you know, I'll go in

1 detail what I mean by that. And then size effects and
2 initiated crack size as well.
3 So the best we tried to do was reach
4 consensus, because when you're dealing with experts you
5 can't always get total agreement, as you probably well
6 know. But we reached consensus on a number of items.
7 The first one I wanted to point out is that the Version
8 1 models that were -- we utilized in that first code
9 are considered the best models that are currently
10 available and that we should continue to use for Version
11 2. Obviously, still, additional work needs to be done,
12 which we have been doing this year and last year.
13 The question of whether or not actual versus
14 circumferential crack initiation is different. It
15 should be modeled different or not. We asked and the
16 consensus was no, you know, the same model should apply.
17 And so we will go forward with it in that aspect.
18 And as far as benchmarking, you know, as
19 Glenn has already mentioned, you know, the available
20 field data seems to be the best way to benchmark, you
21 know, the models that we currently have and the
22 parameters that we are using in the models.
23 During that discussion, we talked about the
24 size effects, and, obviously, the majority opinion that
25 we were able to come up with was that we should continue

1 to use segmentation, although it, you know, may not be
2 the best thing to do, but it is a good approach to use
3 for xLPR.
4 But, you know, we should also look, though,
5 further for, you know, going forward with Version 3
6 whether or not, you know, we need to have more discussion
7 on these size effects and, you know, whether we can get
8 away from the segmentation approach. And so that was,
9 you know, one of the recommendations that came out of
10 the first panel.
11 Okay. Another thing we talked about was
12 the initiated crack size. The expert panel feels that
13 it should definitely be a value that is below the cold
14 work surface layer that we typically see on materials.
15 And so that range is around 200 microns, and, you know,
16 you have heard Glenn mention, you know, half a millimeter
17 to one and a half millimeters I think he said.
18 Variability in weld material can be
19 captured by, you know, counting the residual stress on
20 the surface. So we know there is -- you know, within
21 weld variability we know there is heat-to-heat
22 variability of the weld metals. But, you know, if you
23 can capture the residual stresses, you know, you can
24 capture when it might initiate best in the weld metal.
25 Now, with the initiation threshold, you

1 know, as I mentioned, there is really not, in my opinion,
2 a threshold where you reach a point and then you're over
3 the cliff. It is more a continuum, and so the expert
4 panel consensus was that that value -- if we are going
5 to say there's a threshold, it's on the order of about
6 350 megapascals or 50 ksi stress. But, again, it is
7 not something you draw a line in the sand and say if
8 it's 349 it's not going to crack, and if it's 350 it
9 will crack.
10 In January of this year, we put together
11 a second expert panel. We purposely kept it to a small
12 group of people, so that we could get more interaction
13 among the members. You know, we had a sit-down meeting
14 for, what was it, two and a half days? Yeah, two days,
15 two and a half days, something like that.
16 And we had a good meeting. This is the
17 group of people that were on there. You've heard, you
18 know, Yogen Garud's name, which is the direct model 2,
19 Roger Newman from the University of Toronto, Peter King
20 from BNW Canada, and we also brought in Gerrit Buchheim,
21 who is an independent consultant for an industry that
22 is completely outside of the nuclear industry. So he
23 works in the gas and oil industry. So we tried to get,
24 you know, opinions from others outside of the nuclear
25 area.

1 Okay.

2 So the primary meeting goal of this meeting
3 in January was to reach consensus decisions on which
4 models definitely to go with for Version 2. We looked
5 at, again, the same thing, you know, the models from
6 Version 1 to Version 2, and we also tried to find other
7 applicable models and inputs that were not in Version
8 1.

9 The secondary meeting goal was to come up
10 with a plan for, you know, what would be the best approach
11 and best things to tackle for going on to Version 3 with
12 the code.

13 This one -- the three models that were
14 considered, you've seen them, so I'm not going to go
15 into any detail on those. So the second thing is that,
16 you know, we not only looked at, you know, other models
17 within the nuclear industry that had been proposed, but
18 we asked the University of Michigan, Tyler Moss at the
19 University of Michigan, to take a look at initiation
20 models outside of nuclear.

21 So, you know, do a literature search, see
22 if there is anybody out there that is a little smarter
23 than the people in the nuclear industry, which might
24 have a better way to approach initiation than we have,
25 and let us know what you find. So he did that.

1 I don't want to go into a lot of detail,
2 but, you know, he actually found I think four or five
3 different models. One was a stochastic creep type model
4 which, you know, was basically completely randomly
5 determined type of a model. He found a perturbation
6 analysis model, and he found a couple of fatigue models
7 that -- one was based on a Maso crack initiation type
8 of a model, and the second one was all a
9 microstructurally based fatigue model.
10 And, actually, from my perspective that
11 last microstructurally based fatigue model, it seemed
12 pretty interesting the way it -- you know, it was
13 calculating initiation. Again, it is not directly
14 related to PWSCC, but it may be something to look at
15 for the future, you know, see if we can come up with
16 some parameters that might fit that.
17 So those are the kind of things that came
18 out of the literature, so we have a white paper that
19 was prepared by them. I'm sure it's available if you
20 guys were interested in looking at it.
21 So the main conclusions that came out of
22 both panels basically was that everyone agrees with your
23 conclusions that, you know, it is a challenging issue.
24 Initiation is, you know, something that is difficult
25 to predict. But, you know, as far as the experts are

1 concerned, they are unaware of any better approach to
2 modeling than the three models that were in Version 1.
3 And so, you know, their recommendation is to continue
4 with those for Version 2, which we have been doing.
5 Some short-term improvements that might be
6 considered were, you know, to look at, you know,
7 distributions on the variables which obviously we are
8 doing, and, you know, the Bayesian type of approach to
9 reduce uncertainties, which, you know, again, we're
10 looking at the available operating experience data and
11 incorporating that as best we can.
12 So they were very familiar with direct
13 models 1 and 2, especially after we had Yogen present
14 his model, direct model 2, you know. They weren't very
15 familiar with it at the beginning, but now they were
16 very familiar with it during the meeting.
17 Then, the Weibull model --
18 MEMBER SHACK: Champion.
19 MR. FYFITCH: Yeah. They had a champion
20 there. With the Weibull model, since it wasn't fully
21 developed yet during, you know, this meeting that we
22 had, they didn't really fully understand, you know, what
23 was done in Version 1 and what we are doing with Version
24 2 yet.
25 So I tried to show them our SRD that we had

1 prepared and explained, you know, what we're doing with
2 the Weibull model through that. It helped a little bit,
3 but, nevertheless, you know, they concluded that, you
4 know, it would have merit if it is thoroughly developed
5 and documented. So that's what we're progressing with,
6 and so they -- at the end of the meeting they agreed,
7 you know, that direct models 1 and 2 and the Weibull
8 model were the three models to go with.
9 But to take a close look at the Weibull model
10 and see, you know, if it does start to look like, you
11 know, if we're getting -- if we're making more
12 uncertainty with the Weibull model to forget that
13 approach and stick to the other two, because it seems
14 like we could control uncertainties a little bit better
15 with those two.
16 MR. RUDLAND: Steve mentioned SRD. That
17 is our software requirements documents. It's one of
18 our QA documents that lists the requirements of the
19 modules.
20 MR. FYFITCH: Okay. Next? We also talked
21 about the material factor, which you've heard Glenn
22 mention. Yes?
23 MEMBER BLEY: I'm sorry. On your last one,
24 it's not clear to me why using a Weibull approach ought
25 to give you wider uncertainty. The uncertainty -- the

1 big problems in the uncertainty look like it's
2 determining whether you are epistemic or random. And
3 that ought to apply no matter what you're doing. So
4 I don't quite understand that, or is it just some element
5 of the arithmetic you're doing that is --
6 MR. FYFITCH: I think the expert panel felt
7 that if you didn't model the Weibull approach correctly
8 the uncertainties could be --
9 MEMBER BLEY: Oh.
10 MR. FYFITCH: -- much worse --
11 MEMBER BLEY: Okay.
12 MR. FYFITCH: -- than, you know, what we
13 have with the direct models 1 and 2. And so, you know --
14 MEMBER SHACK: You've got nine parameters
15 with the Weibull, so --
16 MR. RUDLAND: But you're fitting data.
17 You're fitting a lot of data. You're fitting a lot of
18 different data into one -- you know, into one
19 distribution, right, so your scatter is going to be
20 larger.
21 MR. HARRINGTON: And the documents that
22 they were given initially before the meeting were
23 somewhat skewed toward Version 1 because we were still
24 developing the SRD and the other QA documents for Version
25 2. So they had read all of that. But in Version 1 we

1 had three models, but we really only implemented two.
2 We never populated the Weibull model fully with all
3 of the parameters for Version 1. So it was incomplete
4 at that stage, and that was their frame of reference
5 going into the meetings predominantly.
6 MEMBER REMPE: Since we have interrupted
7 you, why were they uncomfortable with the apparent
8 structure of the software requirements document? What
9 was the issue?
10 MR. FYFITCH: No, no. It wasn't that they
11 were uncomfortable with it. They weren't familiar with
12 the information, you know. Like has Craig has said,
13 you know, on the Weibull model, we didn't have a lot
14 of detail to give them on where we were with the current
15 approach for the model, the Weibull model today.
16 MEMBER REMPE: Okay.
17 MR. FYFITCH: At that point in time. So
18 I was going over what we had done in Version 1, and,
19 you know, didn't really use it in Version 1, so
20 that -- you know, that got in their heads, well, maybe
21 the Weibull is not that great of a thing.
22 So then I pulled out the SRD, the software
23 information that we have been working on, Kyle and
24 myself, and tried to walk them through, well, these are
25 the steps we are going through with the Weibull approach

1 to try to make it a better model, so that we can use
2 it for Version 2.
3 MEMBER REMPE: Okay.
4 MR. FYFITCH: So --
5 MR. RUDLAND: I think the
6 uncomfortableness comes from, you know, you have to
7 select the data you use in fitting the Weibull, and it
8 becomes a judgment call, you know. Instead of actually
9 modeling a process that we have, we have -- you could
10 put any -- any data you want and fit a Weibull, you know,
11 slope to it, and what does it mean, you know.
12 MEMBER REMPE: It's more expert.
13 MR. RUDLAND: Yeah, that's right.
14 MEMBER REMPE: Okay. Thanks.
15 MR. FYFITCH: But, you know, what it comes
16 down to, if yo look at direct model 1 and the Weibull
17 model, they are not that different. They are basically
18 the same kind of a model approach.
19 MEMBER REMPE: Okay. Thanks.
20 MR. FYFITCH: So the material factor that
21 is in, you know, direct model 1 from the AREVA work and,
22 you know, the Weibull model should include, you know,
23 a material factor within the Weibull model, which
24 obviously we are looking at. Direct model 2 already
25 has that inherently included in the approach when they

1 came up with it, when Yogen came up with it. So the
2 expert panel agreed, you know, material factor is a good
3 thing to have.
4 Same crack initiation models apply for
5 axial and circumferential. They agreed with the first
6 panel, so no change there. And then, use the available
7 field data for benchmarking the crack initiation models.
8 Again, they agreed with the first panel as well.
9 We got into a little bit about this aleatory
10 and epistemic, and so, you know, the one figure that
11 Dave showed earlier where we looked at the two, you know,
12 I tried to explain that. And I'm not a statistician,
13 so I didn't do a very good job.
14 So it got them talking about, you know,
15 aleatory and epistemic uncertainty, and they said,
16 "Well, Version 1 clearly showed that the overall process
17 is aleatory," which we all agree with. But, however,
18 there are some epistemic parameters of uncertainty
19 within, you know, that you can control, you know, like
20 weld variability or stress values, you know.
21 So basically that's the best I could, you
22 know, tell the expert panel, you know. I'll leave it
23 to the statisticians to explain it even better if they
24 try.
25 The majority opinion was that, you know,

1 we should continue to use the segmentation for
2 Version 2. However, let's -- you know, as I'll show
3 you later, let's go on with Version 3 and see if we can
4 maybe come up with a better way to approach that.
5 CHAIRMAN ARMIJO: What is the reason for
6 wanting to get away from segmentation?
7 MR. FYFITCH: It all pretty much stems to
8 coalescence. The panel was really uncertain, you know,
9 if you have a segment here and a segment here and you
10 have a crack initiate in each of those segments, is that
11 really realistic from what you see, what happens in the
12 field, or what happens in the lab?
13 You know, the whole coalescence approach,
14 you know, you get a little -- in some cases you get,
15 you know, a lot of cracks, you know, all around the weld,
16 and some of them never grow and some of them do coalesce,
17 you know. So we've got one here and one here, you know,
18 are you really modeling it correctly? You know, that's
19 their whole concern with the segmentation approach.
20 CHAIRMAN ARMIJO: But if everything was
21 uniform, uniform stresses, uniform material, uniform
22 everything, you would expect pretty --
23 MR. FYFITCH: Great. Yes.
24 CHAIRMAN ARMIJO: -- it would be perfect.
25 MR. FYFITCH: Yes.

1 CHAIRMAN ARMIJO: That's not how things are
2 built.
3 MR. FYFITCH: No.
4 MR. RUDLAND: Segment size has also been
5 a question, you know. It's basically another
6 calibration parameter, another tweak on parameter, and
7 why -- do we really need it? I mean, it's really not
8 necessarily needed. It used as convenience right now
9 for us.
10 MEMBER SHACK: I mean, how would you then
11 have multiple cracks?
12 MR. RUDLAND: Again, you'd just --
13 MEMBER SHACK: initiate --
14 MR. RUDLAND: -- your stress or your
15 whatever, it would still have to be variable by -- you
16 know, by the circumferential position.
17 MEMBER SHACK: It's a segment by another
18 name, then.
19 MR. RUDLAND: And, again, you know, within
20 xLPR, the only thing we use the segments for is for
21 initiation. Once we have initiated, the segments go
22 away, right, basically.
23 MEMBER SHACK: You have just discretized
24 that variation of the stuff around the thing, so
25 I -- yeah, I can believe that -- you know, I thought

1 that was one of the things you learned from Version 1
2 was that after a while it didn't make too much
3 difference.
4 MR. RUDLAND: Right, right.
5 MEMBER SHACK: You had bigger problems.
6 MR. RUDLAND: But we can't leave, you know,
7 segment size as something that is an inputted variable,
8 right, because it's got to be connected to the
9 calibration of the initiation models.
10 MEMBER SHACK: Unless you use a Weibull
11 thing. Weibulls are all --
12 MR. RUDLAND: Right.
13 MEMBER SHACK: -- connected.
14 MR. RUDLAND: Right, right.
15 CHAIRMAN ARMIJO: Okay.
16 MR. FYFITCH: All right. And they were
17 quick to point out to me that the current ASME code rules
18 for coalescence are not entirely correct, and I think
19 we all agree with that. And so, you know, they wanted
20 us to reevaluate for xLPR use, whether or not, you know,
21 we -- we can come up with a better way to approach
22 coalescence.
23 Glenn sort of touched on that, but, you
24 know, we didn't -- I don't want to go into a lot of detail
25 with it. But the basic consensus was --

1 MEMBER SHACK: Yes. But there's two
2 coalescences here. There is his initiation
3 coalescence, and there is your macro coalescence.
4 MR. FYFITCH: Right. Yeah. The micro and
5 the macro.
6 MR. HARRINGTON: And the expert panel got
7 wrapped around the axle on that topic over and over.
8 It was challenging.
9 MR. WHITE: I would comment -- this is Glenn
10 White -- that we did change for Version 2, the macro
11 coalescence, that the flaws have to touch to coalesce,
12 from a growth perspective. From a stability
13 perspective, we still use conservative rules for the
14 rupture model. So there was a change, and we're not
15 relying on any ASME code rules for coalescence for
16 growth.
17 MEMBER SHACK: But that is still an
18 uncertainty.
19 MR. FYFITCH: Definitely, yes. The
20 working definition of an initiated crack size, again,
21 is below the surface cold work layer. They agree, you
22 know, 200 microns, around eight mil, is the right number
23 to use. Variability in the weld material can be
24 captured by accounting for the stress. Again,
25 agreement with the first panel.

1 Value for the surface stress should be
2 correlated against hardness and yield strength. And
3 it could be used as the initiation threshold per se,
4 and that value is on the order of 350 MPa. But, again,
5 it is not a line in the sand, not a bright line that
6 you jump over and then you are going to crack. So you've
7 got to be careful with using that value.
8 CHAIRMAN ARMIJO: Steve, how would you deal
9 with the material that had no cold work surface layer,
10 just pristine solution annealed, but still under stress
11 from weld residual stress and applied stresses? If you
12 had no cold work layer, could you conclude it will never
13 initiate or it will initiate but it will take a long
14 time or what is --
15 MR. RUDLAND: You've got a couple of
16 different mechanisms. You've got a couple of different
17 things. You've got the bulk residual stresses from the
18 welding process. They can still contribute to
19 initiation.
20 CHAIRMAN ARMIJO: Right.
21 MR. RUDLAND: And you have that very thin
22 cold work layer that will contribute to initiation.
23 So if you don't have the cold work layer you just don't
24 include that in the definition of the stresses. But
25 you still have an ID stress --

1 CHAIRMAN ARMIJO: Sure.

2 MR. RUDLAND: -- that is driven by the bulk

3 residual stresses.

4 CHAIRMAN ARMIJO: I'm just trying to --

5 MR. RUDLAND: It would be lower.

6 CHAIRMAN ARMIJO: Yeah. I'm just trying

7 to -- you don't have a feeling for how important that

8 surface cold work layer is compared to the, let's say,

9 weld residual stress. I think it's --

10 MR. RUDLAND: It's very important.

11 CHAIRMAN ARMIJO: I think it's the name of

12 the game in many cases.

13 MR. FYFITCH: Yeah. I mean, you can run

14 a lab test and show that a highly cold work surface layer

15 is going to initiate much faster than one that has been,

16 you know, electrochemically cleaned of that cold work

17 surface.

18 CHAIRMAN ARMIJO: But it will still

19 initiate eventually.

20 MR. FYFITCH: But, you know, if the stress

21 is high enough, the temperature is high enough, the

22 material is susceptible enough, it will ultimately

23 initiate. It will just take longer.

24 MR. RUDLAND: And in the code we separate

25 those, so that you can play those games. You can look

at it and say, "Okay. What if I have a surface, what if I don't, how does that affect my results?" So --

CHAIRMAN ARMIJO: Okay.

MR. FYFITCH: All right. So moving on to, you know, recommendations for Version 3, their recommendations -- you know, Thierry Couvant at EDF, he is working at what's called the Materials Aging Institute, MAI, and they are doing a lot of modeling right now on initiation of cracks. And that effort is underway right now. It is going to be a few years down the road before we really see some productive, you know, results from it.

CHAIRMAN ARMIJO: What is that organization, Materials Aging? Is it part of a national laboratory, or is it --

MR. FYFITCH: No. It's a European group that has been organized. I forget who all is part of it.

MR. HARRINGTON: It is member organization that -- EDF kind of initiated it, but it is a consortium between EDF and EPRI and PEPCO. So --

CHAIRMAN ARMIJO: Very good.

MR. FYFITCH: So it's an initial group that is working on --

MR. HARRINGTON: And they look at a variety

of materials. I mean, they have some work on concrete and, you know, other things related to nuclear power.

MEMBER SHACK: They have been in business now for a number of years.

MR. FYFITCH: Yeah. Let's see, the second thing was further develop the strain rate damage model, the SRDM model approach, which is Yogen's model. They want to discourage oversimplifications, especially some of these key parameters for the Weibull slope and the power log exponent, because you can get forced errors and bias from that.

We want to continue to look at some of these out-of-the-box models that the University of Michigan identified as being available. We want to look at some of the manufacturing defect initiation models. We want to look at IGSCC, intergranular stress corrosion cracking for the BWRs, and also fatigue initiation models.

Also, looking at some of the hydrogen concentration effects on initiation, you know, the -- you know, as Glenn mentioned, there has been a lot of work recently on that, looking at zinc injection, particularly the concentrations, how that affects initiation. You know, it's basically a chemical mitigation effect for Alloy 600.

1 Incorporate the Bayesian analysis into the
2 efforts, multiple initiation sites per unit area for
3 the micro crack coalescence that we were talking about.
4 Then, crack size versus segment size area versus
5 database sample size, look at all of that, and see if
6 we can up with a better understanding of, you know, what
7 the available USPWR materials are, you know.
8 As Glenn mentioned, you know, when AREVA
9 was doing a lot of their work for the CRDMs, we had a
10 huge database of CRDM nozzle material. We had lab data,
11 we had operating experience, and so we were able to come
12 up with, you know, a very tight-fitting approach to our
13 model, and they would predict fairly well.
14 So, you know, the French regulator
15 completely agreed with the approach and allowed them
16 to continue to operate, inspect as necessary, and to
17 replace the heads, you know, when it came time to find
18 a crack. So, and that approach worked quite well.
19 And that's it.
20 MEMBER BLEY: Before you go on, you said
21 something twice, Steve, that I don't think you really
22 meant, but I --
23 MR. FYFITCH: Okay. If I said it twice --
24 (Laughter.)
25 MEMBER BLEY: -- but I just wanted

1 to -- this issue of the kind of uncertainty we're dealing
2 with, it is epistemic or random, that's not something
3 to be left to the statisticians. There is a lot of
4 engineering issues tied up in that, and I think from
5 what Dave said earlier you are not doing that. But that
6 just worried me; that is not an issue for the
7 statisticians.
8 MR. RUDLAND: I mean, we were using our
9 experts and trying to come to consensus on that kind
10 of thing. I mean, again, it's -- there is a lot of
11 judgment that is involved in it. And within the code
12 at least we are allowing the flexibility, so that if
13 the user wants to, again, change those around to see
14 what the impacts are on the results, they are able to
15 do that, because, again, the team can only make a
16 recommendation on what they think they are.
17 MEMBER BLEY: That's fine.
18 MEMBER SHACK: I'm a little concerned, you
19 know, that when you -- you are able to tweak all of your
20 models to give you roughly the right kind of initiation
21 over the 20 years. You know, you want to get .2 chance
22 of initiation. Well, they can all be tweaked to do that.
23 They can probably all be tweaked to fit the limited
24 database that you have on initiation.
25 The thing that you seem to be unable to do

is to get them to come up with cracks that are shallow enough to be consistent with experience. You know, everything is over halfway through, and it is just not the way the world works.

