



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

March 5, 2013

MEMORANDUM TO: ACRS Members

FROM: Quynh Nguyen, Senior Staff Engineer **/RA/**
 Technical Support Branch, ACRS

SUBJECT: CERTIFIED MINUTES OF THE ACRS MATERIALS, METALLURGY
 AND REACTOR FUELS SUBCOMMITTEE MEETING ON
 FEBRUARY 6, 2013

The minutes of the subject meeting were certified on March 5, 2013, as the official record of the proceedings of that meeting. Copies of the certification letter and minutes are attached.

Attachments: As stated

cc: C. Santos



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

MEMORANDUM TO: Quynh Nguyen, Senior Staff Engineer
Technical Support Branch, ACRS

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

SUBJECT: CERTIFICATION OF THE MINUTES OF THE ACRS MATERIALS,
METALLURGY AND REACTOR FUELS SUBCOMMITTEE
MEETING ON FEBRUARY 6, 2013

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

/RA/

3/5/13

J. Sam Armijo, Chairman Date
Materials, Metallurgy & Reactor Fuels Subcommittee

ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
MINUTES OF THE ACRS MATERIALS, METTALURGY AND REACTOR FUELS
SUBCOMMITTEE MEETING
FEBRUARY 6, 2013

The ACRS Materials, Metallurgy and Reactor Fuels Subcommittee held a meeting on February 6, 2013, in T2-B1, 11545 Rockville Pike, Rockville, Maryland. The meeting convened at 8:30am and adjourned at 11:40pm.

The entire meeting was open to the public.

No written comments or requests for time to make oral statements were received from members of the public related to this meeting.

ATTENDEES

ACRS Members/Consultants/Staff

J. Sam Armijo, Chairman
Dennis C. Bley, Member
Charles H. Brown, Jr., Member
Harold B. Ray, Member
Michael T. Ryan, Member
Stephen P. Schultz, Member
William J. Shack, Member
Quynh Nguyen, ACRS Staff (Designated Federal Official)

NRC Staff

Michael Benson, RES
Michael Case, RES
Jay Collins, NRR
David Rudland, RES
Rob Tregoning, RES
Eric Reichelt, NRO
Tim Lupold, NRR
John Honcharik, NRO
Bob Davis, NRO
Bob Hardies, NRR

Other Attendees

John Broussard, Dominion Engineering, Inc.
Zhili Feng, ORNL
Paul Crooker, EPRI

SUMMARY

The purpose of the meeting is to review the Weld Residual Stress Validation Program (WRSVP). The meeting transcripts are attached and contain an accurate description of each matter discussed during the meeting. The presentation slides and handouts used during the meeting are attached to these transcripts.

SIGNIFICANT ISSUES	
Issue	Reference Pages in Transcript
As context for the briefing, the issue of the Wolf Creek circumferential indications involving dissimilar metal welds found in pressurizer nozzles was discussed. Staff also provided a description of the xLPR Program and the development of a modular-based probabilistic fracture mechanics code.	11, 15-16
Chairman Armijo asked if steps were being taken during the fabrication stage to create a favorable compressive residual stress.	18-20
Member Brown asked about the benefit of a more refined analysis versus conservative plant design.	21-24
Chairman Armijo began a discussion about chemical effects that are causing robust structures to leak and for flaws to grow.	25
Member Bley asked about the staff's interactions with other industries regarding residual stresses.	34-35
After hearing about diffraction-based and strain released-based measurement techniques, Chairman Armijo asked about magnetic and ultrasonic techniques.	49-50
Staff described the deep hole drilling measurement technique.	50-54
Member Shack asked why there are significantly different results between the models. In particular, in Phase IV, there are significant differences in the two kinematic models. Chairman Armijo stated that he is more comfortable with experimental variability rather than calculated uncertainties. The staff explained that there is as much uncertainty in the measurements as there are in the theoretical predictions. However, a unique aspect of the WRSVP is that multiple measurements are taken in a systematic way.	69-71, 74-75, 85-86
Member Schultz asked for clarification of what was meant by "modeling uncertainty." In the round robin, the mean value of the models was consistent with the experiments. From a mean standpoint of all of the analyses, the staff saw little model uncertainty; however, there was modeling uncertainty within the individual models. Staff agreed to be more careful about their descriptions of "modeling uncertainty" in the future.	124-125

ACTION ITEMS	
Action Item	Reference Pages in Transcript
Member Shack requested a copy of an EPRI Report, "Validation of Stress Corrosion Cracking Initiation Model for Stainless Steel and Nickel Alloys," (1025121) dated 12/21/12.	39
Member Shack asked if a finite element analysis was conducted to see when the independent laminar breaks down in the gradient. The staff may contact Vegter, a British Company, for independent verification of results.	54-56

Documents provided to the Subcommittee

1. Letter to R.W. Borchardt, Executive Director for Operations, US NRC; from J. S. Armijo, Chairman, ACRS; dated April 23, 2012, Subject: "Extremely Low Probability of Rupture Project" (ML12108A268)
2. Memorandum to J. S. Armijo, Chairman, ACRS; from R. W. Borchardt, Executive Director for Operations, US NRC; dated May 30, 2012, Subject: "Response to ACRS Recommendations on Extremely Low Probability of Rupture Project" (ML12137A207)
3. Memorandum to B. W. Sheron, Director, Office of Nuclear Regulatory Research; from E. J. Leeds, Director, Office of Nuclear Reactor Regulation; dated August 26, 2010, Subject: "User Need Request on Development of a Probabilistic Method for Evaluating the Probability of Leak-Before-Break of Nickel Based Alloys Exposed to Primary Water Environments" (UNR NRR 2010-018) (ML102140300)
4. M. Kerr, D. Rudland, et al., "Characterization of a Plate Specimen from Phase I of the NRC/EPRI Weld Residual Stress Program," Proceedings of the 2011 ASME Pressure Vessels and Piping Division Conference, July 2011, Baltimore, Maryland.
5. Technical Report, "Materials Reliability Program: Finite-Element Model Validation for Dissimilar Metal Butt-Welds (MRP-316)," December 2011.
6. Technical Letter Report, "Weld Residual Stress Finite Element Analysis Validation Double Blind International Round Robin Study."
7. Fredette, L.F., Kerr, et al., "NRC/EPRI Welding Residual Stress Validation Program - Phase III Details and Findings," Proceedings of 2011 ASME Pressure Vessels and Piping Division Conference, July 2011, Baltimore, Maryland.
8. Technical Letter Report, "Weld Residual Stress Finite Element Analysis Validation PWR Cold Leg Nozzle Study."

Official Transcript of Proceedings

NUCLEAR REGULATORY COMMISSION

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

Docket Number: (n/a)

Location: Rockville, Maryland

Date: Wednesday, February 6, 2013

Work Order No.: NRC-2092

Pages 1-143

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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)

6 + + + + +

7 MATERIALS, METALLURGY AND REACTOR FUELS SUBCOMMITTEE

8 + + + + +

9 WEDNESDAY

10 FEBRUARY 6, 2013

11 + + + + +

12 ROCKVILLE, MARYLAND

13 + + + + +

14 The Subcommittee met at the Nuclear
15 Regulatory Commission, Two White Flint North, Room
16 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 HAROLD B. RAY, Member

23 MICHAEL T. RYAN, Member

24 STEPHEN P. SCHULTZ, Member

25 WILLIAM J. SHACK, Member

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1 NRC STAFF PRESENT:

2 QUYNH NGUYEN, Designated Federal Official

3 MICHAEL BENSON

4 MICHAEL CASE

5 JAY COLLINS

6 DAVID RUDLAND

7 ROB TREGONING

8

9 ALSO PRESENT:

10 JOHN BROUSSARD

11 ZHILI FENG

12

13

14 *Present via telephone

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P R O C E E D I N G S

8:31 a.m.

CHAIR ARMIJO: Good morning. The meeting will now come to order. This is a meeting of the Materials, Metallurgy, and Reactor Fuels Subcommittee. I'm Sam Armijo, Chairman of the Subcommittee. ACRS members in attendance are Steve Schultz. He came in and left, but he'll be back. Bill Shack, Dennis Bley, Michael Ryan, Dana Powers, Harold Ray, and Charlie, well, I mentioned Charlie already, I believe. Quynh Nguyen of the ACRS staff is the Designated Federal Official for this meeting and is a Lead Cognizant Engineer.

The purpose of this briefing is for the staff to discuss the Weld Residual Stress Validation Program. The Subcommittee will gather information, analyze relevant issues and facts, and formulate a proposed position and action, as appropriate, for deliberation by the full Committee.

The rules for participation in today's meeting were announced as part of the notice of this meeting previously published in the Federal Register on January 16th, 2013. The meeting will be open to the public, open to public attendance, with the exception of portions that may be closed for tech

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1 information that is proprietary, pursuant to 5 USC
2 552(b)(4). We have received no written comments or
3 requests for time to make oral statements from members
4 of the public regarding today's meeting.

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

13 A telephone bridgeline has been
14 established for this meeting. To preclude
15 interruption to the meeting, the phone will be placed
16 in a listen-in mode during the presentations and
17 Committee discussions.