MR. RUDLAND: Then read the documents.

MEMBER SHACK: Now, is that in that initiation model, or is that in the residual stress model? And that's --

MR. RUDLAND: I think it's probably in the residual stress model.

MEMBER SHACK: Yeah. And I don't -- you know, I see you tweaking -- you've got two models. You know, it seems to me you need to tweak that more to control that. I mean, and --

MR. RUDLAND: Yeah. The document that you've got all of that information from was our Version 1 calibration document, right?

MEMBER SHACK: Right.

MR. RUDLAND: And so, you know, we have been working really hard on the residual stress thing to try to better -- come up with better ways to model the residual stresses, you know.

MEMBER SHACK: Well, at the moment, I'm not even worried about realistic. I'm just sort of worried, can I come up with some distribution of residual stresses

1 that gives me this magic thought that I'm not going to
2 have everything grow through the wall a whole lot faster
3 than I know it is in the real world.
4 As I say, I think there is -- I mean, the
5 other problem with our initiation model is it's one thing
6 to fit the generalized .2. It's another thing to
7 actually be able to measure material parameters on this
8 weld to know whether it is a .001 weld or a .3 weld,
9 and, you know, that -- to me that kind of thing is really
10 where the initiation models come in.
11 But once they all give you .2 for
12 initiation, I would suspect a lot of this other stuff
13 is really residual stress rather than initiation models.
14 And you're going to have to be looking at these both
15 in a very coupled way.
16 MR. RUDLAND: All we can do is benchmark
17 to the data that we have, right? And that's really all
18 that we can do. And hopefully, you know, and keep -- and
19 be able to, you know, use Bayesian techniques or whatever
20 as we learn more and more about the cracks that are out
21 there. But you're right, you're right. I mean, it's
22 a dual problem, right? I mean, it's a dual problem,
23 and we are juggling -- we juggle both those balls trying
24 to figure out which --
25 MEMBER SHACK: There's a lot of juggling

1 balls here, because you -- you know, you are never sure
2 when to stop juggling one and start juggling the other.
3 MR. RUDLAND: Which is why, you know, from
4 the regulatory side we are still debating on how best
5 to figure out how we want to -- if we want to include
6 those kinds of things like initiation in those
7 processes. So we want to make the code generic enough
8 to be able to do it without initiation, so that we can
9 look at deltas and not have to worry about the initiation
10 probabilities really driving the problems that we see.
11 Okay. Kyle, do you want to drive?
12 MR. SCHMITT: Sure. Okay. I am Kyle
13 Schitt. I work at Dominion Engineering with Glenn White
14 and Jeff Gorman. I have been -- had the pleasure of
15 being involved with Version 2 of the xLPR program, and
16 specifically I have been involved in the implementation
17 of the background documents and the code itself that
18 will carry out some of the models we have been talking
19 about today.
20 And I have had the help of technical
21 expertise from those in xLPR and those in the expert
22 panel. And I will be harkening back to a lot of the
23 stuff we talked about for Version 1, a lot of the stuff
24 we talked about for the expert panel, and Glenn will
25 feel free to chime in to make corrections or

1 clarifications or help answer questions.

2 Before I launch into the slide set, I just

3 want to reiterate that the focus for xLPR Version 2 still

4 remains on the dissimilar metal butt welds, especially

5 with regards to the initiation models. We have been

6 focused on that susceptible area of the primary side.

7 We have expanded in scope in terms of what

8 we can do for Version 2, and we are starting to look

9 at different components, whereas we looked at the surge

10 line nozzle for the pilot study, we have started to look

11 at different geometries as well.

12 And the other thing I will note before I

13 launch into the slide set is that the models are pretty

14 fixed at this point for Version 2. It is the parameter

15 estimation or the input selection that remains a work

16 in progress. And so, in addition to today's meeting,

17 we have had other meetings with the NRR and other expert

18 panels to continue to refine how we do that.

19 So I have about 20 slides here today, which

20 I have to get through relatively quickly, so that we

21 can stay on track. But this gives you an overview.

22 I'll start with purpose and scope.

23 I imagine we could get into some discussion

24 on the assumptions and simplification section. Then,

25 I will sort of give you a procedural high-level summary

1 of how the initiation works, sort of in code space
2 almost. And then we will go on to the description of
3 initiation time models, which Glenn spent some time on,
4 so I may not spend as much time there. And we will finish
5 up with things like parameter estimation.
6 In fact, my last slide gets into
7 weld-to-weld and within-weld variability. It gets into
8 things like epistemic and aleatory uncertainty, which
9 I'm sure we could spend the entire morning discussing,
10 but I'll at least try and touch on those things.
11 Okay. So the purpose of the PWSCC
12 initiation model, both in Version 1 and in Version 2,
13 reflect the probabilistic understanding of the
14 initiation process and represent historical plant
15 experience. So Bullet 1 and 2 are the key ones.
16 We want to reflect variance susceptibility
17 for different component types and materials, and where
18 we can we want to incorporate parametric dependencies
19 supported either theoretically or empirically.
20 And, finally, we want to be able to output
21 initiation times and initial crack sizes that are
22 consistent and sufficiently early in the crack
23 lifetime -- I say here "to accommodate downstream
24 modeling efforts," as in crack growth, inspection,
25 leakage, and so forth, the other things that the xLPR

1 program does.

2 Okay. So as you have seen, the Version 1

3 models were already developed, so this slide focuses

4 on what were our objectives for Version 2. Of course,

5 as Steve already talked about, we assembled an expert

6 panel and collected opinions and tried to incorporate

7 those as much as we could.

8 In doing that, we revisited our model

9 selection. We made some tweaks to the Weibull model.

10 We updated the data collection efforts, as of December

11 2012 I think we are current with. We updated some of

12 the parameter estimation, and perhaps the biggest effort

13 for Version 2 was doing all of this inside of a quality

14 assurance program, developing and -- developing the SRD

15 or the requirements document. And getting buy-in from

16 our many subgroup and group-level members has been

17 challenging, but the fruit of that labor I think will

18 be a very clear model report, which we will put out.

19 Okay. So now we get into assumptions and

20 simplifications. I'm going to note four over the course

21 of the next slides. This one actually has two slides

22 to support it, and that is the idea of spatial

23 discretization or, as we have referred to it,

24 segmentation. This is a method that we are sticking

25 with.

1 So procedurally the susceptible material
2 surface is separated into multiple equal area subunits.
3 The stress in each subunit is taken at its centerline,
4 and then initiation is simulated independently within
5 each subunit. Of course, the subunits are related by
6 their mutual parameters. You may have weld-to-weld
7 variability, which all subunits would have the same
8 parameter for, or things like operating temperature or
9 bulk temperature of the fluid.
10 This is in contrast to -- well, I should
11 say that discretization is common in computational
12 modeling. We often use it to reduce complex or
13 continuous geometries, the ones that are more tractable
14 from a modeling and simulation standpoint.
15 I think in the expert panel minutes I saw
16 some discussion of using a crack density rate approach,
17 which would eliminate the need for this sort of
18 segmentation. And I think that is something we may
19 revisit for Version 3.
20 CHAIRMAN ARMIJO: You know, I don't think
21 you have much choice. If everything is homogeneous,
22 dimensions are homogeneous, the stresses are
23 homogeneous, material is homogeneous, this is about the
24 only way I can see you attacking the problem. But so
25 many of the practical events have, you know -- it is

1 driven by, let's say, a weld repair and not a
2 circumferential weld repair but just certain segments
3 of the weld have been repaired, creating high stresses
4 or -- in that region.
5 So this is kind of a hypothetical. It's
6 not why things are failing. It's failing because people
7 have fabricated things in a very non-uniform way. And
8 I'm wondering if, once you finish with this, you'll say
9 if everything was fabricated perfectly, this is how it
10 will -- how we will nucleate cracks.
11 I don't doubt that it -- that that's the
12 way it will work out, but somewhere along the line we've
13 got to get back to what is really failing in service.
14 And I think it is driven by all sorts of fabrication
15 variability that is -- so I'm just wondering how you
16 are going to predict that kind of actual performance
17 versus this ideal performance.
18 MR. RUDLAND: The structure allows us,
19 though, to vary whatever we want within these subunits.
20 So we could have different stresses. We could have
21 different material properties. We could have different
22 whatever.
23 CHAIRMAN ARMIJO: So you could
24 overlay -- let's say I am going to do a one-quarter
25 segment of a weld repair there and have --

1 MR. RUDLAND: Each of the segments could
2 have a different stress.
3 CHAIRMAN ARMIJO: Oh. Okay.
4 MR. RUDLAND: Now, we have made some
5 assumptions for Version 2, but the structure is that
6 you could have any type of stress distribution within
7 any segment, and they don't have to be the same.
8 MR. SCHMITT: Right. Yeah. Maybe my
9 wording on that second bullet is a little confusing,
10 but that is the idea, that each subunit can possess its
11 own unique properties, be it material properties,
12 stress.
13 CHAIRMAN ARMIJO: So if you were comparing
14 a prediction from this thing to an actual field failure
15 leaks that had, let's say, a part of a weld repaired,
16 this tool would be able to say, "We can make a one-to-one
17 comparison."
18 MR. RUDLAND: The structure allows us to
19 be able to do that. Now, again, in Version 2, we have
20 made some simplifying assumptions because of issues of
21 time and money and things like that. But, yeah, the
22 structure is there such that we can vary any which way
23 we want the stresses, the material properties, in each
24 individual segment.
25 MEMBER SHACK: Whether you believe the

1 result is another question, but --

2 CHAIRMAN ARMIJO: But still, you know,

3 it's --

4 MR. RUDLAND: And that's why I -- it's kind

5 of important.

6 CHAIRMAN ARMIJO: It seems to me like a

7 pretty useful --

8 MR. SCHMITT: So how were the number of

9 subunits selected? may be a question you ask. The

10 subunit -- there are a few guiding points here. The

11 subunit length should be similar or larger to the

12 interaction distances associated with macro sized

13 cracks.

14 The subunit length should reflect -- or it

15 should have a sort of characteristic length on par with

16 the variation of -- I call it macroscopic drivers of

17 crack initiation. For instance, it should -- the

18 characteristic length of a subunit should reflect the

19 gradient of a stress change, for instance. Or, if you

20 had a local repair, it should be capable of separating

21 that area of local repair from the area not affected

22 by it.

23 But then you asked the question, well, if

24 I add more subunits, don't I sort of artificially drive

25 up my incident rate of crack initiation? And the answer

is yes. Now, there is a -- I think, Bill, you are the author on that paper listed. The Weibull model that we have actually includes a scaling term such that the probability of time to first cracking remains constant, no matter how many subunits you have, whereas with the direct models we haven't built that in.

So for the direct models, the subunit -- the number of subunits really needs to be treated as a parameter in the model, that if you use more subunits you may need to revisit the model parameters for the direct models.

Okay. And that brings us to the second assumption I wanted to talk about, which is the use of an engineering sized crack initiation.

Now, as we have heard from Steve, the expert panel recommends the use of micro-scale models, such that we could simulate initiation from 50 to 200 microns. This potentially gives us higher fidelity incident rates as well as aspect ratios for flaws by the time they grow to an engineering significance.

Now, Version 2, as currently written, plans to simulate the initiation of singly dominating cracks of engineering significance. I listed a few advantages to this. The initiation time and aspect ratio predictions can be informed by field detection data and

1 measured flaws that we have seen in the field. And we
2 ensure that the depth -- the initial depths we use are
3 consistent with the initial times that we use.
4 The inclusion of small cracks in xLPR, on
5 the order of 200 microns, should not significantly bias
6 our failure rates simply because detection at that level
7 is very unlikely. So the fact that these cracks are
8 in fact there earlier than the time that we are
9 simulating them shouldn't bias our results because they
10 are too small to be detected. So they will do as they
11 will, but we simulate it from the point of a larger crack
12 forward.
13 This has other practical advantages in that
14 some of the downstream models, especially the fracture
15 mechanics used to calculate K values of the crack tips
16 and simulate growth, rely on cracks of a certain size.
17 You get below that size and you start to have more
18 chemical dependencies, you start to have dependencies
19 on mechanical properties like yield stress that the
20 models that we have built into Version 2 don't -- aren't
21 currently able to simulate.
22 MR. WHITE: And our crack growth rate model
23 is based on K values starting about 15 to 20 megapascal
24 square root meter. If you start with a crack that is
25 relatively shallow, then, depending on the stress, you

1 may end up with a K below that range, whereas if we start
2 with something more like a millimeter and a half deep,
3 then you are reliably going to have a K that is in the
4 range of the laboratory range of K values used for the
5 crack growth rates we're using.
6 MR. SCHMITT: And, finally,
7 implementation -- for implementation reasons, this
8 makes our software performance a little bit faster.
9 Now, we have touched on several budding
10 areas of research that are going to help us tackle these
11 sorts of issues in the future. Glenn covered on the
12 short crack modeling initiation coalescence and growth.
13 There is also the QMN stuff, which may provide insight
14 that would help us in this area. But as of today, this
15 is the plan for Version 2.
16 Okay. We didn't really highlight this
17 today, because we were talking about PWSCC. But Version
18 2 also includes fatigue initiation mechanisms. This
19 slide just simply highlights the fact that we keep those
20 two mechanisms separate. The damages for PWSCC and
21 fatigue are not superimposed. The initiation times
22 aren't correlated.
23 And we don't have any clear technical basis
24 for the interaction between the two initiation
25 mechanisms, but it's something we list as an assumption

1 in our SRD document, and it is something we will keep
2 our eye on as we move forward.
3 And, finally, Dave touched on this. I
4 guess this is more of a simplification, and I called
5 it the initiation conditional run mode. And this is
6 where we can actually start our simulation assuming some
7 set of cracks and crack sizes.
8 The advantages to this, well, we have a
9 better handle on the sort of bulk probability of
10 initiation before 20 years than we have in the evolution
11 of initiation over those 20 years. So something like
12 this might allow us to, you know, simulate from the time
13 of initiation and then incorporate initiation
14 probability during the post-processing stuff.
15 The user may actually be interested in risks
16 when you have cracks, and that bottom bullet is another
17 example. This facilitates the assessment of
18 traditional deterministic LBB procedures.
19 So, mechanistically, the way this would
20 work is the user would specify distributed or
21 deterministic inputs for initial, you know, number of
22 flaws, depths of those flaws, lengths of those flaws.
23 So we would still have some random aspect to this.
24 But the risks would be conditional on the fact that you
25 had initiation prior to the start of simulation.

1 Okay. So --

2 CHAIRMAN ARMIJO: Do you need an

3 initiation? Isn't that what we can do right now with

4 regular -- start with a crack and grow it? Is it just

5 a little bit finer scale or -- I guess I don't understand

6 what this -- whether this is really something new or

7 something that we can do today using the existing models.

8 MR. WHITE: What you can't do with -- you

9 can't say enforce a distribution of crack sizes and

10 number of cracks from day one. So if you want to assume

11 there is some starting condition, for example, an

12 operational assessment, you typically assume some

13 distribution of numbers of flaws and sizes of flaws,

14 and don't model the time to initiation. Or you may

15 assume there are some new flaws that initiate during

16 your cycle, but you also start off with flaws.

17 So you don't start at time zero when the

18 plant starts up. You start at a certain -- beginning

19 of a fuel cycle, for example. So this would have that

20 capability, be able to move -- start from day one in

21 your analysis, presuming some distribution of flaw sizes

22 and numbers.

23 CHAIRMAN ARMIJO: Okay.

24 MR. RUDLAND: Just added flexibility to how

25 we can run the code.

1 MR. WHITE: So if you want to look at that
2 question, what if -- Bill earlier mentioned, you know,
3 how many flaws are you getting in your analysis? Well,
4 you may want to not rely on tweaking your initiation
5 inputs to get that. You can directly bypass that and
6 enforce that starting initial condition and say, "I want
7 to assume there are five flaws all the time," and they
8 have a certain size range and --
9 CHAIRMAN ARMIJO: Yeah. Okay.
10 MR. WHITE: -- the code can do that work
11 for you and look at that case.
12 CHAIRMAN ARMIJO: All right. Thank you.
13 MR. WHITE: Okay. So I thought before we
14 got into the detailed models I would give you sort of
15 a high-level overview. There is just one slide on this.
16 The font may be a little small here, but
17 I will try and sort of take you through step by step.
18 Step 1 in the xLPR program is to set the stress profiles.
19 We take into account operational types of loading, as
20 well as the weld residual stresses or residual stresses
21 imparted by different mitigation methods. So that is
22 set right off the bat.
23 Then, as we have already seen, we sort
24 of -- we segmentize our ID surface. And that is where
25 we begin our loop. We look at each subunit, and within

1 each subunit we simulate the initiation process.

2 Now, the program also can take into account

3 changing conditions. So if you have a changing stress,

4 a changing temperature, over time we take account for

5 that inside of what you see here as the time interval

6 loop. And we use something similar to a Miner's rule

7 to account for changing conditions over time.

8 And you see the equation there in the bottom

9 left where we use our initiation time models, which I'm

10 going to spend the rest of this presentation talking

11 about, to predict an initiation time under those fixed

12 set of conditions. And we compared that initiation time

13 to the duration under those fixed set of conditions to

14 give us an incremental damage, and we -- some of those

15 incremental damages until we reach one, at which point

16 initiation is considered to occur.

17 And as has been mentioned several times

18 today, we have the ability to use three distinct models

19 for PWSCC initiation, and --

20 MEMBER SHACK: Has anybody else run a test

21 to do a Miner's rule for this initiation? Or do we just

22 assume that?

23 MR. SCHMITT: I have not seen a definitive

24 source, although I have seen the use of this type of

25 approach. It is similar to normal sort of adjusting

1 your time, such as using effective degradation.

2 MEMBER SHACK: Well, we use it all the time.

3 Whether it's -- I'm just trying to think if I've ever

4 seen an experiment that could -- I personally have not.

5 MR. SCHMITT: All right. So then we are

6 going to get into the initiation time models. As

7 mentioned before, Glenn covered a lot of this.

8 CHAIRMAN ARMIJO: Kyle, could you go back

9 to that Slide 13? Now, this is where you -- what you've

10 got right now, but eventually you set the goal of this

11 program to have one model as opposed to three, instead

12 of direct model 1, direct model 2, Weibull. Is it

13 really -- is that -- maybe I should ask --

14 MR. RUDLAND: No. It's not the goal. The

15 goal is to try to keep it as flexible as possible. And

16 at this point, I think we would like to be able to keep

17 as much flexibility as we can. Ideally, you know, the

18 way it's set up -- the way the code is set up is that,

19 you know, if somebody else comes up with a different

20 fracture mechanics-based model, or a different crack

21 growth-based model, that these things can be easily

22 ported, right? And so this is our -- an example of how

23 those things can be ported.

24 We actually have three models here. They

25 can be used, you know, per the user's input, and we would

1 do the same for any other model that we had duplicate
2 models for.
3 MR. HARRINGTON: Right now, that is the
4 only place we have multiple models, isn't it? But we
5 have the ability to put multiple models other places.
6 MR. SCHMITT: In our view, if modeling
7 precedence exists for these three different close form
8 initiation models, and they do, then we want to have
9 the flexibility to include that, regardless of if they
10 should, in theory, you know, give the -- give similar
11 results with the same data set.
12 MR. RUDLAND: And the team plans to, as part
13 of their, you know, final development of the code
14 recommend defaults for all of the inputs for the lines
15 that are specifically -- that we are looking at for this
16 particular LBB issue.
17 So the user then can make that decision on
18 whether they like for the regular -- decide whether or
19 not they approve those particular inputs that we have
20 used. That is part of the team development. But,
21 again, the whole goal of the program is not to be specific
22 and to be dictating which models should be used, but
23 making recommendations and giving options.
24 MEMBER SHACK: I mean, especially where the
25 models are uncertain. I mean, you know, if we were

1 absolutely positively convinced that direct model 2 was
2 it, that would be one thing. But, you know, this one,
3 if nothing else you can always try the three models and
4 see just how much difference it would make.
5 MR. HARRINGTON: If we have a dramatic
6 revelation in the next two years, and we know finally
7 what causes PWSCC --
8 MR. RUDLAND: This is it.
9 MR. HARRINGTON: -- then I guess we
10 could --
11 CHAIRMAN ARMIJO: But right now there is
12 no favored or no reason to favor any one of these three.
13 MR. HARRINGTON: No.
14 CHAIRMAN ARMIJO: Okay.
15 MR. SCHMITT: Okay. So I am going to try
16 and wrap this up in the next 20 minutes. And I know
17 we really want to get to the parameter estimation stuff,
18 so I may go sort of quickly through the initiation.
19 So Glenn covered all of this material.
20 What he referred to as the material index model, we refer
21 to in xLPR space as direct model 1. This model had been
22 used deterministically for some years in France, since
23 it has been used probabilistically, as Glenn described.
24 And, in fact, it has been applied and practiced by EDF
25 and AREVA for reactor vessel head nozzles.

1 So getting into the model form and
2 dependencies, you see the equation in the right. It
3 includes dependencies for both surface stress as well
4 as temperature. It includes a parameter out front that
5 you see there, A, which is the material index, and this
6 is going to be important during our parameter estimation
7 talk, because it is there that we are going to capture
8 some of the uncertainty or variability in the initiation
9 process.
10 And then, real quickly, we have
11 recommended, again, inputs is a thing we can always
12 change down the road. But at this point we have
13 recommended the use of the stress exponent of four and
14 the activation energy somewhere between 180 and 210
15 kilopascals. That's somewhere between 40 and 50
16 kilocals per mole.
17 CHAIRMAN ARMIJO: Are those the -- what the
18 French use in this?
19 MR. SCHMITT: The activation, you mean?
20 CHAIRMAN ARMIJO: Yeah.
21 MR. SCHMITT: EDF uses 44 kilocals per
22 mole.
23 MEMBER SHACK: You just have to do the
24 conversion in your head, Sam.
25 (Laughter.)