18 I'd like to remind everyone to please
19 silence all phones. And we will now proceed with the
20 meeting, and I call on Mr. Mike Case of the Office of
21 Nuclear Regulatory Research to make introductory
22 remarks. Mike?

23 MR. CASE: Good morning, gentlemen. My
24 name is Mike Case. I'm the Director of Engineering in
25 the Office of Research. And I think this is a great

1 opportunity to talk about the Weld Residual Stress
2 Validation Program today. I think it's a good
3 opportunity because it's something that's important
4 but not urgent. Often, we get together around things
5 that are urgent, and you have a little bit of time --

6 CHAIR ARMIJO: Urgent but not important.

7 MR. CASE: -- comments, but they're really
8 hard to disposition when things are done. The Weld
9 Residual Stress Program is in progress, and it's
10 important from two aspects: because it gives us
11 insights that really that Jay uses in flow evaluations
12 that come from time to time in the operational
13 experience. So it's applied in the short term. And
14 then, as you'll learn through the presentations, it's
15 also an important item in xLPR, which the Committee
16 has heard about. So it has some safety implications
17 in the long term, and that's what makes it important.

18 Now, as far as what we need specifically
19 from the ACRS today, it's a pretty easy ACRS
20 assignment in that I don't need letters. What we need
21 from you folks are your insights and your experience
22 to help the program do better. And that's, like, in
23 my mind, that's a really easy ACRS assignment because
24 you do that well.

25 But let me make it a little more difficult

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1 for you. When you look at my division, so in my
2 division I'll do materials issues, I do seismic
3 issues, I do digital I&C issues, and some other
4 things. Back when Tim Lupold, who's in the audience,
5 back when he worked for me, we were probably a \$23
6 million operation, and now we're sort of starting into
7 the FY 15 budget cycle and I sort of look at the
8 number that they want me to keep flat and it's around
9 \$16 million.

10 And so the difference is around \$7
11 million. That's a lot of millions. And so I'm really
12 proud of my folks because they've been keeping these
13 programs going, even though that we've been steadily
14 taking resources out of the system. And you'll hear
15 a little bit about how they do it. We partner with
16 EPRI. We partner real well with the program offices.
17 Sometimes, they give some of their extra money to keep
18 some of these things going.

19 But I sort of look at \$16 million, and I
20 say, golly, it's kind of hard nowadays to do more. So
21 as you make comments and help us with the program,
22 just be sensitive to I've really kind of lost my
23 ability to do more, at least until I, you know, sort
24 of stabilize the budget situation. So if you can also
25 give me help because you all also have outside

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1 contacts, like I know Bill works on the LTO program
2 that DOE runs. So if there's ways that we can better
3 leverage what we're doing, that would be a great
4 insight, as well.

5 So thanks for that. You already recognize
6 that --

7 MEMBER SHACK: You have some RELAP-7 --

8 MR. CASE: Right. Thank you. Mike is on
9 the other side of the table, so I'm sure you all will
10 give him the traditional ACRS welcome as he does his
11 presentation. So I'll turn it over to Mike.

12 MR. BENSON: So I think Dave is going to
13 start us off.

14 MR. RUDLAND: Yes, I'll actually start us
15 off. So my name is Dave Rudland, and I'm in Mike's
16 branch in the Division of Engineering and Research,
17 the Component Integrity Branch. My colleague, Mike
18 Benson, here also is going to be making some of the
19 presentations. And my branch chief, Al Csontos, sends
20 his regrets he couldn't be here today, but he's been
21 heavily involved in this also.

22 So I just thought I'd start by giving a
23 little bit of a purpose of why we're here. Mike
24 alluded to the fact that we're going to be talking
25 about the Residual Stress Validation Program. We

1 recently completed four phases of this program and
2 have published some documents and come up with some
3 conclusions on that, so we want to give you an update
4 of where we sit on that and what those conclusions
5 are, where the gaps are, and things like that.

6 And then we'll be talking about the
7 upcoming continued residual stress effort to try to
8 build on not only what we learned but where the gaps
9 are and where we need to go from here because the
10 purpose of the program is a lot more than just looking
11 at individual validation of residual stresses but how
12 we can use that in a regulatory framework.

13 So our objectives, as Mike pointed out, is
14 just to try to achieve a common understanding of the
15 process, the program that we have, the objectives, the
16 results, the conclusions, as well as the planned path
17 forward. And we want your advice, and we want your
18 honest opinion on what we've done and where we're
19 going on the project.

20 And so we're going to give you a little
21 bit of background first to start off. I'm going to
22 start with giving the background and a little bit
23 about regulatory impact. And my colleague, Jay
24 Collins, will help me in that situation. And then
25 Mike will talk about our accomplishments with the

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1 first four phases of the Residual Stress Program, as
2 well as the gaps which lead into what we have planned
3 in the next year or so.

4 All right. So in terms of background,
5 where this all comes from, as Mike alluded to, is that
6 a lot of times when flaws are found or if flaw
7 evaluations need to be done, they're done via ASME
8 Section XI. And if the material is susceptible to
9 stress corrosion cracking, residual stress, per the
10 code, is required to be included in the analysis. And
11 Appendix C of ASME Section XI dictates that residual
12 stress must be used.

13 But the code itself just gives very
14 limited guidance on what residual stress to use, how
15 to get that residual stress, how do you know that a
16 residual stress is appropriate. It just says you need
17 to use residual stress in the analysis. And it
18 doesn't account for any kind of uncertainty. It
19 doesn't say you must use a conservative residual
20 stress. It just says you must use residual stress.

21 So back when the technical basis for the
22 code act for the code was being developed, a series of
23 experiments were done to try to characterize residual
24 stress, and it was all based on the fact that there
25 was a lot of IGSCC happening in the heat effect zones

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1 of dissimilar metal welds. Experiments were done by
2 ANL, Bill Shack was heavily involved in those, as well
3 as by EPRI, looking at stainless steel similar metal
4 welds, and this plot of the data is a sampling of
5 that. And the results from the analysis or from the
6 experiments were that there are significant scatter in
7 the data; but, within the heat effect zone and within
8 the base metal of these particular welds, residual
9 stresses are relatively uniform, relatively consistent
10 between welds.

11 And so the Section XI committee then took
12 these types of results and came up with a set of
13 recommendations that they put into their technical
14 basis document. And those recommendations, again,
15 were segregated by wall thickness and this see note
16 three in this particular illustration demonstrates a
17 high order polynomial to represent a through wall
18 distribution of that stress based on the ID stress.
19 And these, again, came from experimental results that
20 were based on heat effect zones of stainless steel
21 welds. This is in the technical basis again, but it's
22 not actually in the code itself.

23 So like I mentioned, many of the issues of
24 IGSCC were evaluated using these particular plots that
25 I showed earlier. Effects of weld sequencing and all

1 that stuff were not really included or investigated,
2 mainly because those things are insensitive out in the
3 base metal. They're a lot more sensitive when you get
4 into the weld. So the dependence on things such as
5 geometry and welding, weld bead size, weld parameters,
6 weld sequence becomes much more important and a much
7 larger impact on the residual stress when we're
8 talking about the stresses that are in the middle of
9 the weld relative to the stresses that are away from
10 the weld.

11 And that became very apparent when we
12 started looking at a particular problem that occurred
13 in 2006. In 2006, at the Wolf Creek Plant, some
14 indications were found, circumferential indications
15 were found in the pressurizer nozzles, and they were
16 these Alloy 600 or Alloy 82 and 182 dissimilar metal
17 welds, an Inconel weld that joins a carbon steel and
18 a stainless steel base metal. Those welds are
19 susceptible to this primary water stress corrosion
20 cracking, and these indications found were analyzed by
21 both the industry and the NRC.

22 As part of those investigations, both
23 independently, we did residual stress numerical
24 evaluations for those particular welds. This plot
25 shows an example of that. And the differences here

1 are relatively large; and, again, it shows just single
2 analysis results between the industry which are the
3 open symbols in this case and the NRC which are solid
4 symbols. But you see that there are some scatter, and
5 it could lead to very large differences in prediction
6 of time to leakage and/or time to a rupture.

7 This is just an example of some flaw-
8 growth calculations that demonstrate how the residual
9 stress effects the behavior of the flaw. The three
10 lines here represent residual stress fields through
11 the wall thickness of residual stress and mega-pascals
12 on the Y axis. The illustrations here represent a
13 half of a pipe where the white area is the final
14 surface crack at through wall penetration. So when a
15 surface crack, a circumferential surface crack
16 penetrated the wall, using these different residual
17 stress fields, this is what the final shape of the
18 flaw looked like.

19 For no residual stress, the flaw shape is
20 semi-elliptical and relatively uniform. However, as
21 you get these more unusual residual stress fields, you
22 notice the flaw length is much longer and the amount
23 of cracked area is much greater. The difference in
24 stability characteristics between a flaw like this and
25 a flaw like this can be relatively large, depending on

1 the toughness of the pipe, because there is a lot more
2 cracked area. So it becomes very important to
3 characterize the residual stress fields properly in
4 order to understand what the limiting flaw size may
5 be.