1 CHAIRMAN ARMIJO: Yeah. I can't do it fast
2 enough, so I'm just going to be quiet.
3 MR. WHITE: More recently there has been
4 discussion that, you know, should something closer to
5 that for crack growth be used. So that is something
6 that we are -- you know, we are looking at -- the point
7 is that if crack growth makes up a significant portion
8 of crack -- of what is reported as the crack initiation
9 time, that may tend to drive down the activation energy.
10
11 So that is -- you know, there is more
12 uncertainty in the initiation activation energy than
13 growth because it is a less well-defined process. So
14 that's something we're looking at.
15 MR. SCHMITT: All right. A few slides here
16 on direct model 2, which Glenn referred to as the cold
17 works SCC model. The cold work SCC model is based in
18 strain rate damage model methodology. Again, it is
19 based on the assumption that SCC is dominated by the
20 crack trip strain rate disrupting the protective oxide
21 ion films. And it strives to quantify a relationship
22 between those things.
23 And Glenn just -- we went into some detail
24 on the validation efforts that we have been looking at
25 for this particular model. So here you get a good look

at the model form and dependencies again. Once again, we have dependencies for temperature and stress.

However, now we include dependencies from a mechanical properties yield stress and ultimate strength. And we use these properties to sort of estimate proxies for the cold working process, as we will see on the next slide.

There are near threshold stress responses included. We talked a little bit on the low end. There is also the ability to use sort of an upper threshold at which point you say initiation occurs immediately. That is not something we have spent a lot of time and effort on developing.

And, once again, you see that parameter capital B out front. This is the capital -- the same capital B that David Rudland mentioned as -- or Dave Rudland mentioned as driving some of the risk in the pilot version. And this is what Garud refers to as the material environmental uncertainty parameter, and we are going to take advantage of that in our parameter -- or in our sort of calibration.

CHAIRMAN ARMIJO: Is B something like the A in the material index, or does it incorporate it?

MR. SCHMITT: The A material index is intrinsically -- it is an intrinsic value for the

1 material susceptibility as in microstructural type
2 things.
3 CHAIRMAN ARMIJO: Okay.
4 MR. SCHMITT: Whereas, as presented by
5 Garud, the factor can take into account both material
6 as well as environmental variability.
7 CHAIRMAN ARMIJO: Okay.
8 MR. SCHMITT: Functionally, very similar.
9 And we are going to use them very similarly when we
10 try and calibrate or benchmark to field data.
11 MEMBER SHACK: I get very confused with
12 sigma and the yield stress and the ultimate stress in
13 here, and especially when you've got the yield stress
14 is less than sigma, less than sigma maps.
15 MR. SCHMITT: Oh. You know, that should
16 be less than sigma threshold. That is a typo. So
17 that -- the model in the middle, the equation in the
18 middle, applies between two stress thresholds.
19 MEMBER SHACK: Okay. The yield stress
20 that we are talking about, is that the yield stress in
21 the uncold work condition? That is the native yield
22 stress? Or is that now the yield stress after my cold
23 work? That is the current yield stress?
24 MR. SCHMITT: Yes.
25 MEMBER SHACK: Okay. And then sigma is my

1 current applied stress, which can be floating around
2 somewhere in this thing, and so I have two sorts of
3 separate things. I have one that represents cold work
4 and one represents load. Is that -- okay.
5 MR. SCHMITT: And, actually, here we break
6 it down into more detail for you, without any typos this
7 time.
8 So Garud relates cold work and the
9 deformation, kinetics, parametrically, with the series
10 of equations you see here. And with the laboratory data
11 that he has he uses I believe maximum likelihood
12 estimation to come up with estimates for the 10
13 parameters that we saw before.
14 CHAIRMAN ARMIJO: Now, E will give you
15 that --
16 MR. SCHMITT: Yeah. He doesn't
17 actually -- he doesn't regress E, but yes.
18 Okay. So that has been done for us, and
19 we have been working on the model validation as well.
20 So a lot of the parameters are -- in fact, 10 of the
21 parameters are regressed from data in a laboratory
22 setting, whereas we still have that B parameter that
23 sits out front of the model that we can use to sort of
24 relate the results in laboratory to those seen in the
25 field, while preserving the knowledge that we got in

1 the laboratory about the effects of cold work on
2 initiation.
3 Okay. And then I have a few slides here
4 on the Weibull modeling. Weibull modeling is a classic
5 approach for reliability engineering and failure
6 analysis. Now, even though it has a different name
7 than, say, the material index approach, it is very
8 similar, as we are going to see on the next slide.
9 It is an equation which with one key
10 uncertain parameter that parameter just happens to have
11 a Weibull distribution as opposed to an undefined
12 distribution. I believe they use log normal
13 distributions for the material index parameter for
14 direct model 1.
15 But the advantages of the Weibull modeling,
16 what I have seen in literature is that it is an accurate
17 way to regress failure when you have a small sample set,
18 you know, you have a limited amount of failures in your
19 population.
20 It is amenable to classical parameter
21 estimation methods. In fact, there is a 400-page book
22 in our office by Abernathy that gets into these details.
23 It has been widely and successfully used for modeling
24 PWSCC affecting steam generator tubes, and, as Glenn
25 mentioned, it has been used in MRP-type studies on CRDM

1 nozzles as well as dissimilar metal welds.

2 So we think about the Weibull model more

3 statistically, even though functionally it is very

4 similar to the other models that we have presented.

5 So we say we sample an initiation time, but, really,

6 what that boils down to is -- really, what that boils

7 down to is sampling a number and then scaling it by some

8 parameters and some inputs.

9 Again, we include a temperature dependency,

10 a stress dependency, and, as you see in the root, we

11 also include a number of subunits dependency, which is

12 that normalization term that I talked about earlier in

13 the presentation. Okay.

14 MR. WHITE: I would just say that the theta,

15 if we can go back, the theta is the analog of the material

16 factor.

17 MR. SCHMITT: Okay. All right. Which

18 brings us to the parameter estimation. Just a few ideas

19 before we get into the slide with the details. The first

20 idea is that when you do parameter estimation, you want

21 to take credit for as many of the parametric dependencies

22 as you can. As you have seen in some of the models,

23 we have temperature dependency, stress dependency.

24 So we want to use regression where we can,

25 with laboratory or field data, to come up with best

1 estimates for these parametric dependencies. But what
2 we can't get with our parametric dependencies we need
3 to treat statistically, and that is the scatter in our
4 data around our best fit.
5 And the uncertainty that we want to reflect,
6 statistically we want to be representative of what we
7 have seen in the field instead of what we have seen in
8 the laboratory.
9 And then the other thing I will mention is
10 data pooling. The idea of data pooling is important
11 for parameter estimation, not -- Glenn talked a little
12 bit about this, where we could have pooled the failures
13 we have seen in multiple different locations and come
14 up with a model. That model inevitably would have more
15 scatter than if we just look at a specific component
16 type, just look at a specific location, just look at
17 hot leg components, say.
18 What we have strived for in the Version 2
19 effort is to look at dissimilar metal butt weld ID
20 surfaces, although we have looked at several different
21 geometries. We have looked at failures in RCP nozzles,
22 SG nozzles, and so forth, relief nozzles. So that is
23 the parameter estimation I will be talking about here.
24 Okay. So talking about direct models 1 and
25 2, we saw that they both had that scaling parameter that

1 sits out front. So you take care of what parametric
2 uncertainties you can, or parametric dependencies that
3 you can, but you always have that parameter sitting out
4 front that can be useful in sort of calibrating or
5 benchmark to field -- benchmarking to field data.
6 So the laboratory setting is nice, because
7 we can isolate our condition -- certain conditions.
8 But we have seen that the laboratory results can in fact
9 be -- can perhaps be biased and less dispersed than PWSCC
10 initiation that we see in the field. And so we want
11 to be able to account for that.
12 Okay. And Dave mentioned this -- for
13 Version 1 of xLPR, we used what we call calibration
14 studies to try and develop realistic values for our
15 parameter -- for that scaling parameter and the
16 uncertainties in that scaling parameter.
17 So this slide sort of discusses the
18 procedure of that calibration process. We use a
19 software called WinPRAISE to simulate the initiation
20 followed by the growth to failure. And so we pick some
21 benchmark metrics. Those might include rate of
22 initiation, probability of failure, rate of failure,
23 average number of flaws that grow past a certain size.
24 And then for each one of those benchmark
25 metrics we select a target, and that target is based

1 on industry experience. And then we can vary the number
2 of subunits, we can vary the median scaling factor, and
3 we can start to look at things like weld-to-weld
4 variation or within-weld variation. And we alter those
5 values to try and meet the targets we have set for our
6 benchmarking metrics.
7 And then, I guess I didn't mention this on
8 the slide, we stick to WinPRAISE software and sort of
9 a Monte Carlo type of loop, and that is how we are able
10 to generate the probabilities and the averages, and so
11 forth.
12 So that is what we did at Version 1. That
13 is what we plan to do for Version 2. What Version 1
14 did not do is it didn't include the residual stress model
15 variability, which if you -- I think it just assumed
16 one deterministic profile, and it simulated with that
17 profile for every simulation.
18 So it didn't take into account the
19 variability in the residual stress field, so the
20 uncertainty is that we may have calibrated for Version
21 1, may have sort of double-counted the uncertainties
22 that are due to variability in the residual stress
23 profile.
24 So when we revisit this calibration effort,
25 that is certainly something that we will take account

1 for.

2 The other thing the Version 1 effort didn't

3 do is it didn't -- it actually did not include the

4 within-weld variation. So we believe by using that we

5 should be able to get closer on some of our benchmarking

6 metrics.

7 Okay. So then I will talk a little bit

8 about the parameter estimation for the Weibull model,

9 which is mechanistically different than a calibration

10 study. With the Weibull model, we are in fact talking

11 about more of a Bayesian maximum likelihood estimation

12 approach. Prior to the estimation, we want to try and

13 normalize or adjust our data to common reference points.

14

15 We are able to do this for temperature

16 because we have a pretty good handle on what the

17 temperature of the components were in the field, the

18 components that we saw failures in, and those that we

19 did not see failures in.

20 Service stress is a little different. We

21 don't have a very good handle on what that was, and so

22 we are not able to adjust to a common reference point

23 for stress. And that makes things a little tricky, as

24 I think I will talk about on the next slide.

25 So after we have adjusted everything to a

1 common reference point, as I mentioned there is a lot
2 of classical literature out there on how to do the
3 maximum likelihood estimation for Weibull parameters.
4 So we used those methods to develop best estimates for
5 our two Weibull parameters. One is called the shape
6 parameter, and sort of defines -- it is sort of like
7 a shift parameter in how far out the distribution is
8 in time.
9 And the other is a slope parameter, which
10 defines sort of how quickly other initiations will occur
11 after the time that you start seeing failures. So sort
12 of the rate of -- how quick -- you know, I don't know
13 if I can -- Glenn might be able to describe it.
14 MR. WHITE: The scatter in times to
15 initiation.
16 MR. SCHMITT: Right. Now, in addition,
17 with the Weibull model we can use maximum likelihood.
18 Actually, we use ordinary least squares type methods
19 to develop uncertainties for the parameter estimation.
20 I consider this one of the key advantages of the Weibull
21 model -- the classical approaches that exist that allow
22 us to use data for failures as well as data for
23 non-failures, where we have inspected a component and
24 we haven't seen failures.
25 And we can use all of this information

1 within a validated framework to develop best fits for
2 our Weibull model as well as develop uncertainties for
3 our Weibull model.
4 So this slide catalogues all of the
5 detection data that we compiled as of December 2012.
6 You will see here we now have 20 indications, I believe.
7 In 2007, we had only 13, so there is a little more
8 information out there. But we have also compiled all
9 of the inspections -- well, as many of the inspections
10 where we haven't seen initiation, so that we can
11 incorporate that information.
12 One additional step that we took, which I
13 will let Glenn talk details on, is we took note of when
14 overlay had took place in the component history because
15 we understand that the scope of post-overlay inspection
16 is not the same, and would not be expected to find small
17 cracks as prior to overlay. I don't know if you --
18 MR. WHITE: Right. So with weld overlay
19 usually the weld overlay was commonly used on the
20 pressurizer nozzles. It has also been used on hot leg
21 components, but the pressurizers were mostly mitigated
22 using overlay, and usually there was not a performance
23 demonstration exam before the overlay.
24 The overlay gives you a better surface to
25 do inspections on. And after you overlay, then the

1 volumetric -- the examination volume required by the
2 code case is owing the outer half or 25 percent of the
3 original wall plus the overlay. So we don't want to
4 take credit for post-overlay exams, because they would
5 not be required to find flaws in the inner portion of
6 the original wall.
7 So essentially those places are overlaid,
8 so they are -- they have been mitigated. But we don't
9 know that -- whether or not in fact that there were flaws
10 in the inner portion of the original wall, so we don't
11 include them in the Weibull fit at all.
12 The other comment I have is that we are at
13 a point now that -- where the large majority of the
14 locations have either been mitigated or had a
15 performance demonstration exam performed. So now we
16 are getting more complete inspection statistics. And
17 we will, you know, of course have to track how that
18 develops over time, but this is a difference from a few
19 years ago where the exams were -- the first baseline
20 exams were still, you know, being performed.
21 So we think we have, you know, better
22 statistics now. And the reason for the -- you know,
23 the 20 welds with indications, you know, that frequency
24 is -- you know, versus 589 locations where there have
25 been exams of that inner portion using the performance

1 demonstration techniques, that is a fairly low incidence
2 of cracking.
3 And what we think is that reflects, you
4 know, the real range of stress conditions. Some places
5 may not have weld repairs. The surface stresses may
6 be fairly low, even compressive. Some configurations
7 the root is completely machined out, and you may have
8 compressive stresses at the inside surface.
9 And that situation is different than CRDM
10 nozzles where we reliably have stresses near yield level
11 or higher than the nominal yield level, you know, on
12 the inside and outside of a tube. And so that -- you
13 know, that is the challenge, where we have laboratory
14 data that is used to fit these sort of models.
15 You know, we reliably know the stresses are
16 high, and were intended to be high. When we look at
17 the field data, the incidence of cracking is less than
18 you would predict for the field data, and, again, it's
19 the difference between the assumed stress and the actual
20 stress in the field is a big part of that I think.
21 MR. SCHMITT: So to wrap up the latest
22 Weibull model parameter estimation, we took the data
23 as of December 2012 and we redid our Weibull fit. And
24 so you see the updated characteristics of our Weibull
25 model.

1 On the X-axis, you see EDYs, and on the
2 Y-axis you see cumulative fraction of -- does that say
3 units with cracking? Does that say --
4 CHAIRMAN ARMIJO: Maybe it's components?
5 MR. SCHMITT: Okay. So that just gives you
6 a sense for the characteristics of the model we plan
7 on using as a first shot for Version 2.
8 MR. WHITE: And then the fairly low slope
9 of 1.4, you know, that's close to -- a slope of one is
10 an exponential function, which is a constant hazard
11 rate, which is saying that the hazard rate, if you still
12 haven't cracked yet, your chance of cracking in the next
13 year is the same every year going forward.
14 Slope of 1.4 is a little bit more aggressive
15 in that. The hazard rate is starting to -- will start
16 to increase with an aging effect over time. But it is
17 still a fairly low slope, indicative of just a large
18 range of uncertainty due to the -- not correcting for
19 the stress and the difference in the fabrication of all
20 of the welds and surface condition, and so on.
21 MR. SCHMITT: So, as promised, here is one
22 slide on something we could spend the entire day on.
23 And that is some more details on the characterization
24 of uncertainty. We want to allow, both within weld and
25 weld to weld, variation for initiation, where

1 weld-to-weld variation is due to differences in the
2 material heat or the welding procedures, so forth,
3 within-weld variation accounts for microstructural
4 differences and various other things that can be going
5 on to change the initiation rate around the surface of
6 the component.
7 The direct model scaling parameters that
8 we talked about are being separated into the two sources
9 of variation. And then the sort of dispersion or
10 variability for each of those sources of variation are
11 going to be estimated through the calibration procedure
12 that we talked about.
13 For the Weibull model, the Weibull
14 parameters, the theta and the -- well, the slope and
15 the shape parameters, those will be considered to be
16 weld-to-weld variations. Those will get sampled once
17 and apply to the entire weld.
18 But then the samples that are taken from
19 the Weibull distribution with those parameters, and that
20 is the larger chunk of uncertainty, will be done on a
21 within-weld basis. In other words, it will be
22 independently sampled for each of the subunits or
23 segments that we talked about earlier.
24 One bullet on the separation of aleatory
25 and epistemic uncertainty. It is our consensus within

1 the initiation subgroup that for Version 2 we will let
2 the weld-to-weld uncertainty be epistemic, as in lack
3 of knowledge sorts of uncertainties. Whereas the
4 within-weld uncertainty, which I expect to be the bigger
5 chunk of the two, will be aleatory.
6 So the use of epistemic uncertainty for the
7 weld-to-weld uncertainty accounts for the fact that
8 different welds, different procedures within the field,
9 we don't have a very good handle on that today. Could
10 we have a better handle on it? I think the answer is
11 yes.
12 So we believe some of the uncertainty is
13 reducible, and so this is how we plan to parse those
14 two sources of uncertainty, two types of uncertainty.
15 Finally, just a quick bullet, we have built
16 in the ability to correlate initiation parameters with
17 growth parameters. And that gives us the ability to
18 say that if I have faster time to initiation I might
19 have faster growth after normalizing for things like
20 temperature and stress, and that -- there have been some
21 studies to show that.
22 MR. WHITE: Well, in terms of the base
23 metal, for example, CRDM nozzles, we have one group that
24 is known to have the most frequent incidence of cracking
25 in the field. And then that heat was tested at ANL and

1 found to have a relatively high crack growth rate. And,
2 again, from the microstructural features that tend to
3 give you higher crack growth rates would be expected
4 to give you faster initiation times.
5 MEMBER SHACK: Do you correlate those in
6 any way in the model?
7 MR. WHITE: We have allowed that as a
8 placeholder, but we don't think that --
9 MEMBER SHACK: You sort of recognize it's
10 there, but you --
11 MR. RUDLAND: And, again, it can be
12 something in sensitivity studies that we could look at.
13 MR. SCHMITT: So I'll wrap up with two
14 slides here on conclusions. Pilot study implemented
15 three approaches, which we have talked about extensively
16 today. It is the view of the expert panel and in fact
17 the view of the working team on Version 2 that we keep
18 those three models.
19 We talked about some of the key assumptions,
20 both the segmentation of the component and the
21 initiation of flaws on an engineering-type scale. The
22 xLPR Version 2 focus has been on the QA procedure, the
23 collection of new data, and the statistical evaluation
24 or statistical estimation of parameters.
25 There will be a renewed calibration effort

for the direct models. Again, the models themselves are pretty fixed, but we have some time to develop inputs, and we will do that.

And we have also spent a big chunk of our initiation team's resources on the development of the fatigue initiation module, which we didn't get into today. But that took up a good chunk of our time.

MEMBER SHACK: I have sort of forgotten -- the original PRAISE only assumes an initial flaw, and then lets it grow by fatigue. It doesn't initiate fatigue, does it?

MR. SCHMITT: Right. Well, actually --

MR. RUDLAND: I think the newer versions of PRAISE do have initiation models in them.

MEMBER SHACK: Oh, they do.

MR. RUDLAND: Yeah. Based on what -- ANL's work.

MR. SCHMITT: And, finally, I will leave you with this, the modeling of initiation is extremely challenging because of the complexity, some of the knowledge gaps or just information or data gaps. We have some data but maybe not the key things that we'd like to know. And so the statistical approaches we have talked about are key moving forward until there is more information out there.

1 CHAIRMAN ARMIJO: Okay. So here is new
2 data.
3 MR. SCHMITT: Yes. Which actually brings
4 us to a discussion of our new testing.
5 CHAIRMAN ARMIJO: Unfortunately, this is
6 a topic that I'm very interested in, and we are running
7 a little bit behind schedule and we are going to have
8 a -- so I'm just going to have to encourage you to move
9 it along.
10 MR. DUNN: Okay. Well, we can certainly
11 ask questions maybe if we have time to digest it.
12 I'm Darrell Dunn. I'm a materials engineer
13 in the Office of Nuclear Regulatory Research, Division
14 of Engineering, in the Corrosion and Metallurgy Branch.
15 And I'm going to talk about expansion of the PWSCC
16 initiation database.
17 So a little bit of an outline, talk about
18 some of the possible initiation data needs. And I will
19 talk some about initiation testing in general. I'm not
20 going to go into too much about test methods. I will
21 touch on that a little bit.
22 I'll talk more about some of the challenges
23 and how we might -- how we might address those with one
24 of the examples, and then finish up with a little bit
25 of discussion on our ideas for a proposed cooperative

1 effort and why we might want to do that.

2 So I think in some of the previous

3 presentations we have talked about the need to have

4 stress and temperature effects, better data on stress

5 and temperature effects for Alloy 600, 182, and 82,

6 within the xLPR model to do the calibration or

7 verification of those models. That certainly is

8 something that would drive the need to have better

9 initiation data.

10 Beyond that, and maybe in -- perhaps in

11 later versions of xLPR, there is an interest in looking

12 at 690 and some of the higher chromium weld metals, 52

13 and 152, for a number of reasons -- getting a comparison

14 of those materials to 600, 82, and 182. We do that in

15 crack growth rate testing.

16 In some of those dissimilar metal welds with

17 those higher chromium weld metals, we have weld dilution

18 zones where we are going to have a variation in

19 compositions, and we are doing some testing on those

20 in terms of crack growth rates. But the interest is

21 whether or not those variations and compositions could

22 also be more susceptible to initiation.

23 And also, I have mentioned weld defects

24 here. Certainly, in terms of the original material,

25 600, 82, and 182, the weld effects were implicated in

1 some of the initiation sites. A limited number of tests
2 have been done with the higher chromium weld metals,
3 is somewhat variable, and so we don't really have an
4 idea of whether or not those weld defects will result
5 in initiation or not.
6 And then, finally, the effects of cold work,
7 which has been shown to accelerate PWSCC growth rates
8 with 690, and also weld heat effective zones, which may
9 have some amount of residual plastic strain as well.
10 So the diagram here, the plot on the left
11 is somewhat similar to the one that Glenn showed from
12 Staehle. And the thing I really want to point out here
13 is that, obviously, once we get to Stage 4 where we have
14 crack growth, the percent of the usable life or fraction
15 of life has been pretty well used up.
16 And so the key, really, is to detect
17 initiation in this region that is Zone 3, which is small
18 crack growth. So I have a couple of examples on the
19 right that show in terms of what happens to the specimen
20 at those different stages, and the first one in Zone
21 2 is there is some intergranular attack, and some surface
22 oxidation, and, in Zone 3, we actually have some cracks
23 that occur.
24 So the test methods that we use that
25 would -- we would want to utilize to get initiation data

have to be able to -- be able to detect essentially submillimeter size cracks, and we have to keep in mind that we are at high temperature and high pressure environment. So doing very labor-intensive types of test methods where we are putting something in solution and then taking it out and examining it really isn't a practical way to go.

We really have to have some type of instrumented test specimens to detect initiation in a more elegant way, and certainly detect initiation that is -- you know, much smaller initiation events rather than what you would see for a typical U-bin specimen where you have, you know, gross cracks on the specimen after the material has been tested.

So instrumented test specimens have been used. Glenn mentioned some of them, you know, tensile specimens. People have even instrumented U-bin specimens, and the like. So I will give an example of one of these in another couple of slides, but I would like to talk about some of the challenges for doing some of the initiation testing work.

We are certainly aware of the challenges, and one of them really is that, you know, the time for initiation may be very lengthy. So particularly if we go to lower stress, lower temperature, we should expect

1 our initiation times to be quite long, or if we had
2 material that was just resistant to initiation.
3 There have been a number of ways that people
4 have tried to accelerate testing using cold work,
5 elevated temperatures. The question really is whether
6 or not those methods are acceptable means to accelerate
7 initiation testing and how would you use that data -- how
8 would you account for those acceleration factors in
9 models.
10 There are environmental and material
11 parameters that I think we have talked about, so I am
12 not going to address those any more than that. There
13 could be some parameter interactions, combinations of
14 materials, stress, and environmental parameters that
15 may alter initiation susceptibility.
16 Again, one of the challenges is detecting
17 and verifying initiation time. I am involved in a lot
18 of crack growth rate testing. The advantage of the
19 crack growth rate testing work that we are doing is we
20 can get multiple data points for a given sample. We
21 can vary stress; we can sample different parts of a
22 microstructure. We don't have that luxury with
23 initiation testing specimens. You get one data, one
24 datum per specimen, and that is what you get.
25 And then, finally, in terms of technical

1 issues, how you incorporate those data into the models
2 and predictions. And down here at the bottom I have
3 separated here cost. It is not the same type of
4 challenge as what is -- technical challenge as listed
5 above, but it certainly is a challenge if we are going
6 to, in a timely manner, collect statistically
7 significant data that can be used.
8 So the example I have here is a system that
9 we have been aware of for some period of time. This
10 is actually a system at Pacific Northwest National Lab.
11 It is work that is being funded by the DOE test program.
12 And what they have is these small tensile specimens
13 that I show in the top left corner, and they have been
14 able to build systems where they have a number of these
15 essentially loaded into an autoclave.
16 And here on the left side I show a system
17 where they have two specimens. These are instrumented
18 specimens, so we are using direct current and potential
19 drop to detect the initiation of cracks. I saw "we."
20 We are doing that in other programs, but in this program
21 they are using it to detect initiation.
22 And then in the middle picture here, this
23 long chain here is actually an autoclave where they have
24 30 test specimens in this system. These are essentially
25 under a constant load, so the -- all of the specimens

are seeing the same load. There is a mechanism there where there -- the specimens can have varying amounts of strain, and if one of the specimens fails there is a catch, so the test can continue without directly interrupting it.

They cannot instrument all of those specimens in that chain. I think they can instrument about 16 of them. But the advantage of this particular system would be that a variety of materials could be tested, dissimilar metal welds, heat effective zones, specimens with weld defects, and even some of the materials that have been tested before in some of the crack growth rate testing work can be utilized in this type of test.

And, in fact, PNNL has been able to machine some of these initiation specimens out of the unused portion of some compactition specimens that we use for crack growth rate testing.

MEMBER REMPE: Before you leave, could you give me an idea of scale, how big are the samples in diameter at the -- the ends, not the --

MR. DUNN: Right. The specimens are approximately one and a quarter inches tall.

MEMBER REMPE: Okay.

MR. DUNN: So relatively small.

1 MEMBER REMPE: And then, are you monitoring
2 water chemistry in this system?
3 MR. DUNN: Absolutely.
4 MEMBER REMPE: And is there flow through
5 it?
6 MR. DUNN: It is flowing autoclave. Water
7 chemistry is monitored and controlled. So it can vary
8 temperature, hydrogen concentration, core and --
9 PARTICIPANT: pH, everything.
10 MR. DUNN: Yeah. Okay. So this is kind
11 of an aside, because I didn't have a good picture of
12 direct current potential drop for an initiation
13 specimen. But this is an example that we used in crack
14 growth rate, just in case you are unfamiliar with it.
15 Essentially, what is happening here is a
16 current is being applied across a specimen. As the
17 crack grows in the specimen, there is a potential drop
18 that occurs, as the resistance of the specimen changes.
19 You will see on the diagram on the left there is a
20 reference potential because there is some change in
21 resistance that occurs innate to the specimen. So a
22 reference potential is something that has to be compared
23 to in order to get meaningful DCPD data.
24 As I mentioned, this has been adapted to
25 the SCC initiation testing. Within the crack growth

1 rate testing stuff, we have been able to get very
2 sensitive crack growth rates down to about, you know,
3 fives to 10 to the minus 10 millimeters per second.
4 So highly sensitive measurements of crack growth, and
5 the picture in the middle there is just one of those
6 compact tension specimens that has actually been
7 instrumented into the autoclave fixture.
8 So this is actually some DOE initiation
9 testing data. The plot on the right shows the actual
10 DCPD voltage. You can see that this is gradually
11 increasing with time. That's the change in resistance
12 that I referred to that has to be normalized with the
13 reference voltage.
14 And then at some point some -- after about
15 1,650 hours you see a discontinuity in this resistance
16 or the DCPD voltage versus time, and that is the
17 initiation of cracks in the two specimens. One of these
18 is a quite well-polished specimen, a one micron
19 diamond-finish specimen, and the other one is about
20 1,200 grit. We would expect the rougher surface to
21 initiate sooner, but that is not necessarily what
22 happened in this test.
23 And then the pictures here on the right show
24 some of the features that are really located away from
25 the main cracks in the specimen. So there were multiple

1 cracks found on both of these specimens, and most of
2 them were less than 25 microns in length. But this,
3 you know, points out that the initiation testing system
4 can be used to detect fairly small cracks in these types
5 of specimens.
6 Okay. So the last slide I have is really
7 our ideas for our proposed cooperative effort. We would
8 need a driver for this, and that would have to come in
9 the form of some type of modification to an existing
10 user need from the Office of Nuclear Reactor Regulation.
11
12 And then it would also require an amendment
13 to the memorandum of understanding that is in place
14 with -- our deal would be with DOE Nuclear Energies,
15 and they have an existing test system and maybe the
16 capability of replicating that system and having more
17 capabilities.
18 EPRI has an interest in doing initiation
19 work for some of the higher chromium weld materials,
20 but maybe also looking at some of the original 600, 82,
21 and 182 to understand factors of improvement.
22 So the way this would, you know, possibly
23 work is that, you know, DOE has a playing field, they
24 have test systems. We have a number of materials that
25 have been tested in terms of crack growth rates, so we

1 have very good characterizations of how susceptible
2 these materials are in terms of crack growth rates, and
3 we have also done quite a bit of analysis of those
4 specimens in terms of the microstructure and how the
5 cracks propagate through those specimens.
6 And some of those materials are materials
7 that have been removed from surface, which I think Glenn
8 mentioned the Alloy 600 from Davis-Besse. We have a
9 piece of that that we have -- after it was removed from
10 service we made the effort to decontaminate that.
11 And that material would be available for
12 doing initiation testing compared to the crack growth
13 rate testing that would be -- that has already been done.
14 And then, EPRI could perhaps fund some of the testing,
15 along with DOE.
16 This is very early in the stage here of
17 talking about a proposed cooperative effort. So it is
18 not anything that has been agreed to at this point.
19 But we are going to keep discussing it and see if we
20 can come to some mutually beneficial way to tackle this
21 problem.
22 CHAIRMAN ARMIJO: Okay. Just one quick
23 question. What is DOE using that equipment for right
24 now? Is it just idle?
25 MR. DUNN: No. They are actually doing

initiation testing. But their interest really is to understand fundamentally what happens that controls initiation processes.

CHAIRMAN ARMIJO: So scientific kind of stuff, not necessarily engineering-focused.

MR. DUNN: And not with the intention of developing data for a model.

CHAIRMAN ARMIJO: Got it. Okay. Well, look, thank you, Darrell.

We are a little bit behind schedule. We have another meeting coming up, but I'd like to open it up for any questions or comments from the members, first.

MEMBER REMPE: Well, I just wanted to say I appreciated the tutorial. I'm one of the people, it's not my field, and so I learned a lot. I do actually have a lab with autoclaves in it where we do the crack growth work out at my lab, and so I was interested in the initiation work that you are doing.

CHAIRMAN ARMIJO: Charlie? Bill Shack?

MEMBER SHACK: No. No. It's very interesting. You know, I think it is just where it was before. It is challenging, but they are working away at it.

CHAIRMAN ARMIJO: Dennis?

1 MEMBER BLEY: Nothing. I found it very
2 interesting, but no specific comments.
3 MEMBER SCHULTZ: I just want to express my
4 appreciation for the organization of the presentations
5 and the quality of the work as it was presented today.
6 Very helpful to see it presented in such a high quality
7 discussion.
8 CHAIRMAN ARMIJO: I probably should say,
9 if there is any comments from the members, people here
10 in the audience, I should have opened it up. I
11 don't -- do we have anybody on the bridge line? We don't?
12 Okay. If there are no comments from the
13 floor, I would like to add my thanks to all of the
14 presenters. I think very well prepared. Personally,
15 I am very enthusiastic. I was very skeptical about a
16 year ago that you were taking on something that was a
17 noble effort but was unlikely to lead to much. I really
18 changed my mind. I think you're on a track and I urge
19 you to keep going.
20 When you are ready, as far as to really focus
21 on the kind of testing you would need to kind of predict,
22 use your tool at some point, so that the -- if you do
23 any additional testing, it is really rifle shots at
24 resolving weaknesses in your modeling.
25 But with that, thank you very much. Great

1 presentation. And we are adjourned.

2 (Whereupon, at 12:11 p.m., the proceedings in the

3 foregoing matter were adjourned.)

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PWSCC Initiation Background, Mechanisms, and Modeling

by
Glenn White
Jeff Gorman
Dominion Engineering, Inc.

Presentation to ACRS
Rockville, MD
June 4, 2013

Topics

1. History of knowledge about PWSCC and mechanisms involved in its occurrence
2. History of occurrence of PWSCC in plants
3. Historical development of understanding of PWSCC mechanisms
4. State of art regarding fundamental PWSCC research
5. Current modeling approaches to PWSCC initiation predictions
6. Modeling of short crack initiation and coalescence
7. Conclusions

1. History of PWSCC Understanding and Basic Research (1/5)

- Pure or primary water stress corrosion cracking (PWSCC) of Alloy 600 first observed by Coriou, et al., of French CEA in 1959
  - No impurities in water required
  - Required high stress, long time, high temperature
- Results not accepted by most American researchers – attributed to possible contamination
- CEA research in 1960s continued to support occurrence of PWSCC with no impurities, but American research did not
- Germans agreed that Alloy 600 was susceptible and changed to Alloy 800 about 1967 or 1968

1. History of PWSCC Understanding and Basic Research (2/5)

- Other research published by about 1970 and 1971 confirmed susceptibility of Alloy 600 to PWSCC
- In response to secondary side IGA/SCC of Alloy 600 SG tubes in early 1970s and then PWSCC in late 1970s, significant research of the factors leading to SCC of Alloy 600
- By ~1980 it was known that:
  - PWSCC aggravated by high stresses, cold work, high temperature, and some microstructural conditions
  - PWSCC and caustic SCC both decreased by thermal treatment and precipitation of carbides at grain boundaries (GBs)

1. History of PWSCC Understanding and Basic Research (3/5)

- **Substantial research on SCC of Alloy 600 performed in 1980s and 1990s in response to:**
  - **Increasing occurrence of SCC in Alloy 600 and its weld metals in BWRs,**
  - **Increasing occurrence of secondary side and primary side attack of SG tubes in PWRs, and**
  - **Occurrence of PWSCC of thicker wall Alloy 600 components in PWRs starting in 1982**
- **Summary of research results by about 2000:**
  - **Mechanism of PWSCC not firmly identified**
  - **Many empirical trends established, such as the effects of:**
    - Stress, thermal treatment and carbide microstructure, Cr concentration, temperature, primary water chemistry variations, material strength, etc.

1. History of PWSCC Understanding and Basic Research (4/5)

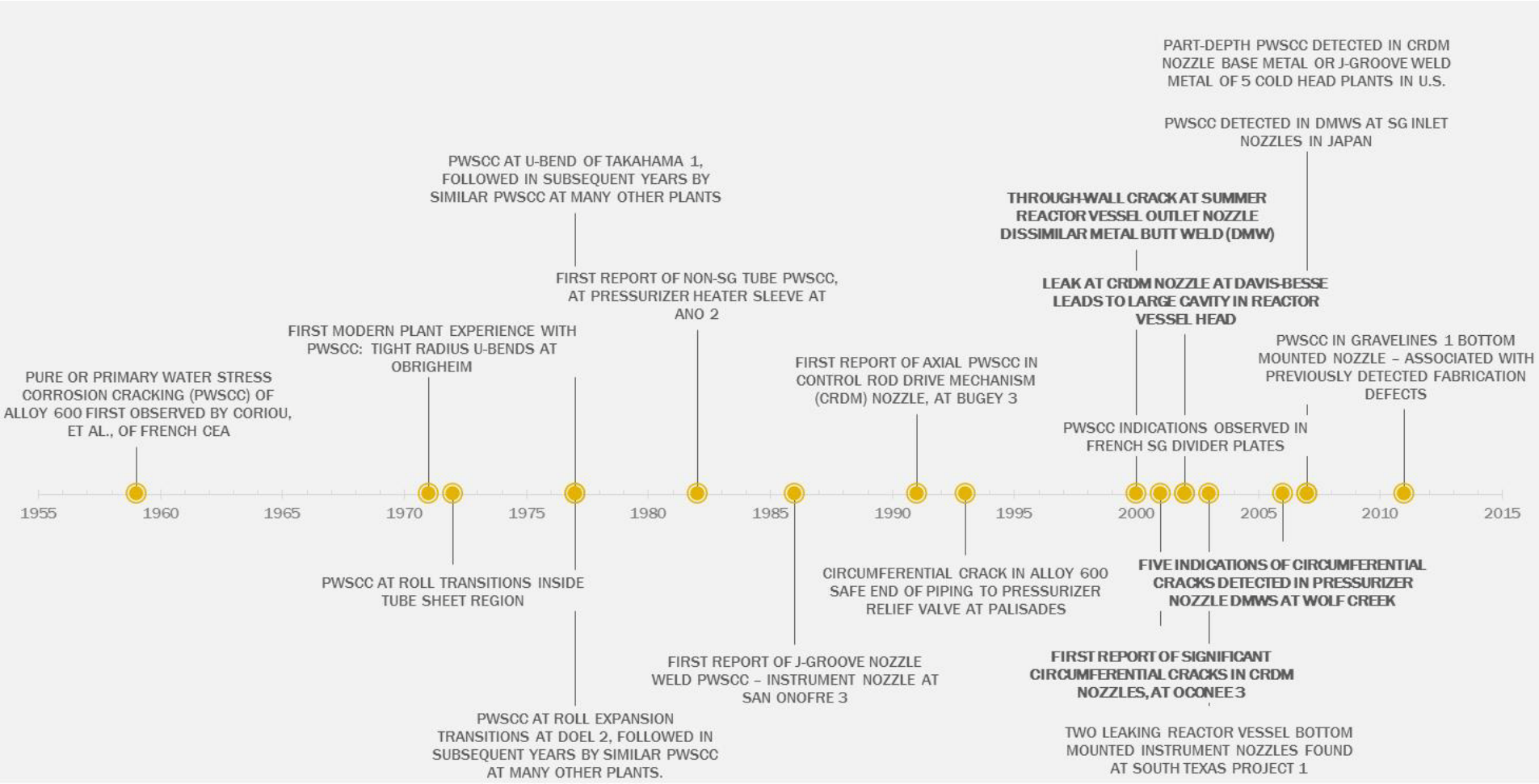
- **In last decade or so there has been increasing research regarding the basic mechanisms involved in PWSCC**
  - **Effects of oxide penetrations at GBs and slip lines**
  - **Effects of complex strain history and resulting localized plastic strain**
  - **Influence of hydrogen on PWSCC**
    - mainly by laboratory tests, but with some limited work on theoretical modeling

1. History of PWSCC Understanding and Basic Research (5/5)

Current Situation

- **Basic mechanism not firmly identified, but many useful correlations:**
  - **Time to failure decreases as stress increases**
  - **Crack growth rate (CGR) increases as stress intensity factor increases, at least up to a plateau level**
  - **Thermal treatment decreases susceptibility**
  - **"Good" carbide microstructure (copious GB carbides, few intragranular carbides) reduces susceptibility**
  - **Susceptibility decreases as Cr concentration increases**
  - **Cold work generally reduces time to initiation and increases crack growth rate**
  - **Higher mechanical properties lead to decreased time to SCC initiation and more rapid CGRs**

2. History of Key Plant Experience with PWSCC (1/2)



2. History of Key Plant Experience with PWSCC (2/2)

Current Situation

- Locations affected by PWSCC are slowly spreading to those with lower temperatures and lower stresses
- Inspection programs are successfully identifying PWSCC flaws at relatively early stages and sizes, such that PWSCC is not significantly impacting safety

3. Development of Understanding of PWSCC (LPSCC) Mechanism (1/5)

- Initially, in the 1960s, many researchers believed that PWSCC did not really occur in pure or primary water, and that impurities such as lead and/or oxidants were required
- By ~1970 it was concluded that PWSCC could occur in deoxygenated pure and primary water in the absence of impurities
- During the 1970-2000 timeframe a great deal of research performed to develop a more complete empirical understanding of the factors controlling the susceptibility and rate of PWSCC

3. Development of Understanding of PWSCC (LPSCC) Mechanism (2/5)

- In the mid 1990s, Staehle introduced the use of the phrase "low potential stress corrosion cracking" (LPSCC) for use in lieu of PWSCC
  - Recognizes that PWSCC occurs under fully reduced low electrochemical potential conditions
  - Emphasizes difference between PWSCC and high potential oxidant driven SCC experienced by Alloy 600 and its weld metals in oxidizing BWR environments
- Currently, there is no consensus on which mechanism is involved in PWSCC

3. Development of Understanding of PWSCC (LPSCC) Mechanism (3/5)

- **The SCC mechanisms under consideration need to account for empirical observations**

Empirical observations:	
• Stresses above about 0.8 times the elastic limit are required for PWSCC to occur in practical timeframes • Susceptibility increases as applied stresses increase • Susceptibility is reduced by thermal treatment • Susceptibility generally decreases as carbide decoration of GBs increases, and carbide concentration in the grain matrix decreases • Susceptibility increases as local cold work increases	• Susceptibility decreases as uniform cold work increases if total stress at surface remains constant (i.e., if total stress at surface is a lower fraction of yield) • CGR increases as mechanical properties increase • Susceptibility decreases as Cr concentration increases • Exposure to oxidants increases rate of attack • Crack growth rate is maximum for hydrogen concentrations (electrochemical potentials) near the Ni/NiO phase transition

3. Development of Understanding of PWSCC (LPSCC) Mechanism (4/5)

- Recent work has noted the following additional factors that need to be taken into account:
  - Oxide penetrations along GBs and slip lines often associated with initiation of cracks
  - Crack tips often observed to be very tight, indicating typical water-based processes may not be able to occur
  - Strain localization caused by complex strain histories often seems to be a factor, e.g., by causing very high local plastic strains at GB intersections

3. Development of Understanding of PWSCC (LPSCC) Mechanism (5/5)

- **Some PWSCC mechanisms or ideas under consideration include:**
  - **Internal oxidation along GBs and slip planes leading to reduced fracture resistance of oxidized regions**
  - **Hydrogen environment assisted cracking**
    - High hydrogen at crack tip reduces tear strength
    - Hydrogen comes from corrosion
  - **Dielectrostrictive stress associated with oxides causing cracking of oxides on grain boundaries**
- **In summary, there is no currently well understood and quantified mechanism for predicting occurrence of PWSCC**
  - **Predictions need to be performed on a semi-empirical basis, aided by insights from research, e.g., regarding effects of temperature, stress, etc.**

4. State of the Art in Fundamental PWSCC Research (1/3)

- Many experiments and analyses to determine the factors that control the development of oxides on surfaces, at GBs, and in cracks
  - See next slide
- Detailed evaluation of the behavior of dislocations at surfaces and GBs, including
  - Use of discrete dislocation dynamics and atomistic modeling, and
  - Experimental studies

4. State of the Art in Fundamental PWSCC Research (2/3)

Experiments and analyses to investigate the development of oxides on surfaces, at GBs, and in cracks:

- Atom probe studies of oxidation at surfaces and in GBs, and the ingress of other species during this process, such as B and Li
- Analytical transmission electron microscope evaluations of crack tips to determine oxide patterns, and compositional changes that occur during GB oxidation and during crack propagation
- The development of oxide films on Alloy 600 surfaces are being studied using a variety of methods, including X-ray photoelectron spectroscopy, time of flight secondary ions mass spectroscopy, photocurrent spectroscopy, scanning tunneling microscopy, scanning tunneling spectroscopy, high resolution transition electron microscopy, and modeling and simulation: atomistic (DFT and KMC) or non-atomistic
- Detailed microscopic studies of the response in high temperature water of nickel alloy surfaces to scratches and cold work, variations in hydrogen concentration, variations in oxygen concentration, and conductivity and pH of the water
- Detailed studies of dissolution and redeposition of oxides on surfaces
- Atomistic simulations of oxide growth on surfaces and initial efforts at extending such simulations to SCC initiation
- Evaluations of the stresses that develop at oxidized GBs and the effects of dielectrostrictive stresses on fracturing the oxides
- Evaluation of the semiconducting properties of surface oxides, e.g., using photoelectric chemistry methods, and evaluating how these properties could affect oxide growth and initiation of SCC
- Detailed atomistic level evaluations of metal – water interfaces and how oxidation at the surfaces could affect SCC initiation