6 As part of that Wolf Creek effort, since
7 we realized that residual stresses are very important,
8 we undertook a small validation program. What we used
9 was we used a pre-published validation program that
10 was done by a European project called NESC III where
11 they had done some similar metal weld analyses, as
12 well as experimental results. And our contractors, as
13 well as the EPRI contractors, analyzed those in an
14 open kind of validation criteria, and we found that
15 there was about a 200 mega-pascal scatter between the
16 analysis results. And we didn't know if this was
17 modeling uncertainty or weld uncertainty or was there
18 measurement error in here or was there some other kind
19 of uncertainty. We just realized that there was a big
20 scatter in that particular kind of data.

21 And, again, these analyses that were done
22 by the NRC and industry in this particular case were
23 not blind. We knew the results ahead of time. We saw
24 the report. We did the analyses, and these are the
25 results that we got.

1 CHAIR ARMIJO: The ND measurements, is
2 that the neutron diffraction?

3 MR. RUDLAND: Yes. The symbols are
4 neutron diffraction measurements.

5 CHAIR ARMIJO: That's the only
6 experimental data there?

7 MR. RUDLAND: Yes --

8 CHAIR ARMIJO: Everything else --

9 MR. RUDLAND: -- only one that was done.

10 CHAIR ARMIJO: Okay. I'm just trying to
11 see --

12 MR. RUDLAND: And you can see the scatter
13 that was predicted in the experimental results. It's
14 not as large as the measurement uncertainty or, I'm
15 sorry, as the analysis uncertainty that was shown.
16 And the results from the NESC project were basically
17 the same as what we have here. They concluded that
18 there was a lot of scatter between, we needed more
19 refined and probably additional measurements of
20 residual stress also.

21 MEMBER SHACK: Yes. I mean, I'd say those
22 error bars are kind of imaginative.

23 CHAIR ARMIJO: That small.

24 MEMBER SHACK: Let two guys make the
25 neutron measurements and see how close they --

1 MR. RUDLAND: That's right, that's right.
2 And we'll see some of that in the later talks of what
3 we did as part of our program. So what happened with
4 this Wolf Creek problem was that the NRC issued in
5 2007 a CAL to 40 plants asking for enhanced leakage
6 monitoring, as well as inspection and mitigation of
7 pressurizer welds for all the PWRs with uninspected
8 182 welds. And in that particular time, there were
9 nine plants that were scheduled for 2008 inspection
10 and mitigation.

11 The staff came here to talk to the ACRS in
12 March of 2007. And the ACRS wrote a letter that
13 concluded that the technical basis was good and
14 sufficient but additional work on residual stress,
15 including validation, was required.

16 A couple of years later, we came here
17 again to talk about the xLPR program, and that was
18 just recently, in the last year or so. And, again,
19 that program is a modular-based probabilistic fracture
20 mechanics code, and it's going to be used to assess
21 the LBB systems that are currently in the fleet to
22 GDC-4, and we had created a pilot study to demonstrate
23 the feasibility. And the ACRS again wrote a letter on
24 that and concluded that the models and the technology
25 was good, but we needed to work on crack initiation,

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1 we needed a more realistic crack initiation model, and
2 we wanted to make sure that we had proper
3 characterization of residual stress and the treatment
4 of uncertainties that we're able to properly account
5 for those.

6 So in xLPR, we are treating uncertainty
7 and residual stress. We're modeling it several
8 different ways. We're able to look at taking a
9 residual stress field and modeling ID uncertainty, as
10 well as the uncertainty when the stress field crosses
11 the x-axis and sample on that particular uncertainty.
12 We're also looking at modeling the uncertainty on a
13 piece-wise linear scale where the residual stress is
14 now, instead of being a functional form that may be
15 represented as a polynomial, is actually represented
16 by discrete points where each of the discrete points
17 have their own uncertainty that are sampled in a
18 correlated fashion. So in this particular program,
19 we're looking at methodologies for properly accounting
20 for residual stress uncertainty in the analysis.

21 In parallel with that effort, the
22 industry, through EPRI, developed MRP-287, which was
23 a non-mandatory guidance for PWSCC flaw evaluation.
24 They incorporated NRC comments informally but has not
25 been formally reviewed by the staff. And that

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1 document gives some suggestions on how to conduct an
2 acceptable residual stress analysis. It talks about
3 geometry, materials, configurations, repairs, safe
4 ends, weld beads, things like that. But the bottom
5 line is that it recommends that the numerical
6 procedures always be benchmarked and validated against
7 experiments.

8 So how are these things used? How is
9 residual stresses used again? Typically, again, like
10 I mentioned, the relief comes in or a review comes in
11 for a flaw evaluation either for an in-service flaw
12 that was found or for some other reason of wanting to
13 get relief from inspection criteria and things like
14 that. The licensee then goes out and finds residual
15 stress either from literature, from a generic
16 analysis, or from a case-specific analysis.

17 When they submit to the NRC, typically,
18 there's really no information about residual stress
19 uncertainty in the relief request. Only a single
20 through wall thickness representation of the residual
21 stress is presented, and the analyses are done based
22 on that residual stress field. It's kind of contrary
23 to what it says in MRP-287.

24 So from a regulatory standpoint, how can
25 we be assured that the residual stresses that are

1 being presented are conservative or representative
2 even of really what's happening out there, and how can
3 we be guaranteed that the residual stresses and the
4 numerical procedures are validated or conservative
5 with respect to uncertainties? Currently, we can't.

6 So there's a couple of things that we need
7 to do. We need to try to add confidence in the
8 residual stresses, which is what we're going to talk
9 about today. Can we develop confidence in our
10 procedures? Can we modify our procedures to become
11 more confident? We need to have some robust
12 validation methods. You can do all the experiments in
13 the world and you can do all the measurements and you
14 can do all of the analysis and you can plot them all
15 together, but you have no method for really coming up
16 with the criteria. You just have a bunch of lines on
17 a plot. So we have to really try to develop
18 appropriate criteria to demonstrate validation. And
19 we need to try to minimize all these different kinds
20 of uncertainties, and that's what's going on in our
21 ongoing residual stress work. That's what we're
22 trying to do.

23 CHAIR ARMIJO: David, is there any work
24 being done by yourselves or EPRI to kind of cut this
25 off, this problem off at the fabrication stage to

1 create a favorable compressive residual stress,
2 particularly at the surface for BWSCC or IGSCC
3 nucleates? If you could be assured of that, then if
4 you never nucleate a crack, then you're not so
5 concerned about through wall variability.

6 MR. RUDLAND: Right.

7 CHAIR ARMIJO: And I know that there have
8 been repair techniques on things that are already
9 cracked, weld overlay and things like that. But is
10 there any work being done in this program that says,
11 hey, look, we're measuring these things on as-
12 fabricated nozzles and welds, but if somebody
13 fabricated them with a conventional technique, even
14 repaired them, and then went in with an internal shot-
15 peening technique and made everything compressive, we
16 would be able to measure that and be assured that that
17 thing will not nucleate a crack. Is there any work
18 going on -- to me, you know, you're faced with trying
19 to analyze what's already out there. I'm thinking
20 about the things that are being built right now or
21 repaired or replaced.

22 MR. RUDLAND: That's really a great
23 question. So what we've done is, in this particular
24 effort, we've come up with lessons learned, and those
25 lessons learned help us inform. And then, through the

1 code, we're trying to work with Section 3 code and
2 incorporate procedures and best practices in weld
3 fabrication to minimize residual stress. And so we're
4 trying to go down that path, and I'll mention that,
5 actually, in the next slide.

6 CHAIR ARMIJO: Okay.

7 MR. COLLINS: But industry is putting
8 forth programs in the new construction of components
9 to try to minimize residual stress as far as in new
10 head replacement and items of that nature.

11 CHAIR ARMIJO: We have these nozzles on
12 the Vogtle vessel, you know, and so it's been
13 repaired, replaced. Maybe they should repair it some
14 more or whatever, but you know that, whatever they've
15 done, the residual stress is not going to be
16 favorable. And --

17 MR. RUDLAND: That's right. And that's
18 why we have to attack it by Section 3.

19 CHAIR ARMIJO: -- to close this problem
20 off early before somebody puts that whole system
21 together and waits for a few years before --

22 MR. RUDLAND: Right. And in Section 3
23 right now, there are no rules that say you can't do
24 those ID repairs the way that they did it in Vogtle.
25 All right. So that's what we're trying to, through

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1 the code actions, change. And maybe it's a peening
2 thing. Maybe it's just a different way of applying
3 the repair that can minimize the stresses.

4 Okay. So that's kind of what we're going
5 to talk about today. Ongoing SME work is looking at
6 trying to develop rules within the code to be able to
7 do flaw evaluations either using best estimate
8 residual stresses from reliable, consistent, and
9 validated numerical procedures, which is probably the
10 most difficult, or, if not possible, using more
11 conservative residual stresses, either yield stress
12 level which is not very, which may be a little bit too
13 conservative, or geometry-specific bounding residual
14 stresses. And so the code right now, Section XI code,
15 is putting together an appendix to try to deal with
16 these kinds of issues and give more guidance in doing
17 these flaw evaluations.

18 MEMBER BROWN: I'm not a metallurgist, so
19 let me ask an ignorant question. Why try to get so
20 refined if you've got -- you said, the method you
21 talked about was relatively conservative, overly
22 conservative. But if we build pipes and stick them
23 together and weld them and they're overly
24 conservative, why do we care if we make them less
25 conservative with a more refined method? We don't

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1 want them to break, so, I mean, I have no problem with
2 doing all the research. That's just fine. But these
3 are huge pipes, lots of water, and the whole thing is
4 predicated on trying to resolve some of the, you know,
5 do we really have a validated leak before break type
6 evaluation, you know, methodology or thought process.
7 But if you know you've got a conservative design
8 because you've made it beefier than it needs to be,
9 based on your methodologies or your knowledge, is it
10 a huge cost to do it that way, as opposed to a little
11 bit more refined? Do you reduce the cost of building
12 the plant by hundreds of millions of dollars? Or if
13 it's \$5,000, who cares?

14 MR. RUDLAND: Yes, but it's not so much in
15 the building of the plant. It's more in the continued
16 operations. So if there's some situation where they
17 come to the NRC for relief of a particular inspection
18 schedule, having extremely conservative residual
19 stress may force them to shut down or to continue to
20 be shut down over a period that may not be necessary,
21 which becomes an economic issue for the plants. And
22 in something that's overly conservative, plus the
23 continued safety factors and other things that are in
24 the code that are conservatism, that conservatism may
25 not be appropriate in that particular case.

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1 Jay, I don't know if you have any comments
2 on that.

3 MR. COLLINS: I think you said it well.
4 I mean, it's the, there is a lot of conservatism
5 already in the design, and there's a conservatism
6 that we are putting in to the flaw analysis as far as
7 even the crack growth rates that we use. And it isn't
8 in every calculation that we need to have these items.
9 We look at a yield and see if it's acceptable. At
10 that point, then we don't have to worry about the
11 refinement. But if we start to see a problem, when we
12 look at the uncertainties in our calculations and we
13 see that it's close to how long the licensee wants to
14 go for a period, we do need to have that confidence in
15 the numbers which we're going to be using to allow
16 that plant to continue to operate.

17 MEMBER BROWN: Okay. But one other
18 thought. Okay. Again, I'm not a metallurgist. So if
19 you look at the conservative setup and you say, well,
20 here, it may shut down for an inspection or do
21 something more frequently than necessary, there's also
22 a lot of uncertainty relative to, if you look at the
23 seismic forces that the plant is supposed to endure or
24 resist. And they're not huge but, yet, there are
25 certainly circumstances where you've had higher, in

1 areas of the country where there's been higher seismic
2 forces applied to certain areas than, quote, within
3 the analysis. I mean, it seems like a little bit of
4 over -- this, again, is my thought process -- a little
5 bit of overkill when that range is not necessarily
6 bad.

7 I mean, if you look at what's advertised
8 in the newspaper, I can only go by the papers, the
9 utility of the utilization factor for the plants is
10 very high. They're up in the 90-percent range or
11 something like that. And compared to other energy
12 generation facilities, I think they're higher than the
13 coal-fired plants or some of the other ones. Now, I'm
14 not absolutely sure, but that's what I -- again, not
15 reading anything you all published but stuff that's
16 been advertised in all the current articles and things
17 relative to energy production in this country.

18 So just, to me, you know, being a little
19 bit, knowing we've got uncertainties in other areas
20 where you have large forces applied and you look at
21 the g-forces. I mean, just my thought -- that's why
22 I had to ask the question. You've answered it, but it
23 just seems to me there's other areas I would have
24 applied instead of -- I'd be hesitant to go to
25 something that reduces what, I guess my buddies here

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1 would probably say the deterministic uncertainty
2 that's too high because you can do it better and be
3 more refined. And that's all nice, but sometimes it
4 doesn't matter.

5 CHAIR ARMIJO: Charlie, I don't want to
6 overstate it, but I think we wouldn't be so worried
7 about weld residual stress but for the environmental
8 effect of water chemistry. IGSCC --

9 MEMBER BROWN: No, I understand. I
10 understand that point.

11 CHAIR ARMIJO: Yes. And that makes a
12 relatively simple mechanical design problem into a
13 complicated one because now you've got this chemical
14 effect that is causing a very robust structure to leak
15 and for flaws to grow that are caused by very small
16 stresses and very small areas.

17 MEMBER BROWN: But you can inspect for
18 those.

19 CHAIR ARMIJO: Not so easily.

20 MEMBER BROWN: Well, but you talk about
21 shutdowns, you know, to look at the various things.

22 CHAIR ARMIJO: I don't know. Was Wolf
23 Creek found by an indication or by a leak?

24 MR. RUDLAND: By indication. UT
25 inspections.

1 CHAIR ARMIJO: Most of them are found by
2 leaks.

3 MR. COLLINS: Well, actually, we are
4 looking at some of the ND data, and the quality of UT
5 and going back to the IGSCC, and it looks like there's
6 almost a five-to-one ratio of where we're finding
7 indications, SCC of some type, by UT before we're
8 finding those leaks in weld type like areas.

9 CHAIR ARMIJO: Well, it's changing. In
10 the IGSCC, most of them were found by leaks. But now
11 I don't disagree that it's --

12 MR. COLLINS: It's getting better.

13 MR. RUDLAND: Inspection processes are
14 getting better, and they're better qualified head of
15 time.

16 CHAIR ARMIJO: Yes. But to Charlie's
17 point, if the NRC could say it and there was ways to
18 do it and you said, hey, we want all welds to be in a
19 state of compressive stress as fabricated. Now, the
20 ones that are out there are out there, and they're
21 going to be whatever they are. But that would suit
22 you because these cracks won't start in a state of
23 compressive stress, but we're not doing that yet. And
24 the industry isn't coming to you with fabrication
25 techniques that says, yes, I welded all this way back

1 and, after all is said and done, I do this additional
2 process and it puts it all in compression. And if
3 they could prove it, you'd be happy, I would guess.

4 MR. RUDLAND: Right. And I know the
5 industry is working hard to develop and get approved
6 peening processes and things like that. So they're
7 diligently working on that kind of stuff.

8 MEMBER BLEY: Another non-metallurgist
9 with a question. Could you go back to graph six?
10 Most everything you talked about, if I followed you
11 properly, is about the ability to predict and measure
12 the residual stress and the variability. It hasn't
13 been about our knowledge of the impact of the residual
14 stress on the corrosion cracking problem itself,
15 except maybe this slide. And I'm having trouble
16 looking at this, and I know what Sam said is what I've
17 always heard: if compressive stress, you're not going
18 to initiate to cracks. But the stresses here vary in
19 both directions. And even out at the through wall
20 side, we see them both compressive and tensile. How
21 well do we know the relationship and --

22 CHAIR ARMIJO: This is the way I look at
23 that thing, and Bill may jump in --

24 MEMBER BLEY: I'm not quite sure what I'm
25 looking at here.

1 CHAIR ARMIJO: On the zero, that's the ID
2 of, let's say, a pipe.

3 MR. RUDLAND: This is the inside surface
4 over here of the pipe.

5 CHAIR ARMIJO: Right.

6 MR. RUDLAND: So this is on the inside
7 surface of the --

8 CHAIR ARMIJO: And that's where the stress
9 corrosion cracks will nucleate. You've got very high
10 tensile stresses, and they'll nucleate and they'll
11 grow as long as you have tensile stresses. When you
12 cross the zero line, you go into compression and the
13 cracks should stop, unless the state of stress is
14 changed due to the relaxation of all these other
15 things.

16 MEMBER BLEY: That makes physical sense to
17 me, but what are these other points I'm seeing?

18 MR. RUDLAND: So let me clarify this some
19 a little bit. So the points are different
20 measurements. Back in the, I don't know if it was the
21 70s or the 80s --

22 MEMBER SHACK: Eighties.

23 MR. RUDLAND: -- when these were done.

24 MEMBER SHACK: We're not that old.

25 MR. RUDLAND: The residual stress measure

1 techniques weren't as sophisticated as they are today,
2 and so they created these through wall measurements in
3 different ways. In Bill's particular case where it's
4 just the closed symbols, you know, measurements were
5 made by strain gauges, and then the wall thicknesses
6 were machined away and the change in strain was
7 measured and these stresses were inferred. And so for
8 different measurements, you got a different set of
9 curves. And so there's --

10 MEMBER SHACK: But those are different
11 welds, too.

12 MR. RUDLAND: And they're different welds,
13 also. So there's different welds and --

14 MEMBER BLEY: I guess the thing that was
15 bothering me is if we go over to the right side of
16 that, that point down below in the compressive region,
17 we've got a through wall crack with compressive
18 stress.

19 MR. RUDLAND: And this is a stress in the
20 uncracked, in an uncracked condition. This is the
21 stress in an uncracked condition.

22 MEMBER BLEY: Okay.

23 MR. RUDLAND: So what happens is, you
24 know, you end up with --

25 MEMBER BLEY: You start up here --

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1 MR. RUDLAND: You start up here and you
2 end up with a high crack.

3 MEMBER BLEY: Okay. And then it's --

4 MR. RUDLAND: Right. What fraction
5 mechanics tells us is that the tensile stress that's
6 on the crack surface is going to drive the crack. So
7 as we grow this thing through -- and, remember, this
8 is just residual stress. We also have normal
9 operating conditions on top of this, which basically
10 moves this whole curve up.