4. State of the Art in Fundamental PWSCC Research (3/3)

- Studies of the effects of stress/strain, temperature and coolant hydrogen concentration on SCC initiation using tensile specimens instrumented with potential drop measuring equipment
- SCC initiation tests in PWR primary water containing tracers ($H_2{}^{18}O$, D_2O) to investigate hydrogen and oxygen transport in oxides
- Detailed studies of dislocation and slip plane interactions and fracture behavior at GBs to see how these occur and affect SCC
  - Analytical and micromechanical test methods

5. Current Modeling Approaches

5.1 Quantitative Micro Nano (QMN) Approach

5.2 Hydrogen Assisted and Related Strain Energy Density Models

5.3 Cold Work SCC Model

5.4 Material Index Approach

5.5 Statistical Approach Using Plant Data

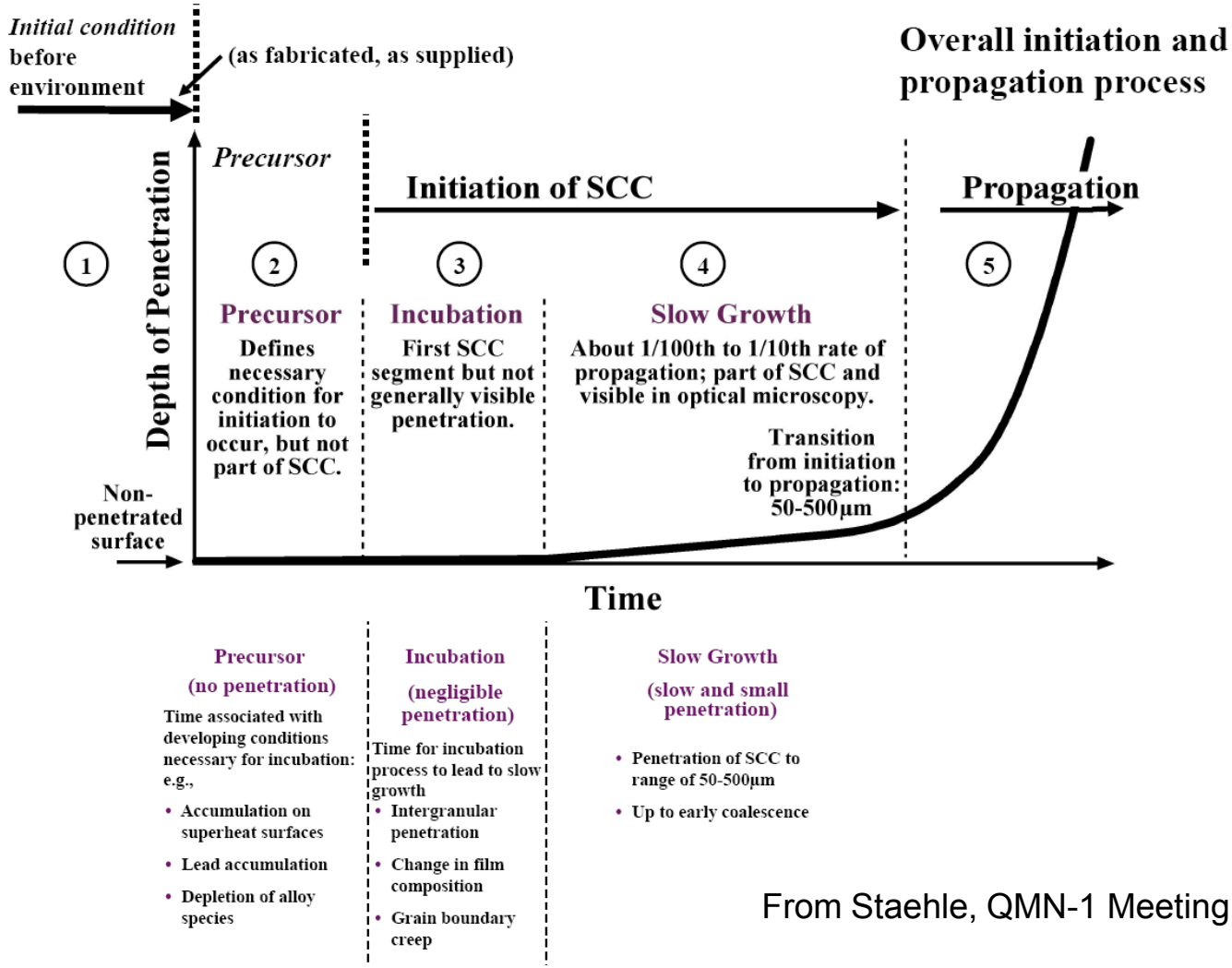
5. Current Modeling Approaches

5.1 Quantitative Micro Nano (QMN) Approach (1/4)

- **This approach develops models for each step in the SCC initiation and growth process and then links them together into an integrated model**
- **Envisioned as a multi-phase process**
  - **See next slide**
- **Each phase (or process in the phase) is first individually modeled in as detailed and rigorous manner as achievable**

5. Current Modeling Approaches

5.1 QMN Approach (2/4)



From Staehle, QMN-1 Meeting, 2010

5. Current Modeling Approaches

5.1 QMN Approach (3/4)

- QMN-1 2010; QMN-2 2011; QMN-3 2012
- QMN-4 June 2013 in Toronto
- QMN-5 and QMN-6 planned
- At QMN-6 methods for integrating the phases will be reviewed
- Addresses all forms of SCC affecting nuclear power plants, not just PWSCC
- Emphasis is on
  - PWSCC of nickel base alloys in PWRs and
  - IGSCC of stainless steels in BWRs

5. Current Modeling Approaches

5.1 QMN Approach (4/4)

- **The steps or processes that are being individually modeled include:**
  - **Development of precursor conditions such as the growth of oxides and related injection of vacancies into the metal**
  - **Development of oxide penetrations at surfaces such as at GBs or slip planes**
  - **Dislocation formation and interaction in response to strains**
  - **Formation of small cracks**
  - **Coalescence of small cracks into larger cracks**
  - **Development of mature stress intensity factor controlled cracks**
- **Each step or process is modeled in as detailed and quantitative manner as achievable, starting with atomistic modeling**

5. Current Modeling Approaches

5.2 Hydrogen Assisted and Related Strain Energy Density Models (1/3)

- **Extensive testing has shown that hydrogen embrittlement is involved in the *low temperature* SCC of Alloy X750 and Alloys 82 and 182**
  - **Tests indicate that this behavior is affected by hydrogen produced by corrosion, and also to a lesser extent by the hydrogen concentration in the water**
- **At plant *normal operating temperatures*, tests show that the CGR in Alloys X750, 600, 82 and 182 are influenced by the hydrogen concentration in the water**
  - **Peak CGR occurs close to the hydrogen concentration – electrochemical potential (ECP) of the Ni/NiO phase stability point**
- **It is also known that hydrogen concentrations in the metal near PWSCC fractures are much higher than in other areas**

5. Current Modeling Approaches

5.2 Hydrogen Assisted and Related Strain Energy Density Models (2/3)

- **Models regarding how hydrogen can assist in the PWSCC process have been proposed, e.g., by Hall (Bettis, retired) at QMN-1**
- **Hall proposed a hydrogen-assisted creep rupture model**
  - **Based on the idea that intergranular rupture occurs if the hydrogen content at the GB exceeds a critical value**
- **The model has not been developed to the point of making quantitative predictions for plant components**

5. Current Modeling Approaches

5.2 Hydrogen Assisted and Related Strain Energy Density Models (3/3)

- **Hall earlier proposed a strain energy density (SEDEN) model for SCC initiation (EPRI report 1018908) where initiation occurs when SEDEN reaches a critical value**
- **SEDEN**
  - ***Smooth specimens*: calculated as integral under the stress-strain curve**
  - ***Notched specimens*: calculated for a small process zone at the notch tip**
- **Model fits X750 SCC data both**
  - **at low temperature, where it is hydrogen embrittlement related, and**
  - **in high temperature PWSCC regime**
- **However, no published work shows**
  - **how this model would be applied to plant materials, nor**
  - **how the critical value of SEDEN would be determined for materials with different microstructures**

5. Current Modeling Approaches

5.3 Cold Work SCC Initiation (CW-SCC) Model (1/3)

- **CW-SCC Model developed by Garud for EPRI (EPRI 1019032)**
- **Assumes that SCC is dominated by crack tip strain rate that disrupts protective oxide films**
- **Assumes that crack tip strain rate is affected by**
  - **temperature,**
  - **material properties,**
  - **cold work (CW), and**
  - **total stress**
- **Inputs include**
  - **total stress,**
  - **ultimate strength and yield strength in CW condition, and**
  - **several fitted parameters for the material that reflect its low stress threshold for SCC, environmental resistance, microcracking resistance, and non-CW related resistance to SCC**

5. Current Modeling Approaches

5.3 Cold Work SCC Initiation (CW-SCC) Model (2/3)

- **Model has been fitted to several sets of experimental data and represents them well**
- **The approach was implemented in the xLPR Pilot Study and has been selected for inclusion in xLPR 2.0 as one of three approaches to modeling of the time to PWSCC initiation**
- **xLPR applies this approach using the following inputs:**
  - **Operating temperature**
  - **Surface stress**
  - **The assumed values of ultimate strength and yield strength**
  - **A series of fitted parameters that are used in various expressions, including expressions that are a function of the ratio of ultimate strength and yield strength ($\zeta = \sigma_{ult}/\sigma_{ys}$)**
- **The material strength values in xLPR are sampled from distributions developed to describe their variability, but do not currently account for differences in weld-specific material and fabrication practices**

5. Current Modeling Approaches

5.3 Cold Work SCC Initiation (CW-SCC) Model (3/3)

- **Validation of the CW-SCC Model is documented in a separate, EPRI Proprietary report: EPRI 1025121, published December 2012**
  - **Involved use of independent data sets for as-received and cold-worked material conditions, as well as an alternate method of estimating SCC initiation life**
  - **Alloy 600 in PWR-like environments**
  - **304SS in BWR-like environments**
  - **Application of the CW-SCC Model to multiple independent data sets demonstrates its validity in estimating the initiation life within the expected data variability**

5. Current Modeling Approaches

5.4 Material Index Approach (1/2)

- **Developed and applied in France for several years**
- **Assumes that time to initiation is governed by:**
  - **temperature via an activation energy parameter,**
  - **total surface stress raised to the fourth power, and**
  - **a material index factor related to the material microstructure**
- **Three iterations:**
  1. **Deterministic material index approach**
  2. **Treatment of statistical scatter of SCC initiation times using a fitted Weibull distribution**
  3. **Monte Carlo approach, which Benhamou and Amzallag* reported provides a more realistic distribution of failure times**

*EPRI report 1018908, 2009 Beaune meeting

5. Current Modeling Approaches

5.4 Material Index Approach (2/2)

- **For the Monte Carlo approach, distributions are developed for four parameters:**
  - **Stress**
  - **Temperature**
  - **Activation energy**
  - **Material susceptibility index**
- **EDF and AREVA have successfully applied this method to reactor vessel head (RVH) nozzles**
  - **The distributions were developed using the extensive field and laboratory data available for French RVH nozzles**
- **A challenge to this approach is that abundant data are not available for determining a material index distribution for DMWs**

5. Current Modeling Approaches

5.5 Statistical Approach Using Plant Data (1/2)

- **This approach is based on statistical fits to plant data, e.g., using the Weibull distribution**
- **It has been widely and successfully used for modeling PWSCC affecting SG tubes**
- **It has also been applied for modeling of PWSCC of CRDM nozzles (MRP-105 and MRP 2011-034) and of DMWs (MRP-307 and MRP-335R1)**
- **Adjustments to fits are made based on laboratory test results regarding effects of temperature, stress, and in some cases cold work**
  - **These take into account known differences for the plant components**

5. Current Modeling Approaches

5.5 Statistical Approach Using Plant Data (2/2)

- **Approach**
  - **Use statistical methods based on occurrence of PWSCC of similar components in the operating fleet, with adjustment to account for differences in temperature (and stress as practical)**
- **Advantages**
  - **Has been widely and successfully used for predictions of SCC affecting SG tubing on both primary and secondary sides, and reflects actual plant experience**
  - **Takes into account differences in temperature using accepted activation energy methods**
  - **Does not require input of parameters that may not be well characterized such as surface condition and carbide microstructure**
- **Challenges**
  - **Uncertainty in inspection data used in developing statistical fits**
  - **Difficulty in characterizing near-surface stress corresponding to plant experience**

6. Modeling of Short Crack Initiation and Coalescence (1/4)

- **Parkins*,** developed an approach to modeling of development of SCC to the point where a mature crack starts to grow per linear elastic fracture mechanics (LEFM):
  - **Random nucleation of small cracks (not LEFM controlled), initially on grain boundaries (GBs) but later also on shear bands**
  - **Growth of the small cracks with possible periods of dormancy**
  - **Coalescence of cracks as they grow and approach each other (based on the length of the cracks and the x and y spacing of adjacent cracks)**
- **Experimental data are used to develop statistical distributions input to Monte Carlo calculations**

*R. N. Parkins and P. M. Singh, "Stress Corrosion Crack Coalescence," *Corrosion*, v46, n6, p485-499, June 1990.
**Y. Z. Wang, D. Hardie, and R. N. Parkins, "The Behaviour of Multiple Stress Corrosion Cracks in a Mn-Cr and a Ni-Cr-Mo-V Steel: III - Monte Carlo Simulation," *Corrosion Science*, v37, n11, p1705-1720, 1995.

6. Modeling of Short Crack Initiation and Coalescence (2/4)

- **Example results for Parkins (1995) approach**
- **Max crack length versus time for 10 Monte Carlo realizations**

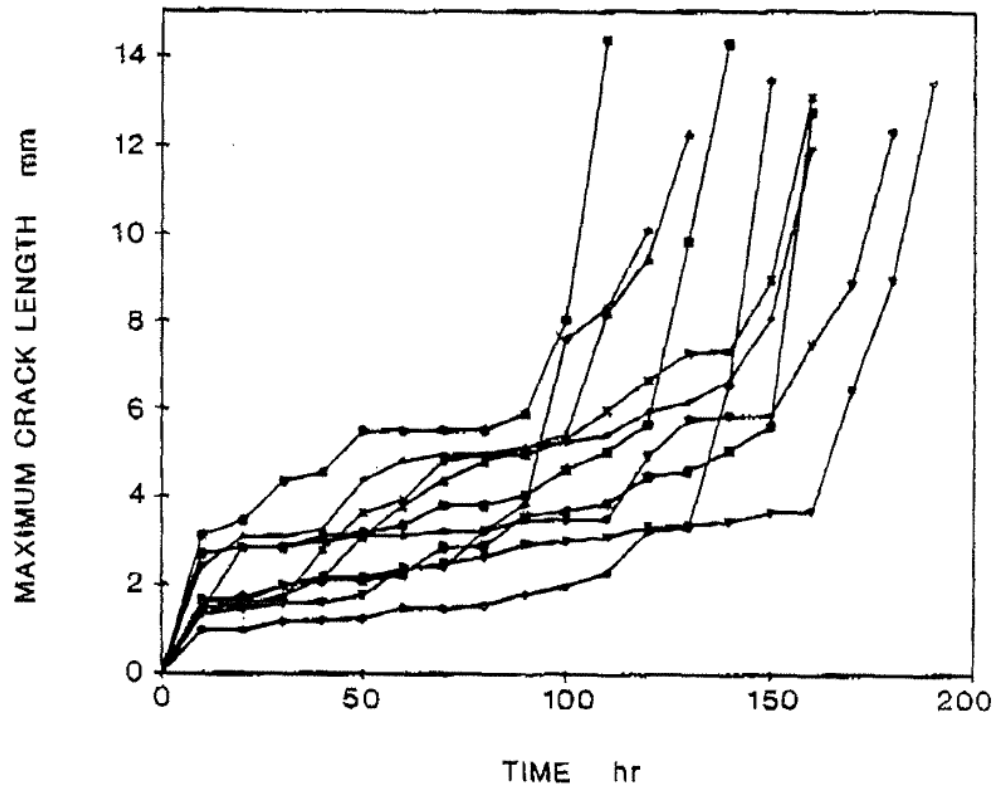
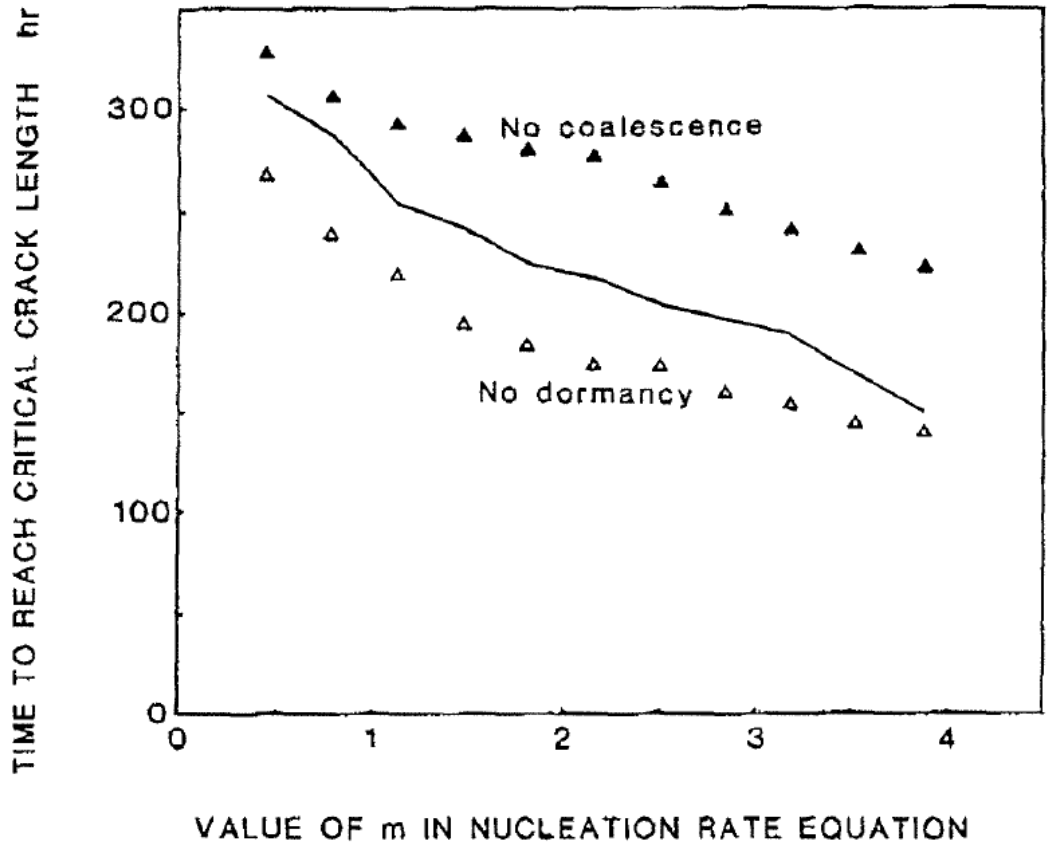


Fig. 2. Maximum crack length against time for 10 simulation runs for the Mn–Cr steel exposed to de-ionized water at open circuit potential and 70°C. The crack density used was in the form $N = 3.88\ t^{0.4}$ and crack propagation followed the rules obtained from the statistical approach for the experimental data when the maximum applied stresses were at or above 850 MPa.[2]

Source: Y. Z. Wang, D. Hardie, and R. N. Parkins, "The Behaviour of Multiple Stress Corrosion Cracks in a Mn-Cr and a Ni-Cr-Mo-V Steel: III - Monte Carlo Simulation," *Corrosion Science*, v37, n11, p1705-1720, 1995.

6. Modeling of Short Crack Initiation and Coalescence (3/4)

- **Example results for Parkins (1995) approach**
- **Influence of the value of *m* in the nucleation rate expression $N=m\cdot t^{0.4}$ on the average time required for the critical crack length to be reached for the Mn-Cr steel**



Source: Y. Z. Wang, D. Hardie, and R. N. Parkins, "The Behaviour of Multiple Stress Corrosion Cracks in a Mn-Cr and a Ni-Cr-Mo-V Steel: III - Monte Carlo Simulation," *Corrosion Science*, v37, n11, p1705-1720, 1995.