11 MEMBER BROWN: To make it tensile.

12 MR. RUDLAND: To make it a little more
13 tensile. The residual stress may still be in
14 compression through some part of it.

15 MEMBER SHACK: Total stress may be --

16 MR. RUDLAND: Total stress may be in
17 compression. But what it is is that the driving force
18 stays tensile through the entire growth process of the
19 crack. So as the crack grows, things redistribute
20 some and the driving force stays positive in some
21 cases. If this dips low enough, yes, it may slow down
22 and it may arrest. But it's a function of the crack
23 size. It's a function of the normal operating
24 stresses and a few other things.

25 So by the time you get down where the

1 crack is 90-percent through, you don't have this
2 stress field anymore above the crack, you know. It's
3 relieved. The stress is redistributed, and you have
4 a huge tensile stress right at the crack tip.

5 So these stresses, again, are just
6 stresses in the non-cracked condition. So seeing this
7 back here doesn't really tell me anything about how
8 the crack is going to grow. What I need to know is I
9 need to know, you know, the fact that I have high
10 stresses here, it's going to initiate, and that I have
11 enough tensile stress across the entire surface of
12 where the crack is going to grow to keep it growing.
13 And so that's why we do, when we do these analyses,
14 they're very incremental. You grow the crack a little
15 bit, you update. You grow the crack a little bit, you
16 update. You grow the crack a little bit, you update.
17 And that allows for that redistribution of stresses,
18 and it allows you to determine whether or not these
19 cracks are going to slow down and arrest.

20 MEMBER SHACK: I mean, it was your Wolf
21 Creek picture that sort of showed the implications of
22 the stress field, which really controlled the kind of
23 crack size that you would get if this thing went to
24 leakage, what it would look like.

25 MEMBER BLEY: Yes, that's right.

1 MR. RUDLAND: So this particular blue
2 curve that has a lot of the region that's above zero,
3 it ends up with a much bigger looking crack. For one
4 that is not, like the red one, you see that the crack
5 is kind of skinny, you know, as you come up to the
6 crack tip surface on the ID. But, again, the cracks
7 are all driven by the stuff that's above -- you see
8 the stuff actually goes below and then comes back
9 above zero. It wasn't enough to arrest the crack
10 because, again, there's operating stresses that are on
11 this. But it was enough to stop the crack from being,
12 from creating a cracked area that was so large.

13 MEMBER SHACK: I mean, the message is that
14 it's good if you stopped it, but if you just slow it
15 down you let the crack get bigger and bigger before --

16 MR. RUDLAND: Yes. This one could be even
17 actually more detrimental because you could end up
18 with a 360-degree crack, you know, that's shallow kind
19 of. And in that case, you may end up with a rupture
20 before it leaks. On something like this, you're going
21 to definitely have a leak before a rupture.

22 MEMBER BROWN: So show that one again.
23 Something like you have a leak before rupture --

24 MR. RUDLAND: So, for instance, if you
25 have a case like this where you end up with the cracks

1 growing around the circumference much more than it's
2 growing through the depth, you can end up with a very
3 long surface crack, and it could possibly rupture.

4 And in this case here, you have a very short crack
5 that grows deep, and so it's going to probably leak
6 because you have all this uncracked area to resist.

7 MEMBER BROWN: So a little bit -- okay, I
8 got it.

9 MR. RUDLAND: We spent a lot of time at
10 Wolf Creek learning how these cracks grow and using,
11 you know, the ASME code uses very idealized solutions.
12 And in Wolf Creek, we went through and actually
13 developed procedures to grow the crack a lot more
14 naturally to get these kind of shapes that you
15 wouldn't get from Section XI types of analyses.

16 Okay. I'm going to swing just to the last
17 slide before I let Mike take over. Some of the things
18 that we already talked about I want to touch on again.
19 You know, certain things we need to do to have
20 confidence in using residual stresses in regulatory
21 space. We have to try to reduce the uncertainty in
22 the industry-submitted flaw evaluations by getting a
23 little bit more confidence in the residual stresses.
24 And we're doing that by working with the ASME code to
25 incorporate some of these tiered approaches that we

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1 talked about into the code, as well as into 50.55(a).

2 We have to have technologies to be able to
3 incorporate residual stress uncertainty into analyses,
4 and we're doing that in xLPR. That's going to have
5 the ability to be able to incorporate residual stress
6 uncertainty.

7 And then, as Sam pointed out, we have to
8 come up with best practices so that we can use those
9 in new fabrications. We have to learn from our
10 experiences. We have to learn from the fabrication
11 methods that we know give us bad residual stresses.
12 We have to learn not to do those things.

13 And then there's also a lot we can learn
14 from other industries in terms of residual stress best
15 practices and things like that. There's some
16 industries, like the aircraft industry, that's
17 slightly head of us in terms of understanding this
18 stuff, so we can learn from them also. And all of
19 this stuff leads into some of the work that we've done
20 and some of the work that we're going to be doing that
21 Mike will be talking about.

22 MEMBER BLEY: Since you brought up that
23 last one, what kind of interfaces have you had with
24 the aircraft industry?

25 MR. RUDLAND: Well, recently, we had,

1 there's a lot of workshops that are going on, and
2 recently we had one that EPRI organized that some of
3 the guys that have worked on industry aircraft stuff
4 that came and made presentations on what they're
5 doing. And the outcome of those particular workshops
6 are trying to develop generic best practices, and so
7 the NRC, as well as EPRI, are involved in those kinds
8 of discussions.

9 MEMBER BLEY: Okay.

10 MEMBER SHACK: Well, I was impressed when
11 I looked at the ASME PBB conference in 2009 to look up
12 one of your references just to find out how many
13 papers there now are on residual stresses. I mean,
14 this is --

15 MR. RUDLAND: Yes. For the last six or
16 seven years --

17 MEMBER SHACK: It's really gotten people's
18 attention, certainly.

19 MR. RUDLAND: Yes. Six or seven years,
20 we've probably had nine to ten sessions with four to
21 five papers every year. And they range, you know,
22 from the numerical guys to the experimental guys to
23 the fabricators, you know, coming to make
24 presentations. So it's a very hot topic in that type
25 of industry right now.

1 MEMBER SCHULTZ: When you have, when you
2 describe we want to learn from operating plant
3 experiences, how much information has been developed
4 as a result of the expectations, the letter, the
5 confirmatory action letters coming from the plants in
6 2007 and the EPRI programs that have come to follow
7 that?

8 MR. RUDLAND: I think an extreme amount of
9 data has been generated since that time. That effort
10 kicked off a very large program within EPRI to do
11 these inspections and mitigations, and from that came
12 a lot of really great research, not only in terms of
13 residual stress but some things like these MRP-287 on
14 flaw evaluation, a lot of upper head work, a lot of
15 things like that have come out of that. So it's been
16 very advantageous from a research standpoint.

17 MR. COLLINS: The flaw evaluation
18 guideline that was worked on by industry and we were
19 in the meetings as that was being developed and the
20 idea of what needs to go into a good weld residual
21 stress, even though we knew we were still working
22 through this program and you'll see the results of
23 that as it was going through, was trying to address
24 some of the uncertainties that we were seeing here and
25 trying to put them into a better thing. And I think

1 that's been a very worthwhile review of these things.

2 MEMBER SCHULTZ: Thank you.

3 MR. BENSON: Okay. So are we ready for
4 the next talk?

5 CHAIR ARMIJO: Sure.

6 MR. BENSON: Today's talk was meant to set
7 the stage --

8 MEMBER SHACK: You know you only have a
9 morning, right, Mike?

10 MR. BENSON: Yes, yes. Well, it's a lot
11 of slides. And some slides I'll spend more time on
12 than others. Some of them will just be flashing the
13 slide and say the data is there. However, since it is
14 a long talk, I did provide an outline here to help
15 guide the discussion. So I'm just going to start out
16 with an overview.

17 And this cartoon here shows the type of
18 weld geometry that Dave described in words that we're
19 trying to understand. You have a carbon steel nozzle,
20 and then there's usually an Inconel butter layer. And
21 then in the fabrication shop a dissimilar metal weld,
22 Inconel weld, is welded to the safe-end. And then
23 this gets post-weld heat treated, and then this gets
24 shipped to the site and you get this stainless steel
25 weld to the stainless steel pipe that happens at the

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1 nuclear plant site. So that's what we're trying to
2 understand.

3 And the overall goals of the WRS
4 Validation Program are to identify, quantify, and
5 minimize sources of model uncertainty. And then, if
6 we can do that, we can develop reliable and consistent
7 modeling procedures that they've hit upon. We also
8 want to validate weld residual stress models with
9 robust measurement techniques and, eventually, develop
10 acceptance criteria for WRS inputs to flaw evaluations
11 to help out the regulator.

12 And as Mike actually mentioned in his
13 opening remarks, this work is performed under a
14 Memorandum of Understanding with EPRI, and we actually
15 have in the audience is Paul Crooker. He's the main
16 EPRI contact for the Weld Residual Stress Program, and
17 we have one of his contractors from Dominion Engineer,
18 John Broussard. He's actually -- oh, Zhili is from
19 Oak Ridge National Lab, also a contractor of EPRI,
20 Zhili Feng. And John actually was the author of the
21 MRP-316 document that you received.