6. Modeling of Short Crack Initiation and Coalescence (4/4)

- The main challenge to implementation of this approach to practical predictions of PWSCC for plant components is that the needed experimental data are not available (especially for highly variable and not well defined plant conditions)
  - Data for nucleation of small cracks in Alloys 600/82/182
  - Data for growth of small cracks, below the size controlled by LEFM
- The current xLPR approach, basing PWSCC prediction on plant experience, is more practical for this version of xLPR
  - Assumption of relatively long flaws (compared to flaw depth) in plant-experience-based PWSCC initiation model addresses the observation that short crack coalescence may lead to relatively long shallow flaws
  - Stages of degradation prior to short crack coalescence and production of engineering-scale flaw are typically not detectable via NDE

7. Conclusions (1/3)

- **Major factors with strongest influence on initiation of PWSCC, including:**
  - **Total stress at surface, normally dominated by residual stress**
  - **Local surface cold work (residual plastic strain) and surface damage**
  - **Carbide microstructure**
  - **Temperature**
  - **Water chemistry**
  - **Mechanical properties**
  - **Chemical composition**
  - **Exposure to thermal treatment (e.g., post weld heat treatment)**
  - **Duration of exposure to PWSCC inducing environment**

7. Conclusions (2/3)

- **Consider level of knowledge regarding important factors at DMWs:**
  - **Total stress: limited knowledge since there are generally little quantitative data re weld repairs and surface grinding**
  - **Local surface cold work and surface damage: limited knowledge since there are generally little quantitative data re weld repairs and surface grinding**
  - **Carbide microstructure: limited knowledge since details of material thermo-mechanical processing history generally not available**
  - **Mechanical properties: Starting properties known, but possible effects from installation steps not always well characterized**
  - **Temperature, water chemistry, chemical composition, duration of exposure, thermal treatment: Usually well known**

7. Conclusions (3/3)

- The following modeling approaches are developed for use in practical component life calculations such as those performed by xLPR:
  - Cold Work SCC Initiation (CW-SCC) Model
  - Material Index Approach
  - Statistical Approach Using Plant Data
- All three methods are being incorporated into xLPR 2.0 to facilitate comparisons and sensitivity studies
- Similar results are expected if each model is calibrated using the same dataset

xLPR Primary Water Stress Corrosion Crack Initiation Models

xLPR V1 PWSCC Initiation Models

David Rudland
Senior Materials Engineer
RES/DE/CIB

ACRS Subcommittee on
Materials, Metallurgy, & Reactor Fuels
June 4, 2013

xLPR Development

- NRC goal to develop "modular" code for evaluating the risk of pressure boundary integrity failure

- Currently focusing on piping issue
  - Develop a ***probabilistic*** assessment tool that can be used to ***directly*** assess compliance with 10CFR50App-A GDC-4
  - May be applicable to other needs

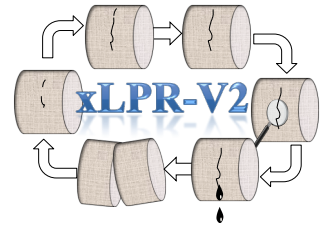
- Working cooperatively with EPRI through MOU addendum

- Initial pilot study to assess effectiveness of approach

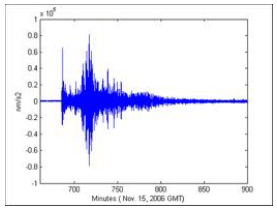
xLPR Pilot Study

- Pilot study (xLPR Version 1) objectives
  - Develop and assess xLPR management structure
  - Determine the appropriate probabilistic framework
  - Assess the feasibility of developing a modular-based probabilistic fracture mechanics computer code
- Focused on pressurizer surge nozzle DM weld with PWSCC only
- Developed detailed program plan (objective, schedule, deliverables, budget, communications) for Version 1.0 and Version 2.0 code

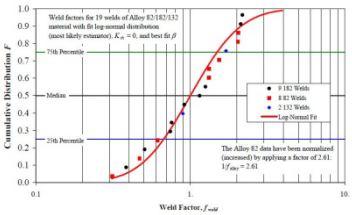
xLPR Technical Flow

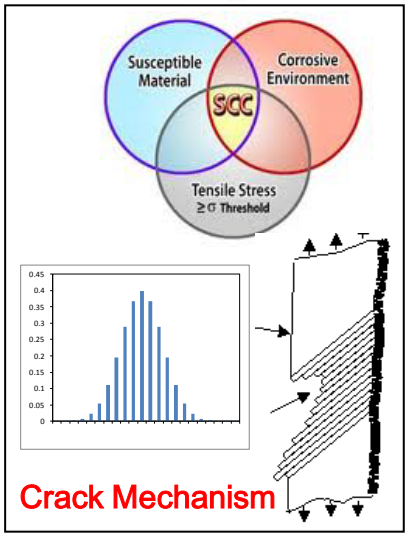


Loads

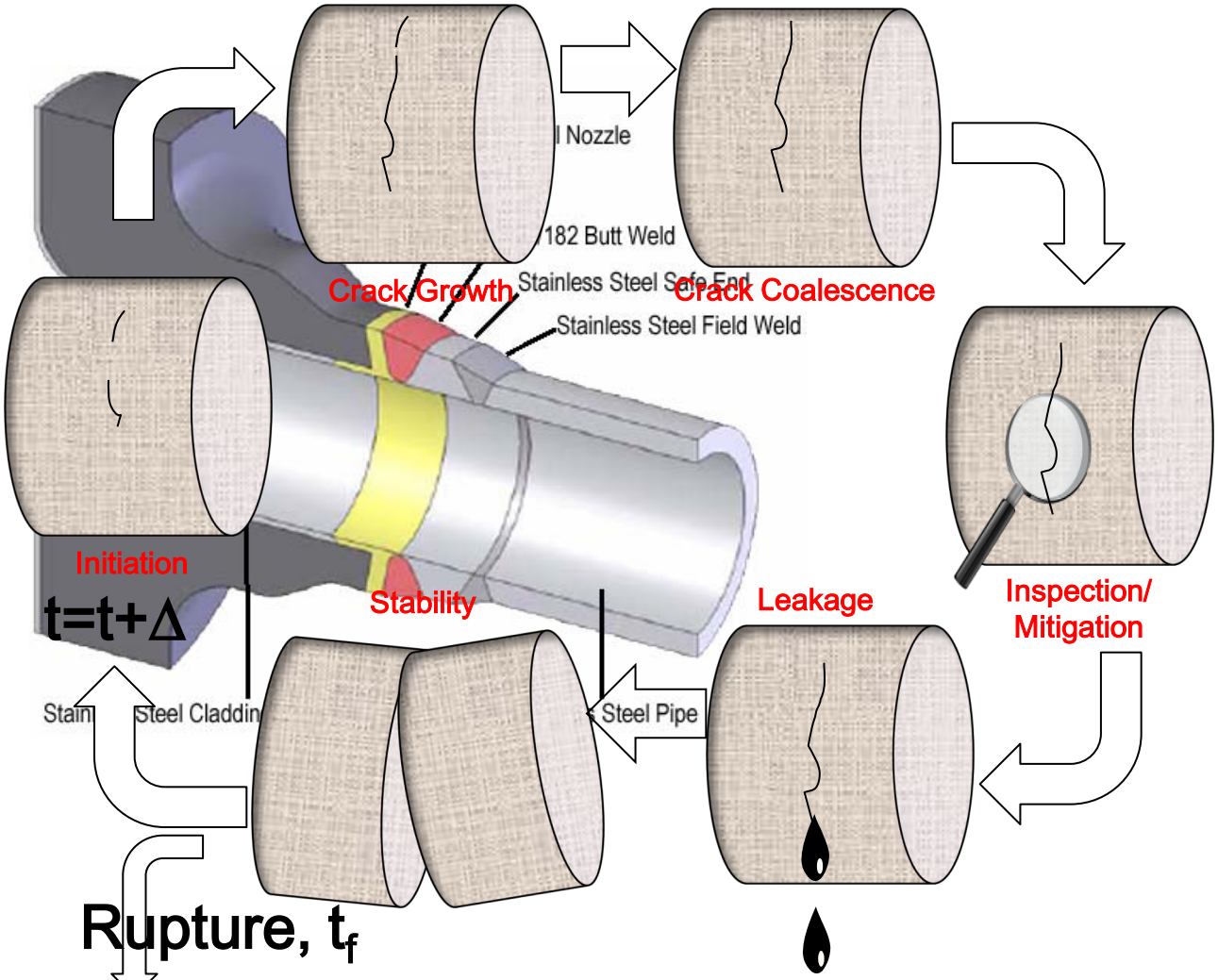


Material Properties





Crack Mechanism



CI Models Considered in xLPR V1

CI Models Considered for V1	Group Members
Weibull models = fit to data (t, T, sigma) AREVA Weibull-based model including Monte Carlo simulations Westinghouse 600 model Arrhenius-based modified for 82/182 Mack Hall SEDEN SCC initiation model (strain energy density) Arrival rate model (V1 alpha only) Material Index Approach Cold Work Modified Strain Rate Damage Model	Cliff Lange, SIA David Harris, SIA Yogen Garud, SIA Steve Fyfitch , AREVA Bruce Bishop, Westinghouse Glenn White, DEI David Rudland, USNRC Bob Kurth, EMC^2

Version 1.0 Models Description

Crack Initiation

Several models were used for initiation probability

A.) Direct Approaches

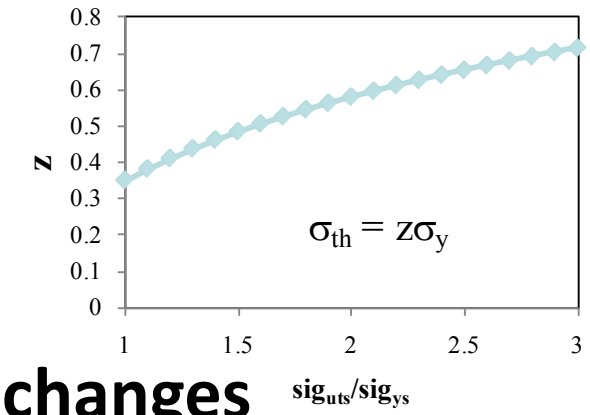
$$\frac{1}{t_I} = Ae^{-Q/RT}\sigma^n \quad (\sigma > \sigma_{th})$$

σ_{th} = 137MPa (20ksi)

Cold Work Modified Strain Rate Damage Model

$$t_I = Be^{Q/RT}\ln[(D-z)/(\sigma/\sigma_{ys}-z)]$$

$$where\ B = B_I m^q \ln[D]/\ln[(D-z)/(1-z)]$$



B.) Weibull

$$P(t_I < t) = 1 - e^{-(t/C)^3}$$

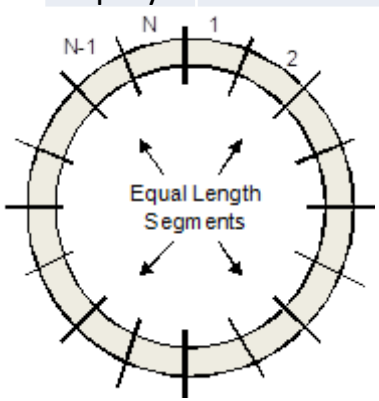
$$C = C_1 e^{Q/RT}\sigma^{-n}$$

- **Capable of handling zinc/hydrogen changes**

V1 Model Calibration

- **For Version 1.0, models are "calibrated" to MRP-216 surge nozzle data and base WRS**

Pressurizer Nozzle DMW Inspections (mid 2007)			
Nozzle	# inspected	# circ cracks	# axial cracks
Surge	10	5	2
Safety	20	1	4
Relief	6	1	2
Spray	7	0	0



0.01 cracks/year

calib		Direct Model 1	Direct Model 2	Weibull
		Amzallag	Garud	
first	Segment length	0.051	0.051	**0.051**
	Median coefficient	1.28	8.01×10^{-11}	--
	μ_{h-h}	1.16	0.4331	--
	μ_{w-h}	0.40	0.1494	--
	Q	22000	22000	--
Poisson	Segment length	0.051	0.051	**0.051**
	Median coefficient	0.141	1.20×10^{-9}	**4.08***
	μ_{h-h}	1.13	1.607	--
	μ_{w-h}	1.07 or 1.45	0.555	--
	Q	**22000**	**22000**	**22000**

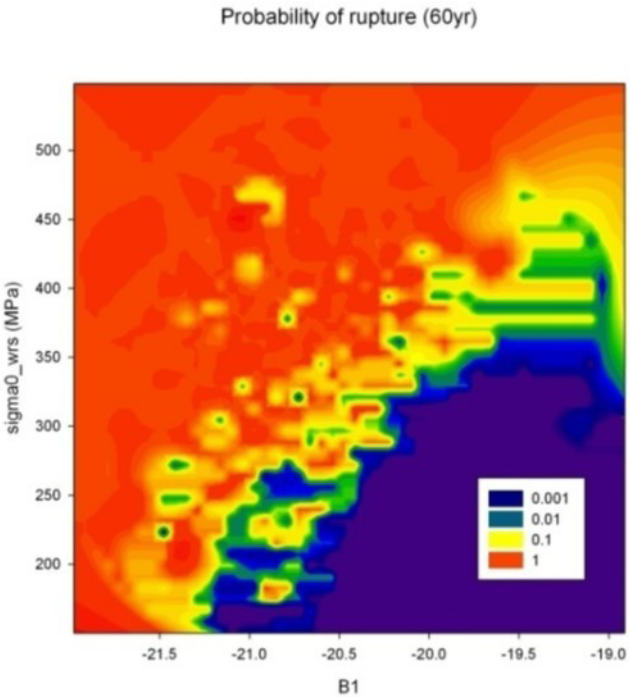
- **Multiple circumferential crack initiation allowed**
- **Axial cracks not allowed in V1**

xLPR Base Case Results

Sensitivity analyses were conducted to determine driving variables

EXPCFO: 50 yr				EXPCFO: 60 yr			
var.	R^2	R^2 inc.	SRRC	var.	R^2	R^2 inc.	SRRC
SIG0WRS	41.80%	41.80%	0.5363	SIG0WRS	43.90%	43.90%	0.5764
B1	57.10%	15.30%	-0.3299	B1	60.70%	16.80%	-0.3568
FWELD	57.80%	0.70%	0.0701	FWELD	61.60%	0.90%	0.0853
RANDL17	58.00%	0.20%	0.0369	RANDP05	61.80%	0.20%	0.0391
				ODRAND	62.00%	0.20%	-0.0358

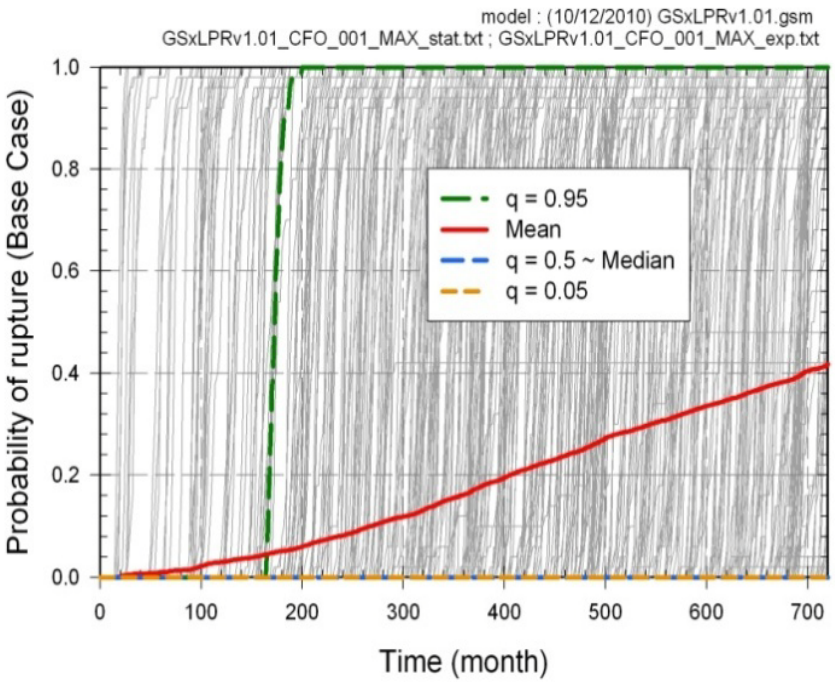
- **R^2 - how much of the output variance is explained with the current input and all previous inputs**
- **The incremental R^2 - how much variance is explained by the addition of this input**
- **SIG0WRS – ID weld residual stress**
- **B1 – crack initiation parameter**



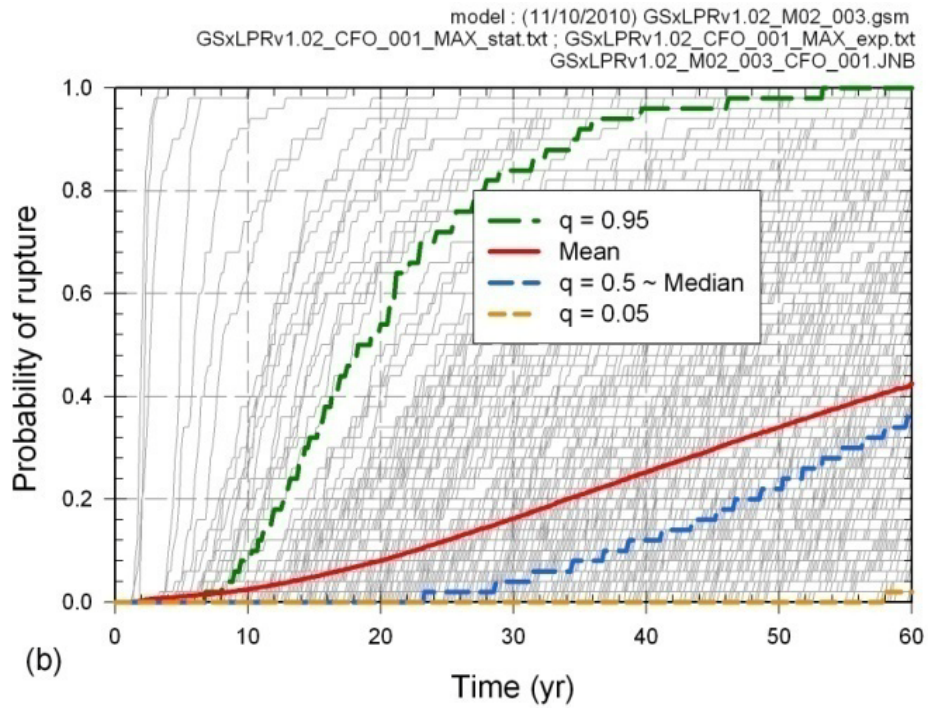
Probability of rupture at 60 yrs

Base Case Results

No leak detection, no inspection, high WRS



Crack Initiation categorized as epistemic by models group



Crack Initiation categorized as aleatory

Summary

- The project team demonstrated that <u>it is feasible</u> to develop a modular-based probabilistic fracture mechanics code within a cooperative agreement while properly accounting for the problem uncertainties
- SCC initiation has large impact on xLPR V1 results
- SCC initiation model flexibility aids in performing sensitivity studies for initiation impact
- Due to impact, team revisited the PWSCC initiation models for V2 by convening an expert panel (next presentation)

xLPR Primary Water Stress Corrosion Crack Initiation Models

PWSCC Expert Panel Meeting Summary

Stephen Fyfitch
Technical Consultant
AREVA Inc.

ACRS Subcommittee on
Materials, Metallurgy, & Reactor Fuels
June 4, 2013

Presentation Outline

Topic	Presenter
SCC Initiation Background, Mechanisms, and Modelling	Glenn White, DEI Jeff Gorman, DEI
xLPR V1 SCC initiation model	David Rudland, RES
PWSCC Expert Panel Meeting Summary	Steve Fyfitch, AREVA
xLPR V2 SCC initiation Model	Kyle Schmitt, DEI
PWSCC initiation testing plans	Darrell Dunn, RES

Discussion Points

- Expert Panel – November 2011
- Expert Panel – January 2013
- Models Considered
- Conclusions and Recommendations for xLPR-V2
- Recommendations for xLPR-V3

Expert Panel Participants

November 2011

- Bruce Bishop – xLPR PIB Member, Retired (Westinghouse)
- Steve Fyfitch – AREVA Inc., Expert Panel Facilitator
- Barry Gordon – SIA
- Craig Harrington – EPRI
- David Harris, SIA
- Richard Jacko – Westinghouse
- Matthew Kerr, NRC
- Cliff Lange – SIA
- Dave Morton – Bechtel Maine Corporation (KAPL)
- David Rudland – NRC
- Peter Scott – Independent Consultant, Retired (AREVA)
- Tetsuo Shoji – Tohoku University
- Jean Smith – EPRI
- Dennis Weakland – xLPR PIB Lead, Independent Consultant
- Glenn White – DEI

Expert Panel Discussions (1/3)

November 2011

Topics Discussed

- Assessment of current models in xLPR-V1
- Datasets to use for benchmarking xLPR-V2 models
- Material variability and significance
- Initiation "threshold"
- Size effects
- Initiated crack size

Expert Panel Discussions (2/3)

November 2011

Consensus agreements reached:

- xLPR-V1 models are best models currently available for xLPR-V2
- Same crack initiation model(s) apply for both axial and circumferential flaw initiation
- Use available field data for benchmarking crack initiation models in xLPR-V2
  - Discussion of size effects led to majority opinion that for xLPR-V2 segmentation should continue to be used
  - However, size effects should be further evaluated for xLPR-V3

Expert Panel Discussions (3/3)

November 2011

Consensus agreements reached (cont'd):

- Working definition of initiated crack size is below surface cold-worked layer (~ 200 microns)
- Variability in weld material can best be captured by proper accounting of residual stress present on surface
- Initiation "threshold"
  - A value for surface stress (correlated against hardness and yield strength evaluations) should be used
  - Value appears to be on order of ~350 MPa (~50 ksi)

Expert Panel Participants

January 23-25, 2013

- Steve Fyfitch – AREVA Inc., Expert Panel Facilitator
- Peter Scott – Independent Consultant, Retired (AREVA SAS)
- Thierry Couvant – EDF
- Yogen Garud – Independent Consultant
- Roger Newman – U. of Toronto
- Peter King – B&W Canada Ltd.
- Gerrit Buchheim – Independent Consultant
- Darrell Dunn – US NRC Office of Nuclear Reg. Research
- Gabriel Ilevbare – EPRI Primary Sys Corrosion Research
- Craig Harrington – EPRI Project Manager

Expert Panel Goals

January 23-25, 2013

- **Primary meeting goal:**
  - **Reach consensus decision on PWSCC initiation model(s) to incorporate into xLPR-V2 Code**
    - Assessment of models included in xLPR-V1 for xLPR-V2
    - Other applicable models and inputs not in xLPR-V1
- **Secondary meeting goal:**
  - **Develop plans for improvement of consensus model(s) or development of entirely new model for xLPR-V3 Code**

Models Considered (1/2)

- **Direct model 1**

$$\frac{1}{t_{INI,nom}} = Ae^{-Q/RT}\sigma^{n} \qquad \sigma \geq \sigma_{th}$$

- **Direct model 2**

$$\zeta \equiv \frac{\sigma_{ult}}{\sigma_{ys}}$$

$$t_{INI,nom} = BGe^{Q/RT}\ln\left[\frac{D-z}{\frac{\sigma}{\sigma_{ys}}-z}\right]$$