22 So the MOU, in general, sets forth terms
23 of cooperative research. It's a high-level legal
24 document. But then there are these addenda that
25 address specific research topics. And the two that

1 are of most relevance to today's talk are the
2 extremely low probability of rupture addendum and the
3 WRS Validation Program addendum. We're currently, the
4 old WRS addendum has actually expired, and we're
5 currently working on creating a new one.

6 MEMBER SHACK: Sam and I noticed that EPRI
7 had just published a new report on initiation of SCC.
8 I just wondered is that available to you folks through
9 this memorandum?

10 MR. RUDLAND: I don't know. Paul?

11 MEMBER SHACK: I can give it to you in a
12 few seconds here, but it's a recent report on a
13 validated model for ISCC.

14 CHAIR ARMIJO: It sounded really good.

15 MR. RUDLAND: Our past experience, Bill,
16 is that, if it's applicable to xLPR, we're usually
17 able, through the program, to get a copy of it.
18 That's usually been the past history.

19 MEMBER SHACK: If you get a copy of it,
20 Sam and I would like to see it.

21 MR. RUDLAND: Do you know the MRP number?

22 MEMBER SHACK: I'll look it up and give it
23 to you on a piece of paper.

24 CHAIR ARMIJO: What was the title, Bill?

25 MEMBER SHACK: I have to -- validation of

1 stress corrosion cracking initiation model for
2 stainless steel and nickel alloys, 1025121.

3 MR. RUDLAND: Was it an MRP document or
4 not?

5 MEMBER SHACK: No, I think it's not an
6 MRP. It's one of their scientific thingy or others,
7 but it's 150k job.

8 MR. RUDLAND: We will definitely look into
9 that.

10 MEMBER SHACK: 1025121, 12/21/2012. So
11 we'll follow up with EPRI on that.

12 MR. RUDLAND: If I can say something about
13 that real quick, I know that in May we're coming back
14 to this committee to talk about crack initiation, and
15 we haven't developed the agenda yet, but the hope was
16 that EPRI was going to make presentations on their
17 ongoing research on crack initiation, which I'm
18 assuming this will probably be part of that.

19 CHAIR ARMIJO: That's why we want to get
20 ahead of it.

21 MR. RUDLAND: Okay.

22 MR. BENSON: So in the MOU, in the MOU
23 addendum I should say, there are specific tasks that
24 are laid out and each organization is assigned a lead
25 and sometimes it's co-led, depending on the task. But

1 this slide just gives you an overall feel for how some
2 of the work was split up between the two
3 organizations. EPRI designed and fabricated some
4 specimens and mockups for the weld residual stress
5 measurement, and they also created finite element
6 models. NRC did some finite element modeling,
7 organized the finite element round robin studies that
8 we're going to talk about, and we also designed and
9 fabricated some mockups.

10 And I'm going to talk about each of these
11 four phases of the research in more detail, but this
12 just shows that there were four phases. They weren't
13 necessarily done one after the other. Some of the
14 work overlapped. But the idea with these research
15 phases was to go from simple specimens to
16 progressively more prototypic.

17 Okay. So if there are no questions on the
18 overview, I'll go right into the Phase I.

19 CHAIR ARMIJO: In this plant components,
20 you had good information on the fabrication
21 techniques, whether they were repaired or not
22 repaired. They were just nozzles that happened to be
23 sitting around.

24 MR. RUDLAND: Especially the pressurizer
25 nozzles. We didn't really know anything about the

1 fabrication history at all. By cleaning up the
2 surface on the ID, you were able to tell whether or
3 not there were repairs. In some cases, there were
4 small repairs. And I believe the same was for the
5 cold leg nozzle, but I'm not sure. I don't think we
6 had any of the fabrication history on the dissimilar
7 metal weld.

8 CHAIR ARMIJO: Okay. So it made it a
9 little bit tougher.

10 MR. RUDLAND: Yes. Well, that was kind of
11 the point was that, from Phase II, we wanted to say we
12 had all the information. We developed those welds.
13 We had details. We wanted to go all the way down to
14 Phase IV where we knew almost nothing about the welds
15 and see if our predictions had the same amount of
16 scatter or if the scatter got worse.

17 CHAIR ARMIJO: Okay.

18 MEMBER SHACK: Well, I was actually going
19 to ask that, whether you sort of at least done
20 numerical experiments where you've varied the welding
21 parameters within the specs and seen --

22 MR. RUDLAND: Oh, yes.

23 MEMBER SHACK: -- how big a variation that
24 makes in residual stresses. I mean, is it comparable
25 to the scatter you get from model to model? You know,

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1 Phase IV has one weld and, you know, a hefty amount of
2 scatter between models, but if you took one model and
3 you did four welds would scatter look the same?

4 MR. RUDLAND: Stay tuned.

5 MEMBER SHACK: Stay tuned.

6 CHAIR ARMIJO: All right. It's in the
7 reports.

8 MEMBER SHACK: I didn't see that in the
9 reports, but okay.

10 MR. BENSON: Okay. So Phase I. Phase I
11 was simple, lightweight specimen geometries. Namely,
12 it was a flat groove plate and butt-welded to
13 cylinders. And really the objective in Phase I was to
14 demonstrate and develop weld residual stress
15 measurement and modeling capabilities. And this slide
16 just shows in more detail the flat plate specimen
17 geometry. It was stainless steel plate and then Alloy
18 82 weld metal was deposited in the groove, and the
19 plate was constrained by this extreme.

20 The cylindrical specimens are shown in
21 this slide. There was actually three different
22 cylindrical specimens with increasing complexity. We
23 started out with just welding stainless steel base
24 metal to stainless steel base metal. And then we
25 welded the carbon steel to the stainless steel base

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1 metal with the buttering layer. And then in the most
2 complex specimen, we actually put in a safe-end.

3 MEMBER SHACK: One thing that makes this
4 problem more complicated than the BWR problem is your
5 problem really is in the weld.

6 MR. RUDLAND: Right.

7 MEMBER SHACK: In the BWR days, our
8 problem was in the heat-affected zone, and it made
9 life simpler because all those details kind of washed
10 out a little bit by the time you got to the heat-
11 affected zone, whereas you get to see everything.

12 MR. RUDLAND: That's right.

13 MEMBER BROWN: Why is it different?

14 MEMBER SHACK: The susceptible material
15 here is actually the weld metal. In the BWR, the weld
16 metal was basically immune to cracking. The
17 susceptible material was the heat-affected zone in the
18 pipe. So the cracking actually occurs outside the
19 realm --

20 MEMBER BROWN: What's the physical between
21 BWRs and PWRs?

22 MEMBER SHACK: Different materials and
23 different environments.

24 CHAIR ARMIJO: Well, the 300 series
25 stainless steels are the same, but the environment

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1 makes all the difference.

2 MR. RUDLAND: The water chemistry makes
3 the most difference.

4 MEMBER BROWN: Okay. So it's a chemistry
5 issue.

6 MEMBER SHACK: And materials because
7 they'd have the nickel alloy weld metals, rather than
8 the --

9 MEMBER BROWN: Carbon steel.

10 MEMBER SHACK: No, they're austenitic weld
11 metals in the BWR.

12 MEMBER BROWN: As opposed to?

13 MEMBER SHACK: This nickel, you know, this
14 is nickel. Yes, the nickel alloy is where the problem
15 here is in the --

16 MEMBER BROWN: Okay. Not the austenitic
17 stainless.

18 MEMBER SHACK: Not the austenitic
19 stainless.

20 MEMBER BROWN: Okay.

21 MR. BENSON: Okay. And then also, in the
22 most complex cylindrical specimen, there was a weld
23 repair, so there was a machine grooved, yes, a grooved
24 machine into the specimen is shown in this diagram,
25 and then weld metal would have been deposited back

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1 into the groove. During the welding, there was in-
2 process characterization. Thermocouples were spot-
3 welded to the specimens at different locations, and
4 you get temperature history at those locations. And
5 also laser profilometry was used to measure each
6 individual weld bead. So you got the weld bead
7 geometry, as shown on the left-hand side here.

8 CHAIR ARMIJO: These are all machine
9 welds? They weren't hand welds, they were machine
10 welds?

11 MR. RUDLAND: I believe they were for the
12 phase, yes. We looked at both throughout the program.
13 For these welds, I think they were all automated.

14 MR. BENSON: Okay. On Slide 15, I'm
15 introducing some of the measurement techniques. And
16 since Phase I was really a developmental stage, we
17 considered a whole range of measurement techniques.
18 And this figure here just demonstrates how different
19 techniques can differ from one another. They can go
20 from non-destructive to completely destructive. They
21 also differ in whether it's a surface measurement or
22 a bulk measurement of the stress.

23 And so I'm going to talk about some of
24 these techniques in a little more detail, especially
25 the ones that we ended up using in subsequent

1 programs. So we'll talk first about diffraction-based
2 techniques, and here you're really measuring the
3 lattice spacing based upon the position of a
4 diffraction peak. And then you also measure this
5 reference lattice spacing, which depends on the
6 experiment. And you calculate your strain that way,
7 and then, if you measure three components of the
8 strain, then you can calculate your stress through
9 Hook's Law.

10 And so diffraction is kind of nice because
11 it shows in a simple fashion how these residual stress
12 measurements work. You're actually measuring some
13 type of deformation, and you're going to calculate
14 stress. But when we get to the strain release-based
15 techniques, the methods of calculating stress get a
16 little more sophisticated than what we're showing
17 here.

18 There are also two types of ways to make
19 a diffraction measurement. There's x-ray diffraction
20 that's considered a surface technique because the beam
21 can't really penetrate into the metal.

22 CHAIR ARMIJO: Five, ten microns. Any
23 deeper than that --

24 MR. RUDLAND: Back one slide. It will
25 show you. So you can see that the x-rays go to, you

1 know, not quite to a tenth of a millimeter probably,
2 maybe a millimeter for the synchrotron stuff. Even
3 neutrons themselves can't penetrate all that far,
4 especially for some of the heavy components.

5 MEMBER SHACK: It depends on how big a
6 neutron source you have.

7 MR. RUDLAND: Neutron sources that are in
8 existence, I guess, can only go not quite 50
9 millimeters, I think.

10 MR. BENSON: So that's diffraction-based
11 techniques. Also, strain release-based techniques.
12 One example is this incremental slitting where you're
13 actually slitting a small line out of the thickness of
14 your component, and you have a strain gauge on the
15 other side and you're making measurements as you
16 incrementally slit the component through the wall
17 thickness. And there's contour method --

18 CHAIR ARMIJO: Before you go too far, what
19 about this magnetic and ultrasonic techniques? Did
20 you use those in this Phase I through IV?

21 MR. BENSON: So I did take some notes on
22 each of these techniques. Magnetic and ultrasonic
23 weren't used, but I do have some information on how
24 those techniques work, if you're interested.

25 CHAIR ARMIJO: I was just wondering if

1 they were difficult to use or very unreliable or
2 basically not in favor.

3 MR. BENSON: Right. I know with the
4 magnetic techniques you have to have a ferromagnetic
5 material for it to work.

6 CHAIR ARMIJO: Yes, if the carbon steel
7 cracked we'd be in good shape.

8 MR. RUDLAND: I think when we started the
9 program we tried to take the most well-accepted
10 techniques.

11 CHAIR ARMIJO: And so you picked the x-ray
12 neutrons and then these strain --

13 MR. RUDLAND: Right, right. We did
14 contour measurements, but we didn't do those until
15 late in the program after we had done a bunch of other
16 things. And the contour method was still being
17 developed and vetted, and so we did that one kind of
18 last because it wasn't a recognized technique at the
19 start of this program.

20 CHAIR ARMIJO: Okay.

21 MR. TREGONING: Rob Tregoning, staff. The
22 ultrasonic technique, there's a lot of uncertainty in
23 that because you measure velocity of the propagating
24 wave, and it's dependent on stress, but it's a second
25 order effect. So it's incredibly difficult to do that

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1 measurement, and there's a ton of uncertainty. So it
2 was wise not to choose that, even though that is --

3 CHAIR ARMIJO: Especially for a big
4 component.

5 MR. TREGONING: Yes. Even though it is
6 potentially a valid way.

7 CHAIR ARMIJO: Okay.

8 MR. BENSON: Okay. So I'll start out with
9 the contour method. In this method, you're actually
10 completely sectioning the component, and then you come
11 along after you section it with a CMM machine and you
12 read how the surface is deformed and you back-
13 calculate the stress that would make the surface flat
14 again.

15 MR. RUDLAND: That's exactly right. And
16 the measurements, you can imagine, the measurements
17 are very small, and so it takes a very precise
18 measurement technique to be able to do that and to do
19 it properly.

20 MR. BENSON: And so with the contour
21 method, you get complete stress contours throughout
22 the cross-section.

23 MR. RUDLAND: But finite elements are
24 required in order to do the calculation.

25 MEMBER BROWN: So you cut the specimen

1 through the thickness then, as if going from outside
2 diameter to inside or inside to outside, whatever.

3 MR. RUDLAND: Right. And then as you do
4 that, it deforms. They measure the deformation.

5 MEMBER BROWN: That's through the weld.

6 MR. RUDLAND: Through the weld. They
7 measure the deformation, and then they go to finite
8 elements and take that deformation and push it back to
9 see if it's stressed.

10 MEMBER BROWN: All right. Thank you.

11 MR. BENSON: There's also incremental
12 center hole drilling, as demonstrated on this slide.
13 This photograph here on the right side is actually
14 brand new. It's coming from some stress measurements
15 that are ongoing even as we speak. So that just gives
16 you an idea of how that looks.

17 MEMBER BROWN: Let me ask another
18 uneducated question. Once you slice or drill a hole,
19 why doesn't that introduce stresses in there that
20 aren't accounted for?

21 MR. RUDLAND: In some cases, it does, and
22 so they have corrections for that. A lot of times,
23 when they're making these cuts, you get plasticity
24 ahead of the cut that's messing everything up. And so
25 they go back and they're able to, through the finite

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1 elements, correct for that. So they realize that kind
2 of stuff happens.

3 MEMBER SHACK: Measurement is kind of a
4 loose term for some of these approaches.

5 MEMBER BROWN: Okay. I mean, I like the
6 diffraction thing. That seems to be non-destructive.
7 But these other ones, how do you know your corrections
8 are correct? I mean . . .

9 MR. RUDLAND: And once you cut it, you
10 know, it's done, right? You're not going to use the
11 component again.

12 MEMBER BROWN: No, I understand that.
13 But, I mean, it's the old once you measure something
14 you've disturbed what you were trying to measure in
15 the first place. I think that was a principle --

16 MR. RUDLAND: These papers at PBB that
17 Bill was talking about, 50 percent of them are talking
18 about that kind of stuff, the fact that there's so
19 many things that happen during these cutting processes
20 that could affect residual stresses and how do you
21 account for those and validate that process? Which is
22 why we do many different techniques and see how they
23 compare because of those kind of things.

24 MEMBER BROWN: Yes, all right. Thank you.

25 MR. BENSON: Deep hole drilling is shown

1 in this slide. And, again, a brand new photograph
2 here from one of our contractors showing the
3 experimental setup. And, basically, in deep hole
4 drilling, you gundrill a hole, and then you take an
5 air probe measurement, and then you come along behind
6 that and you electro discharge machine out that hole
7 and release the stresses and then take a second air
8 probe measurement so that --

9 CHAIR ARMIJO: Could you go through that
10 a little bit slower?

11 MR. BENSON: Sure.

12 CHAIR ARMIJO: First of all, what's a
13 front and back bush?

14 MR. BENSON: So the bushing, I think, is
15 this little, if we look at the photograph, it's this
16 little circular piece that gets, I don't know --

17 MR. RUDLAND: It's sacrificial. They
18 don't want things skipping on the surface, so it's a
19 sacrificial piece that they put on the front and back
20 end to make sure that things are coming and going
21 properly.

22 CHAIR ARMIJO: So they come in with a
23 clean hole and --

24 MR. RUDLAND: Right, right.

25 CHAIR ARMIJO: Okay. So that's just a

1 technique.

2 MEMBER BROWN: Do they glue it on?

3 MR. RUDLAND: I think it's glued on. I'm
4 not positive, but I think it's some kind of -- it's
5 not welded on I don't think.

6 CHAIR ARMIJO: And then you drill this
7 hole, and then what happens?

8 MR. BENSON: You drill a hole, and then
9 you take an initial measurement.

10 MR. RUDLAND: It's a very small, a very
11 small hole. I think this is not necessarily very
12 appropriately sized, but I'm thinking -- John, help me
13 -- five millimeters, one millimeter. How big are the
14 initial drill hole?

15 MR. BROUSSARD: I think it might be, I
16 think it might be even smaller than that, like one and
17 a half millimeters.

18 MR. RUDLAND: Yes, one and a half
19 millimeters is the original size of the first hole in
20 the upper left-hand --

21 MR. BROUSSARD: I think that second hole
22 where the electrode is going around, I think that's
23 more like a five-millimeter hole or something like
24 that.

25 CHAIR ARMIJO: And what is the thing

1 you're measuring that's deforming from residual
2 stress?

3 MEMBER SHACK: The diameter of the hole.

4 MR. RUDLAND: That's right.

5 CHAIR ARMIJO: The hole actually.

6 MR. RUDLAND: So the probe is a, you know,
7 it's a rod that has air that shoots out of it that's
8 calibrated to pressure. So it goes in there and it
9 can measure the diameter of the hole in different
10 orientations as it's going through there.

11 MEMBER SHACK: That seemed nifty enough in
12 itself.

13 MR. RUDLAND: Right, right.

14 MEMBER SHACK: And then he relieves it all
15 with the EDM cut.

16 MR. RUDLAND: Then he basically takes the
17 first hole and pulls it out of a specimen with another
18 five millimeter cut and then measures that thing again
19 to see what the changes in those displacements are.