- **Weibull model**

$$\ln\left(-\ln\left(1-F\right)\right) = \beta\ln\left(t\right) - \beta\ln\left(\theta\right)$$

$$y \quad = \quad \beta x \quad + \quad c$$

$$t_{INI,nom} = \theta\left(\left(-\ln\left(U_{INI}\right)\right)^{1/\beta}\right)$$

(Details described in other presentations)

Models Considered (2/2)

- **Literature Search**
  - Crack initiation modeling approaches outside of nuclear industry were reviewed by T. Moss (University of Michigan) at request of EPRI
  - Several potential models identified for consideration
    - **None clearly directly applicable or easily applied to PWSCC initiation in PWRs**

Expert Panel Conclusions (1/5)

Version 2.0

- **Agree with earlier ACRS comments:**
  - **Initiation is most challenging technical issue for xLPR and any improvements in prediction uncertainties can only make it better**
- **Unaware of a better approach to modeling PWSCC initiation than those incorporated into xLPR-V1 and presently recommended for xLPR-V2**
  - **Possible short-term improvements would incorporate operating experience and provide for update as needed over time**
    - **Develop proper distributions on variables**
    - **Use a Bayesian approach to reducing uncertainties**

Expert Panel Conclusions (2/5)

Version 2.0

- Continue with Direct Models 1 & 2 for xLPR-V2
- Weibull model development should be completed
  - Expert Panel did not fully understand all V1.0 aspects
  - V2.0 draft SRD helped but Panel remained somewhat uncomfortable with its apparent structure
  - Nevertheless, a Weibull approach was considered to have merit if thoroughly developed and documented
  - However, if results lead to greater uncertainty than Direct Models 1 and 2, it should not be included in xLPR-V2

Expert Panel Conclusions (3/5)

Version 2.0

- A material factor (I_m) should be included in Direct Model 1 and the Weibull Model (if completed satisfactorily) for xLPR-V2
  - Direct Model 2 seems to already have such a factor imbedded within its parameters but User Manual must address its use
- Same crack initiation model(s) apply for both axial and circumferential flaw initiation
- Use available field data for benchmarking crack initiation models in xLPR-V2

Expert Panel Conclusions (4/5)

Version 2.0

- Initiation should be defined as an aleatory uncertainty and not epistemic
  - Seems to have clearly come out of V1.0 sensitivity studies
- Majority opinion that segmentation should continue to be used for xLPR-V2
- Current ASME Code rules for coalescence are not entirely correct and should be reevaluated for xLPR use
  - Appropriate for engineering-scale cracks
  - One-dimensional crack placement is not realistic or consistent with coalescence rules
  - Uncomfortable representing the full complexity of "initiation" as a simple binary event producing an engineering scale crack

Expert Panel Conclusions (5/5)

Version 2.0

- Working definition of initiated crack size is "below surface cold-worked layer"
  - Value appears to be on order of ~ 200 microns (~8 mils)
- Variability in weld material best captured by proper accounting of residual stress present on surface
- Value for surface stress (correlated against hardness and yield strength evaluations) should be used as initiation "threshold"
  - Value appears to be on order of ~350 MPa (~50 ksi)
  - Not a "bright line" – must be applied judiciously

Recommendations (1/2)

Version 3.0

- An improved initiation model should continue to be pursued for xLPR-V3
  - Follow T. Couvant's Materials Aging Institute modeling efforts
  - Further develop SRDM approach and to support modeling assumptions and sensitivities for key initiation factors in EPRI Initiation Model
  - Discourage over-simplifications
    - Esp. key parameters (e.g., fixed Weibull slope, power-law exponent, etc.)
    - Will introduce forced errors and bias unlikely to be corrected by benchmarking
    - Will likely scale the inaccuracies (from location-to-location or from one probability level to another)
  - "Out-of-box" models for xLPR-V3
  - Manufacturing defect initiation model(s)
  - IGSCC initiation (for BWRs)
  - Fatigue initiation model(s)

Recommendations (2/2)

Version 3.0

- R&D recommendations
  - Hydrogen concentration effects on initiation
  - Zinc injection (concentrations) effects on initiation
  - Incorporate Bayesian analysis into efforts
  - Multiple initiation sites/unit area, initiated short (micro) crack coalescence
  - Crack size vs segment "area" vs. database sample size
  - Better understanding of US PWR weld materials

xLPR Primary Water Stress Corrosion Crack Initiation Models

Description of xLPR Version 2 Models

Kyle Schmitt
Associate Engineer
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ACRS Subcommittee on
Materials, Metallurgy, & Reactor Fuels
June 4, 2013

Overview of Presentation

- Purpose and Scope
- Assumptions and Simplifications
- Procedural Summary of Initiation Simulation
- Description of Initiation Time Models
- Parameter Estimation for Dissimilar Metal Welds (DMWs)

Purpose and Scope

Purpose of PWSCC Initiation Model

General Scope

- Reflect probabilistic understanding of initiation process
- Represent historical plant experience
- Reflect varying susceptibility for different component types and materials
- Incorporate parametric dependencies supported theoretically or empirically, for variables that can be characterized
- Output initiation times and initial crack sizes that are consistent and are sufficiently early in the crack lifetime to accommodate downstream modeling efforts

Purpose of PWSCC Initiation Model

Version 2.0 Objectives

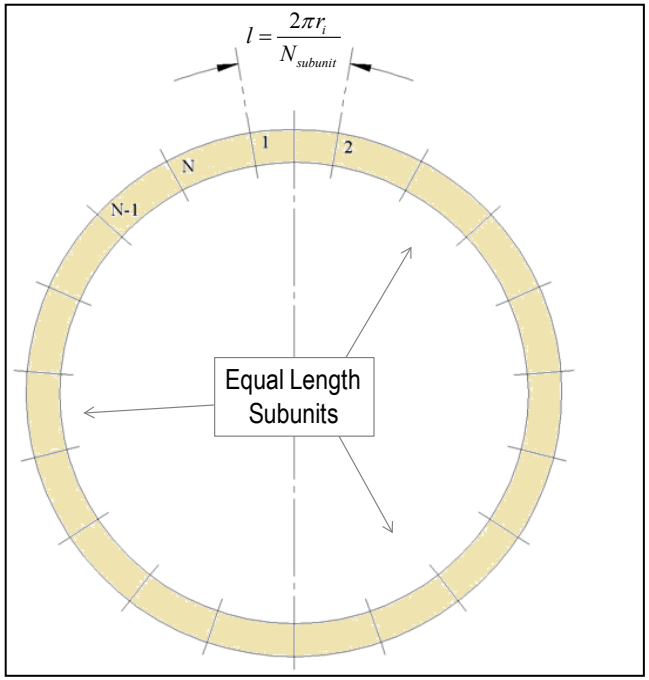
- Assemble Expert Panel to collect opinions for modifying PWSCC initiation model
- Revisit PWSCC initiation time model selection
- Update data collection efforts
- Update parameter estimation including characterization of uncertainty
- Develop code within QA program
  - Requirements
  - Design
  - Implementation
  - Verification and validation

Assumptions and Simplifications

Assumptions and Simplifications

Spatial Discretization for Multiple Crack Initiation

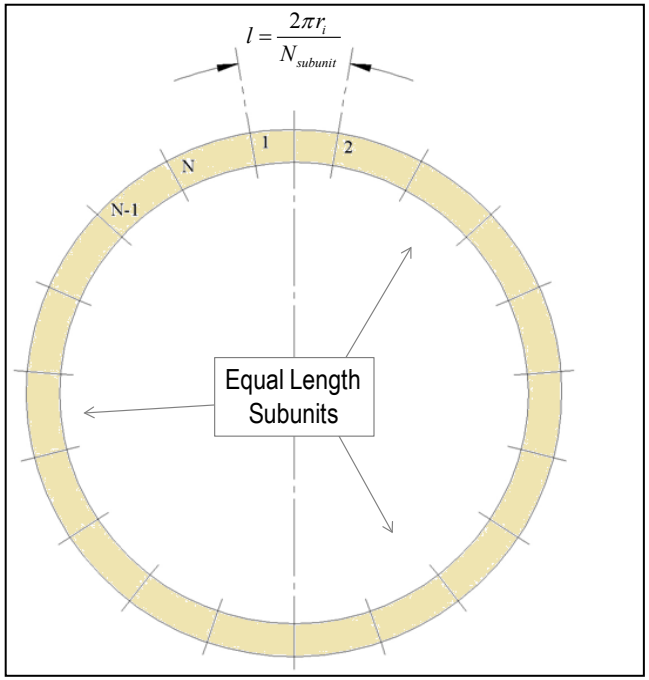
- **Susceptible material surface is separated into multiple equal area subunits**
- **Stress at subunit center is assigned to entire subunit**
- **Initiation is simulated independently within each subunit**
  - **Subunits are related by mutual properties (e.g., operating temperature)**



Assumptions and Simplifications

Spatial Discretization for Multiple Crack Initiation

- **How is the number of subunits selected?**
  - **Subunit length is similar to or larger than interaction distances associated with initial crack sizes**
  - **Subunit length reflects variation of macroscopic drivers of initiation (e.g., surface stress)**
  - **Within above constraints, subunit length can be used as degree of freedom in regression/calibration**
- **The Weibull model includes a scaling term for the number of independent subunits (PVP2007-26731)**



Assumptions and Simplifications

Engineering-Sized Crack Initiation

- **The Expert Panel recommends the use of microscale models for initiation, coalescence, and growth simulation of short cracks (e.g., ~50-200 µm)**
  - **Potentially higher fidelity incidence rates and aspect ratios for flaws that grow to engineering significance**
- **Version 2.0 models simulate the initiation of a singly dominating crack of engineering significance**
  - **Initiation time and aspect ratio predictions can be informed by field detection data**
  - **The inclusion of small cracks in xLPR should not significantly bias predicted failure rates; e.g., UT detection of small cracks is very unlikely**
  - **Traditional K-dependent growth models are reliable**
  - **Practical implementation and faster software performance**
  - **In the spirit of Coffin-Manson rule for fatigue life as well as engineering standards (e.g., AMSE Section III)**

Assumptions and Simplifications

Separation of PWSCC and Fatigue Initiation

- PWSCC and fatigue initiation mechanisms are modeled separately
  - Damages are not superimposed
  - Initiation time models are not correlated
- Within each segment, the earlier of the two predicted initiation times is used
- No clear technical basis for the superposition or correlation between PWSCC and fatigue initiation processes

Assumptions and Simplifications

Initiation-Conditional Run Mode

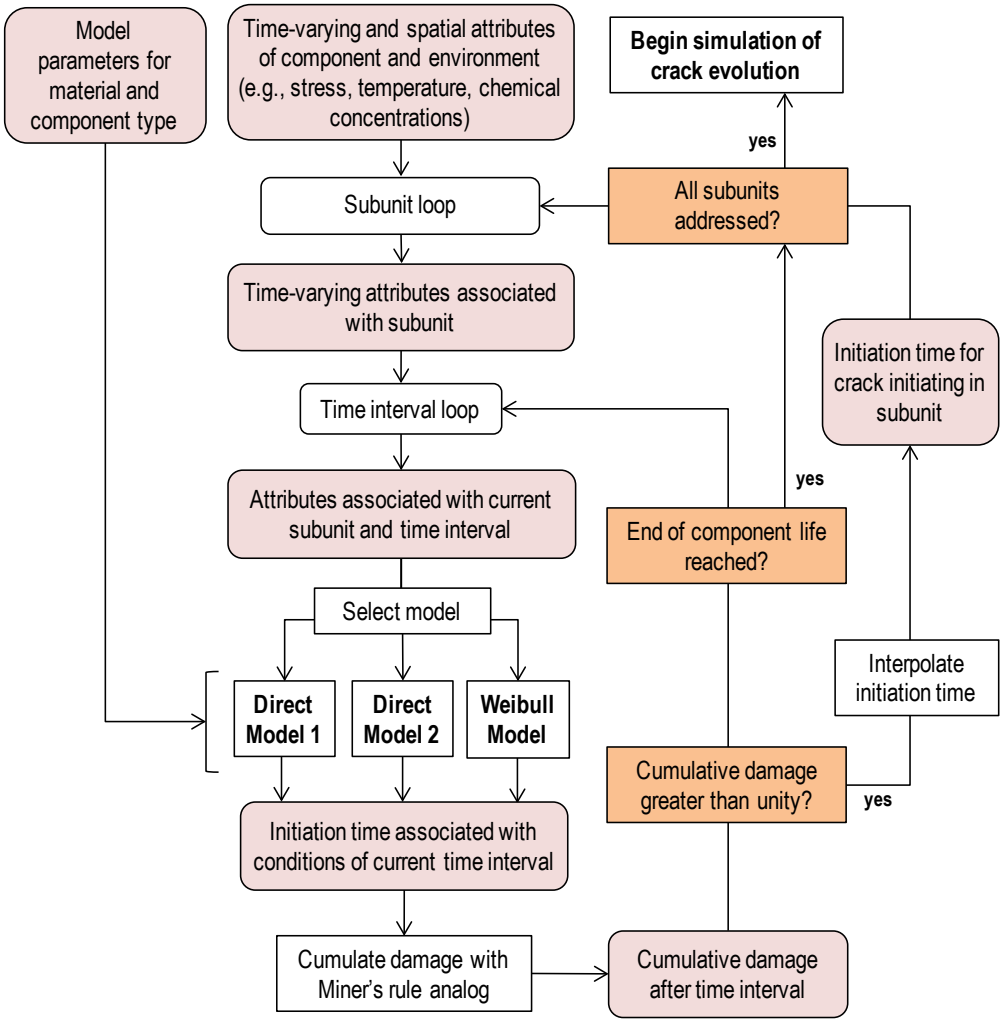
- Independent review teams have expressed the need for a capability to predict probability conditional on initiation
  - Incorporate initiation probability during post-processing
  - User may also be interested in certain initial crack conditions
- Conditional mode assumes initiation(s) at time zero
- User specifies distributed or deterministic inputs for initial flaw density, depth and length
  - For example, one might evaluate the risks of a circumferential crack of marginal detectability originating at the location of maximum bending stress
- Facilitates assessment of traditional deterministic LBB procedures and margin factors

High-Level Summary

Procedural Summary of PWSCC Initiation Calculation

- Initiation times calculated at the onset of each realization
- Three distinct models available for initiation time prediction under fixed conditions
- Time-varying conditions addressed with analog of Miner's rule

$$[\text{cumulative damage}] = \sum_{i=1}^{k} \frac{\Delta t_i}{t_i}$$



Initiation Time Models

Direct Model 1 (Material Index)

Technical Basis

- A deterministic material index approach for predicting PWSCC initiation was used in France for several years
- Since, it has been concluded that a probabilistic material index approach yields a more realistic distribution of failure times (e.g., EPRI 1018908)
- EDF and AREVA have successfully applied this method to reactor vessel head (RVH) nozzles

Direct Model 1 (Material Index)

Model Form and Dependencies

- **Parametric dependencies for temperature and surface stress**

$$\frac{1}{t_{INI}} = Ae^{-Q/RT}\sigma^n \quad \sigma \geq \sigma_{th}$$

- **Uncertainty quantified through material index (*A*)**
- **Other parameters:**
  - **Based on laboratory testing of Alloy 600, stress exponent (*n*) is set to 4 and activation energy (*Q*) is set between 180 and 210 kJ/mol**
  - **Stress threshold (σ_{th}) is calculated based on cold work modified strain rate damage model (see next slides)**

Direct Model 2 (CW-SCC Model)

Technical Basis

- A cold work (CW) modified strain rate damage model (SRDM) has been developed by Garud (EPRI 1019032)
- SRDM model assumes that SCC is dominated by crack tip strain rate that disrupts protective oxide films
- Model validation efforts include (EPRI 1025151):
  - Application of model to new data sets, including as-received and cold-worked Alloy 600 and Type 304SS materials under varied conditions, demonstrates validity
  - Good agreement with alternate prediction method developed from independent data set with constant extension rate tests (CERT)

Direct Model 2 (CW-SCC Model)

Model Form and Dependencies

- **Parametric dependencies for temperature, surface stress, and basic mechanical properties**
  - **Mechanical properties are used to estimate proxies for CW process and SCC resistance (see next slide)**

$$t_{INI} = B \cdot \exp\left[Q / RT\right] \cdot g\left(\sigma, \sigma_{ys}, \sigma_{uts}, E\right) \quad \sigma_{ys} < \sigma < \sigma_{\max}$$

- **Near-threshold stress response included**
  - **Surface stress less than stress threshold results in no damage; greater than max stress results in immediate initiation**

$$\sigma_{th} = z\sigma_{ys}$$

$$\sigma_{\max} = D\sigma_{ys}$$

- **Material-environmental uncertainty quantified through scaling factor (*B*)**

Direct Model 2 (CW-SCC Model)

Cold Work Effects

- **SCC susceptibility associated with micro-structural changes caused by CW**

$$g\left(\sigma,\sigma_{ys},\sigma_{uts},E\right)=m^{-q}\ln\left[\frac{D-z}{\frac{\sigma}{\sigma_{ys}}-z}\right]\frac{\ln(D)}{\ln\left(\frac{D-z}{1-z}\right)}$$

- **CW and deformation kinetics parametrically related to mechanical properties**

$$m=k\left(\sigma_{ys}/E\right)^{a}\left(\zeta-1\right)^{b}\left(\zeta\right)^{c}$$ measure of cold work

$$z=z_1+z_2\ln\left(\zeta\right)$$ SCC threshold factor

$$D=v\cdot\exp\left(w\cdot\zeta\right)$$ microcracking resistance

$$\zeta=\sigma_{uts}/\sigma_{ys}$$ strength ratio

- **Parameters quantified and validated using experimental time-to-initiation data**
  - **Initiation implied by depth on the order of 0.4-2mm**
  - **Different for Ni-based alloys and austenitic SS**

Weibull Model

Technical Basis

- Weibull modeling is a classic approach for reliability engineering and failure analysis
  - Capable of representing increasing failure rate over time
  - Amenable to classical parameter estimation methods
  - Reasonably accurate with small sample sets
- It has been widely and successfully used for modeling PWSCC affecting SG tubes
- It has also been applied for modeling of PWSCC of CRDM nozzles (MRP-105 and MRP 2011-034) and of DMWs (MRP-307 and MRP-335R1)

Weibull Model

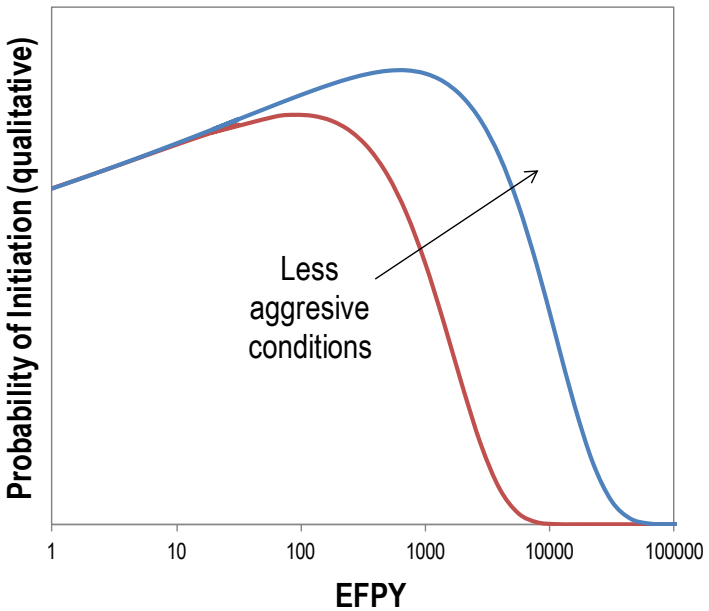
Model Form and Dependencies

- **Initiation time is sampled from a Weibull distribution**
- **The characteristic time (*θ*) is adjusted as a function of temperature and surface stress**

$$\theta = \exp\left[\frac{Q}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right]\left(\frac{\sigma}{\sigma_{ref}}\right)^{-n}\left(N_{subunit}\right)^{1/\beta}\theta_{ref}$$

- **The characteristic time includes normalization for number of subunits (PVP2007-26731)**

$$t_{INI} = \theta\left(\left(-\ln\left(U\right)\right)^{1/\beta}\right)$$



Parameter Estimation

Direct Models 1 and 2

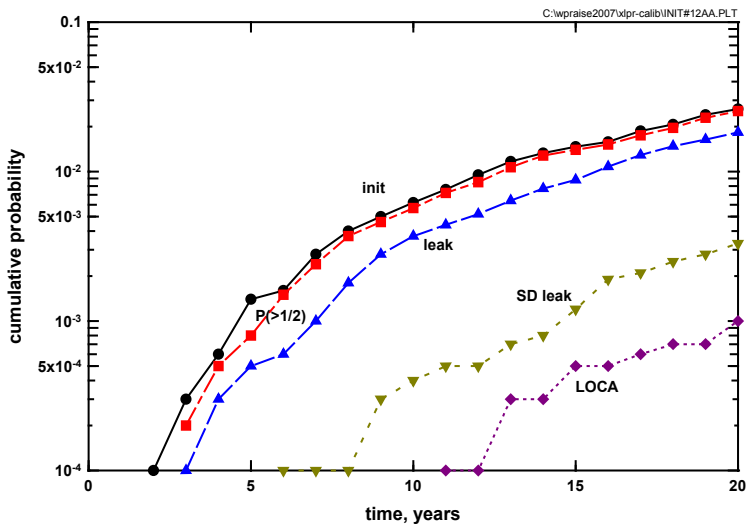
Scaling Factor Estimation

- Laboratory testing allows precise quantification of parametric dependencies
- However, specimen test results can be biased and less dispersed than PWSCC initiation in the field
- Both direct models include scaling factor to adjust parametric models to better reflect field conditions
  - For example, "Material index" distribution for Direct Model 1 has been estimated with maximum likelihood estimation (MLE) using data for French RVHs

Direct Models 1 and 2

Scaling Factor Estimation for DMWs

- MLE is not considered feasible for DMWs given sparse and weakly characterized detection data set
- Instead, scaling factor distributions are estimated with calibration studies
  - Simulate probabilistic initiation followed by growth to failure using WinPRAISE software
  - Use benchmark metrics including rate of initiation, probability of failure, average number of flaws, etc.



  - Set targets based on industry experience
  - Vary number of subunits, median scaling factor, weld-to-weld variation and within-weld variation to meet targets

Weibull Model

General Parameter Estimation

- Data is adjusted to common reference temperature
  - Surface stress adjustment is not practical for DMWs
- Weibull parameters are estimated with MLE, which is preferred over ordinary least squares (OLS) for limited data
  - Suspended items give credit for components without indications at recent inspections (Abernethy 1996)
- Weibull parameter uncertainty is estimated with ordinary least squares

$$\ln\left(-\ln\left(1-F\right)\right) = \beta \ln\left(t\right) - \beta \ln\left(\theta\right)$$

$$y \quad = \quad \beta x \quad + \quad c$$

Weibull Model

DMW Detection Data (December 2012)

Location	Temp.	Plant Type	Alloy 82/182 Welds with Reported PWSCC Indications	Inspected Alloy 82/182 Welds without Reported PWSCC Indications (2)	Inspected Alloy 82/182 Welds after Weld Overlay (3)	Total Identified Alloy 82/182 Piping Welds (4,5)
RVON	Hot	W	3	113	0	116
RVIN	Cold	W	0	114	0	114
RCP inlet/outlet	Cold	CE	0	72	0	72
RCP inlet/outlet	Cold	B&W	0	48	8	56
RV CFN	Cold	B&W	0	12	2	14
Pressurizer	Press.	All	8 (1)	50	213	271
HL Branch	Hot	CE	3	22	16	41
HL Branch	Hot	B&W	3	1	10	14
CL Branch	Cold	CE	1	121	13	135
CL Branch	Cold	B&W	1	31	6	38
SGIN	Hot	W	1	2	0	3
SGON	Cold	W	0	3	0	3
		Totals	20	589	268	877

Notes

(1) One PWSCC indication was located in the heat affected zone of the Alloy 600 safe end.

(2) PDI exams were performed on unmitigated welds, prior to overlay or before or after MSIP/inlay/onlay.

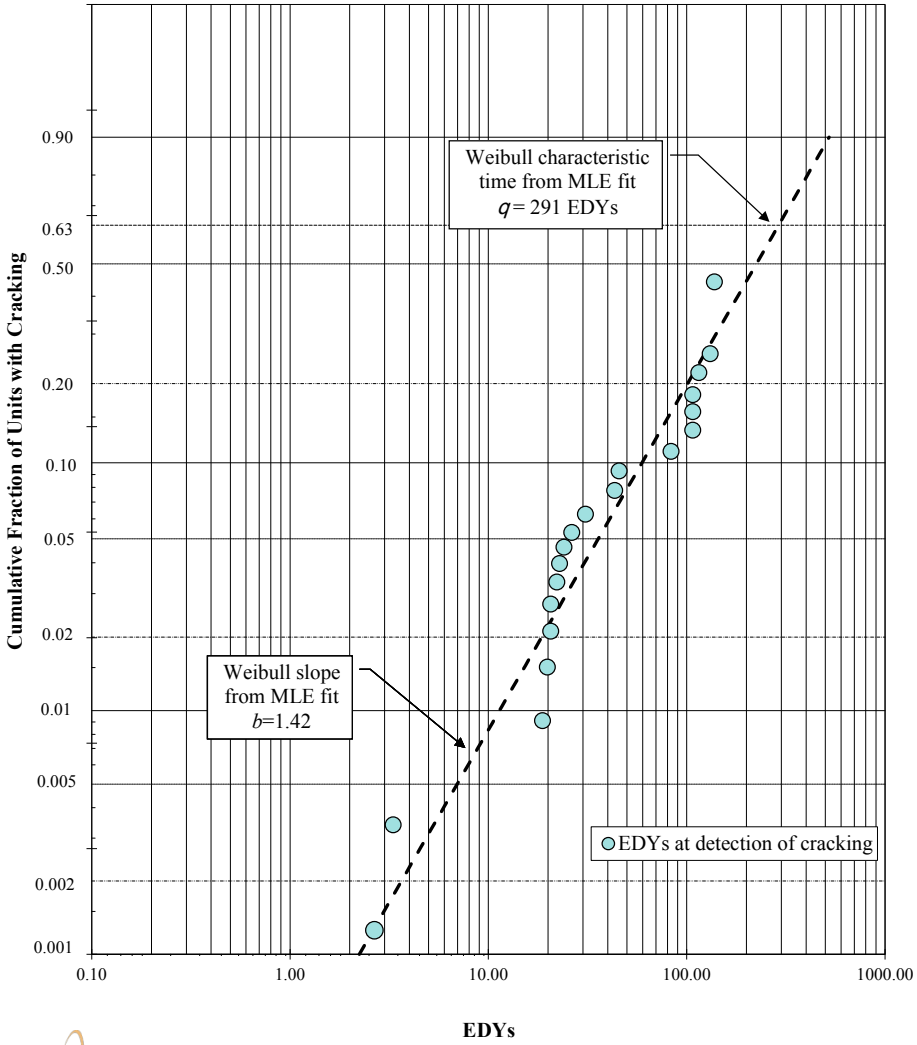
(3) PDI exams were performed after overlay. If it was unclear when the PDI exam occurred relative to overlay, it was assumed that the overlay was performed after PDI.

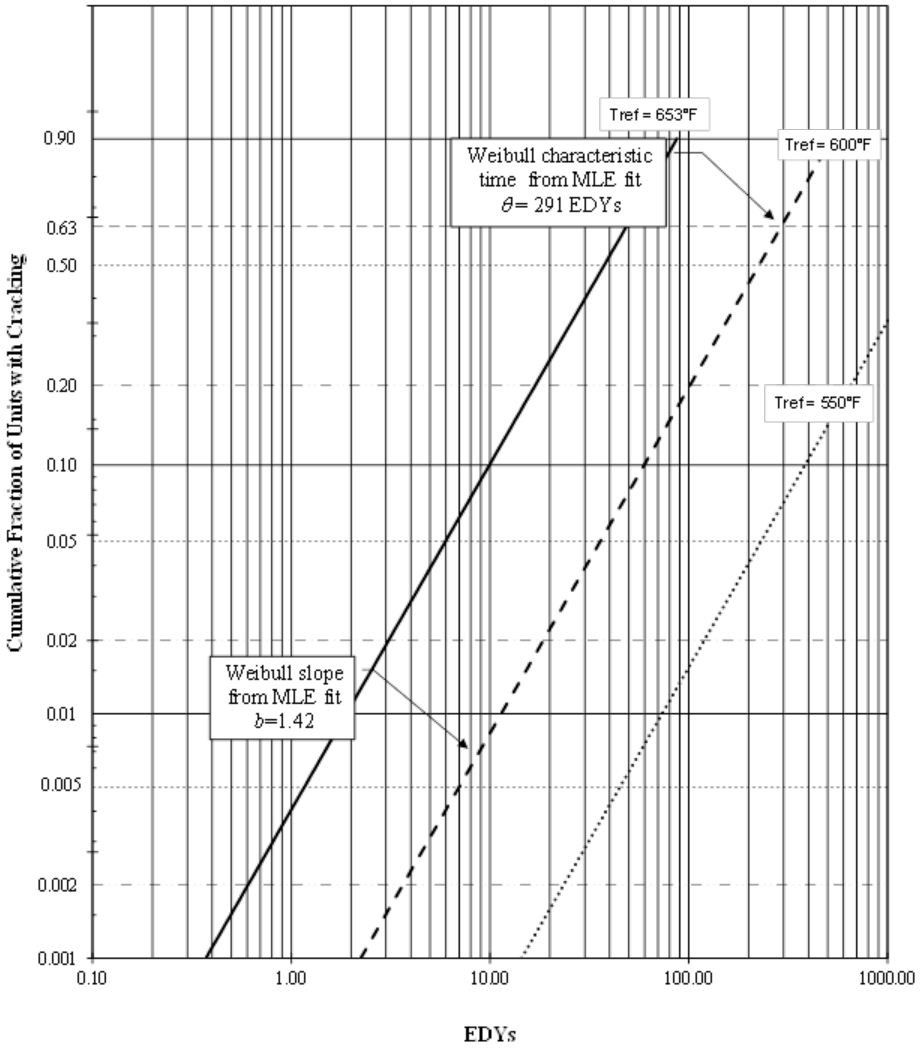
(4) Subject to ASME Code Case N-770-1 Volumetric/Surface Inspection Requirements (≥ 2" NPS and operating temperature ≥ 525°F). However, welds that were identified to be cladded on the ID with stainless steel or Alloy 52 have been excluded from the table because the Alloy 82/182 material in these welds is not expected to be exposed to primary coolant.

(5) Alloy 82/182 weld locations that were replaced using PWSCC-resistant material before MRP-139R1 / N-770-1 PDI baseline exam deadlines were excluded from the table.

Weibull Model

Parameter Estimation for DMWs





Characterization of Uncertainty

- **Within-weld vs. weld-to-weld variation**
  - **Direct Model scaling parameters are separated into the two sources of variation; the dispersion for each is estimated through calibration**
  - **Sampled Weibull parameters represent weld-to-weld variation; random sample from Weibull distribution represents within-weld variation**
- **Aleatory vs. epistemic uncertainty**
  - **Weld-to-weld uncertainty is characterized as epistemic**
  - **Within-weld uncertainty is characterized as aleatory**
- **Analogous initiation and growth parameters can be correlated**

Conclusions

- **Pilot Study implemented three approaches to simulation of PWSCC initiation**
  - **Material Index Approach (Direct Model 1)**
  - **Cold-Work Modified Strain Rate Damage Model (Direct Model 2)**
  - **Weibull Model Based on Plant Experience**
- **Each approach assumes:**
  - **Initiation of flaw of engineering scale**
  - **Possibility of initiation in each component segment, and subsequent coalescence of engineering scale flaws**

Conclusions (cont'd)

- **The effort for xLPR 2.0 is concentrating on:**
  - **Development of nuclear software QA documentation for the approaches taken in the Pilot Study**
  - **Statistical evaluation of PWR inspection experience for Alloy 82/182 piping welds**
  - **Refinement of model inputs, including calibration using available data sources**
  - **Implementation of fatigue initiation module**
- **Modeling of initiation is challenging because of process complexity and unknown key factors. Statistical approaches are key**

xLPR Primary Water Stress Corrosion Crack Initiation Models

Expansion of the PWSCC Initiation Database

Darrell Dunn
Materials Engineer
RES/DE/CMB

ACRS Subcommittee on
Materials, Metallurgy, & Reactor Fuels
June 4, 2013

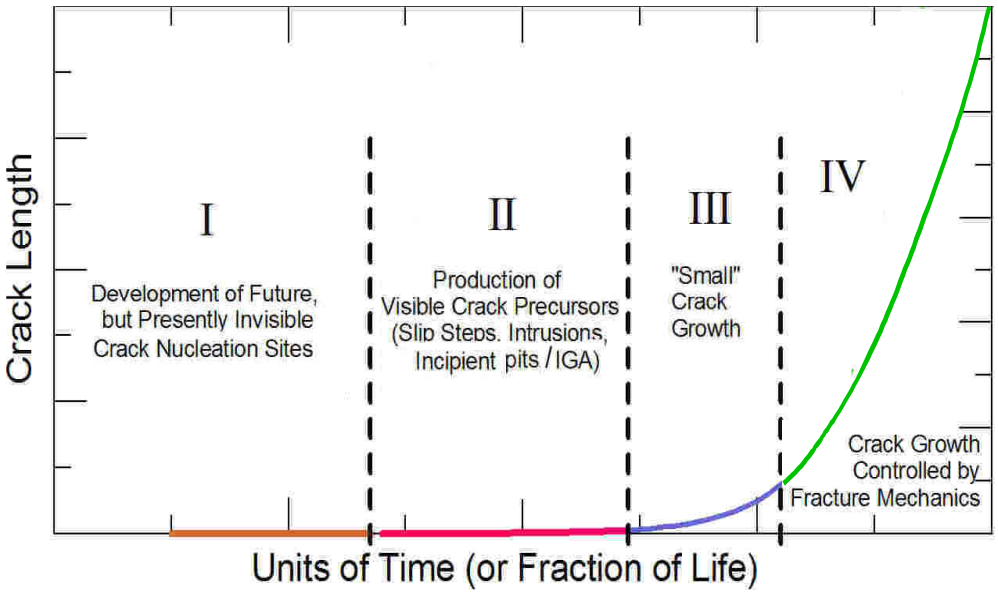
Outline

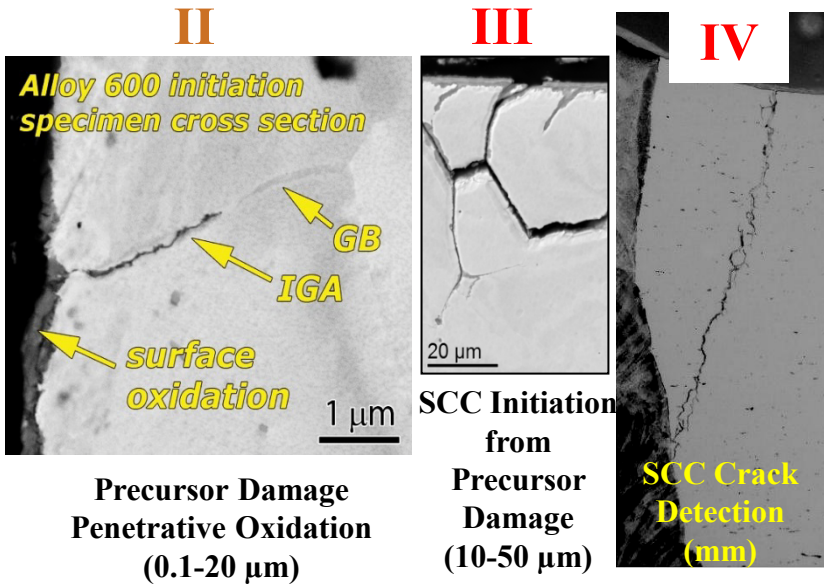
- PWSCC initiation data needs
- Initiation testing
  - Test methods
  - Challenges
  - Initiation testing example
- Proposed cooperative effort

PWSCC initiation data needs

1. Stress and temperature effects in alloy 600/182/82
2. Alloy 690/152/52
   - Comparison to 600/182/82 (improvement factors)
   - Weld dilution zones and weld defects
   - Cold work and weld heat affected zones

PWSCC initiation testing





Precursor Damage Penetrative Oxidation (0.1-20 µm)

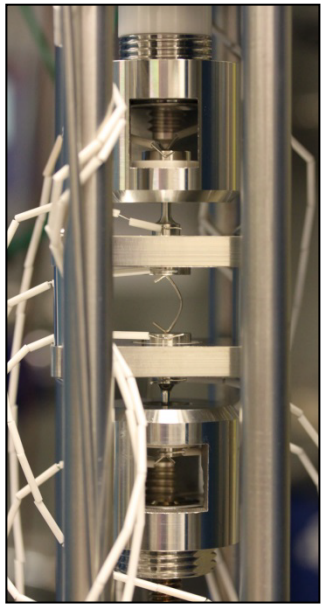
SCC Initiation from Precursor Damage (10-50 µm)

Initiation testing challenges

- Time for crack initiation may be very lengthy
- Acceptable methods to accelerate testing
- Effects of environmental and material parameters
- Parameter interactions
- Detecting/verifying initiation time
- Only 1 datum per specimen
- Incorporation of data into models/predictions

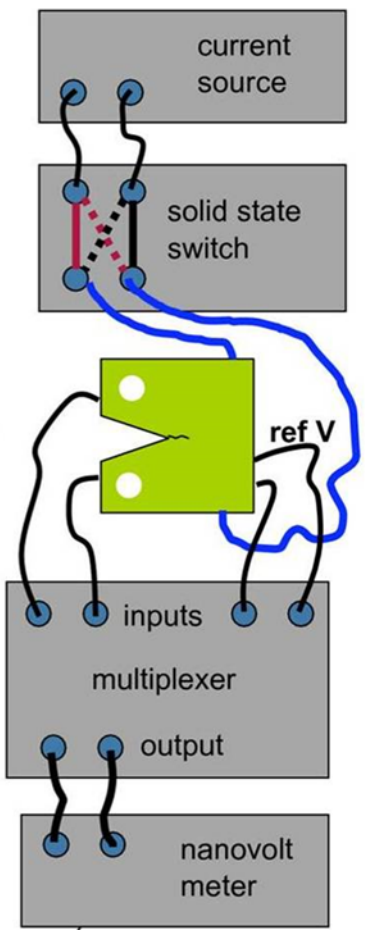
- Cost

DOE-NE test systems



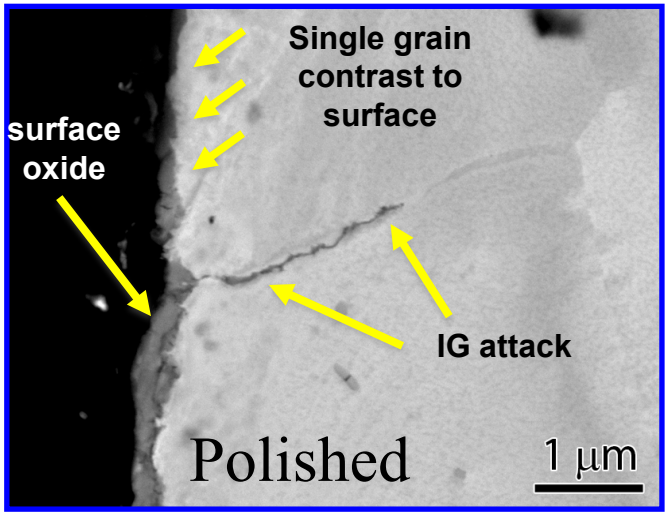
- Instrumented tensile specimens
- Up to 30 specimens per autoclave
- Allows testing of cold worked, DMW, weld HAZ and weld defect specimens
- Crack initiation detected using direct current potential drop (DCPD) monitoring

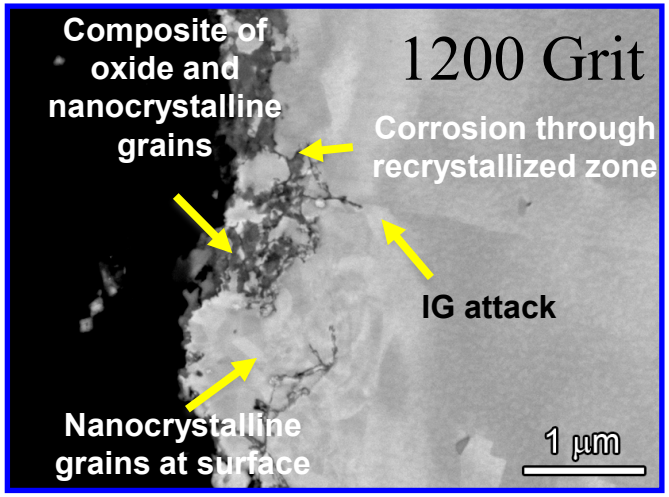
Direct current potential drop monitoring

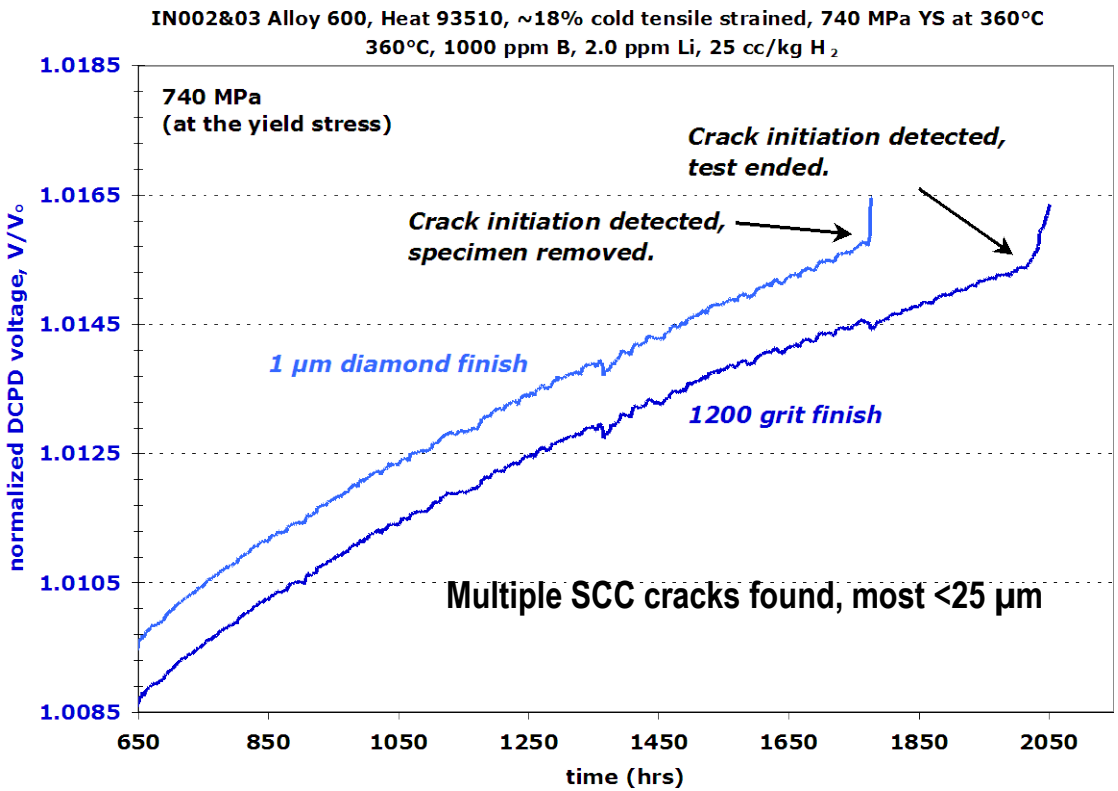


- Direct current potential drop (DCPD) method to measure crack length as a function of time and obtain crack growth rate
- Crack growth rate sensitivity: 5 x 10^{-10} mm/s
- DCPD systems have been adapted to SCC initiation testing

PNNL/DOE initiation testing data







Proposed cooperative effort

- **Amend existing MOU in place with DOE-NE and EPRI**
  - **DOE contributes the testing systems**
  - **NRC contributes samples (e.g., alloy 600 materials removed from service, alloy 152 welds)**
  - **EPRI conducts the testing**