20 CHAIR ARMIJO: Okay, okay. Tricky.

21 MEMBER SHACK: Now, when I looked at the
22 ASME paper, and there's not enough details there, so
23 I can't claim I really understand what's going on.
24 But it looks as though they do the analysis as though
25 this is a set of laminar that are independent, and so

1 they just do the analysis as though it was a sheet
2 that they incrementally make out, which means that,
3 again, you're going to have limitations on the kind of
4 gradients that you can have. This is something that's
5 in equilibrium but not compatible, so it's kind of a
6 lower bound on the stresses, in a simple-minded way.

7 Have you done -- the validation paper I
8 looked at, they were sort of looking at gradients like
9 four millipascals per millimeter. You guys have like
10 20 millimeters or 20 mPa per millimeter. Have you
11 done a finite element analysis to see when that
12 independent laminar sort of breaks down in the
13 gradient?

14 MR. RUDLAND: We haven't, but I know that
15 Vegter has done -- Vegter is the contractor that does
16 these deep hole drillings, and they've done a lot of
17 work --

18 MEMBER SHACK: Are they a British company?

19 MR. RUDLAND: They are a British company.
20 They're a spinoff of the University of Bristol.

21 MEMBER SHACK: A spinoff from the
22 University.

23 MR. RUDLAND: But I know they've done a
24 lot of finite analysis because of this plasticity
25 effect. So they've taken --

1 MEMBER SHACK: Yes, but I didn't see
2 anything that would sort of address the fact that
3 there's a limited stress gradient, which, again, in
4 your problem, it could be pretty significant.

5 MR. RUDLAND: Yes, I don't know, I don't
6 know. That's a really good question to ask them. We
7 will look into that.

8 MEMBER SHACK: I mean, your measurements
9 and your analyses all seem consistent, so it doesn't
10 seem to be a problem. But it would be sort of nice to
11 have an independent verification of that.

12 MR. BENSON: Yes, so we'll follow up with
13 that.

14 MR. RUDLAND: But they do use, a lot of
15 times they end up using our residual stress analyses
16 to be able to be able to try to account for this
17 plasticity effect. So they actually model the deep
18 hole drill process to try to figure out how that
19 plasticity is affecting the surface.

20 MR. BENSON: Any other questions? Okay.
21 So that's a summary of some of the main measurement
22 techniques that we've looked at. This slide here
23 shows how the measurement techniques were applied for
24 the plate specimens. This is a cross-section of the
25 plate specimen. The purple diamonds are neutron

1 diffraction measurements. If you want to use the
2 contour method to get the component of stress parallel
3 to the weld line, the longitudinal stress, you have to
4 slice that plate parallel to the plane, like we're
5 showing here. And if you want the contour measurement
6 to give you the transverse stresses, you have to slice
7 the plate along the dash line, as shown here.

8 CHAIR ARMIJO: But did you do that to
9 compare the two techniques on the same specimen?

10 MR. BENSON: Yes. Same specimen, right,
11 John?

12 MR. BROUSSARD: Yes, yes.

13 MR. BENSON: For both. Yes, both, both
14 stress components. And then on Slide 22, we just
15 showed the same type of thing for the cylinder
16 specimens. And I think here we took two measurements
17 of the axial stresses with contour measurements along
18 two different lines, and you see the neutron
19 diffraction locations. And also there was deep hole
20 drilling measurements along the weld center line. And
21 I should also mention that x-ray measurements were
22 taken at the surface right on top of the neutron
23 diffraction points.

24 Now, we can begin to start looking at some
25 actual data. This slide shows results from the

1 surface stress measurements. We're showing residual
2 stress versus depth from the surface. And one thing
3 we point out here is we're getting relatively high
4 values up around 1500 mega-pascals, so we start to
5 really wonder if we believe that high stress.

6 MEMBER SHACK: Now, this is not your deep
7 hole, right? This is the strain gauge on the surface
8 kind of --

9 MR. BENSON: Yes, this would be the center
10 hole drilling.

11 CHAIR ARMIJO: You're talking this P6
12 measurement, transverse, P6 longitudinal that gets up
13 to --

14 MR. BENSON: That's right, yes.

15 MEMBER BROWN: In your earlier stuff, you
16 had kips. Now you're in mega-pascals. Can you --

17 MR. RUDLAND: Did we show kips?

18 MEMBER BROWN: Back in the first
19 presentation somewhere, there were kips along the axis
20 for stresses. Now you've got --

21 MR. RUDLAND: About a factor of seven.

22 MEMBER BROWN: Well, just what is it? I
23 keep forgetting. Kips, I understand. Mega-pascals,
24 that's SI, and I could care less about this --

25 MR. RUDLAND: Yes, ksi is just kilopounds

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1 per square inch for stress and pascal is a millimeter
2 square. So it's just an SI, mega-pascals --

3 MEMBER BROWN: What is a mega-pascal in
4 terms of pounds per square inch or something?

5 MR. RUDLAND: Yes, it's a factor of seven.
6 So there's about seven mPa to ksi. It's actually
7 6.895.

8 MEMBER BROWN: One-thousand psi equals
9 seven mega-pascals?

10 MR. RUDLAND: Yes, yes.

11 MEMBER BROWN: 6.895. Is that like
12 Avogadro's number, blah, blah, blah, whatever?
13 Or 3.14159, if you can go out to 74 places.

14 MR. RUDLAND: Probably, in the first
15 presentation, you know, and the stuff that we
16 presented that was Bill's experimental stuff,
17 everybody used ksi back then in the 80s. Now, we are
18 heading towards trying to use more mPa.

19 MEMBER BROWN: It was less understandable
20 than ever --

21 MR. RUDLAND: That's right. To confuse
22 you even more.

23 MEMBER BROWN: -- for any reasonable
24 engineer. Okay.

25 MEMBER BLEY: I finally understand why the

1 transition has been so hard.

2 MEMBER SHACK: There up to computers, you
3 know, real computers now.

4 MR. RUDLAND: So if you take these numbers
5 and divide by seven, that's about ksi.

6 MR. BENSON: Sam, did you have a question?

7 CHAIR ARMIJO: Yes. I was just noticing
8 just the range of, near the ID surface. I'm fixated
9 on ID surface because I'm an initiation guy, and
10 that's a big range of, you know, as low as a little
11 under 200 up to almost 700.

12 MR. BROUSSARD: So I can make a comment
13 real quick. The center hole drilling technique is
14 really more intended for elastic-level stresses. It's
15 only rated up to 50 percent yield, 70 percent yield.
16 And, obviously, in the middle of a weld, you're
17 dealing with a pretty high level, you're near plastic
18 stress cold work material. So what happens is you
19 have a stress concentrator at a hole, and so when
20 you're drilling into this material it's at near yield
21 levels. As you're drilling that hole, you're
22 generating some plasticity, and that's going to
23 completely mess with your strain gauge measurements.

24 So we did the incremental hole technique
25 because it is a technique that's used sometimes in

1 near weld material, but we wanted to characterize what
2 was going on. And I think that the variability that
3 you're seeing is not necessarily indicative of what
4 you're actually getting at the surface if you have a
5 magic true residual stress-measuring machine. But
6 it's more indicative of some of the variability in the
7 process that you can get.

8 MR. BENSON: And then also here on the
9 right-hand side, we just showed different techniques
10 as they compare with one another. It's just one
11 example, but really there wasn't a lot of
12 repeatability. So, in general, we're not real
13 confident in surface stress-based measurements.

14 MR. RUDLAND: And this will be a recurring
15 theme as we go through these different phases, that we
16 have a little trouble with the ID stresses in the
17 welds. And, again, it goes back to a metallurgic
18 issue. You know, the problems that we're having in
19 the welds is that our grain sizes are so uneven and
20 we've got columnar grains and other things going on
21 where, back in the heat-affect zone, we're much more
22 equi-axed types of grains and it's much easier to make
23 those kinds of measurements. In welds, we're having
24 a lot of problems with these techniques because of the
25 differences in the metallurgy.

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1 MR. BENSON: So this shows another example
2 of stress-based measurements, and these are the x-ray
3 measurements. In this case, we're showing residual
4 stress along the line transverse to the weld center
5 line, transverse to the weld line with the weld center
6 line being zero in the figure. And, again, we're
7 seeing some large numbers, up around 950, and then
8 there are these large fluctuations. And also the data
9 is asymmetric about the center line, and with
10 dissimilar metal weld in the plate specimen we sort of
11 expect some symmetry, and we didn't see that. So,
12 again, losing confidence in the surface-based
13 measurements.

14 MR. RUDLAND: And you get out into the
15 base metal, though, you end up with some better
16 comparisons, right? So, again, it's in the weld where
17 we're having problems.

18 MEMBER SCHULTZ: Again, we have error bars
19 here, but how many of the error bars are representing
20 expected error?

21 MR. BENSON: Yes, as Bill mentioned, those
22 are probably pretty small, smaller than what's true.

23 MEMBER RYAN: Are those kind of measure
24 errors, as opposed to system errors?

25 MR. BROUSSARD: Yes. I think, usually, in

1 the diffraction techniques, well, I know for neutron,
2 and probably for x-ray as well, it's more about, well,
3 with neutron diffraction you're measuring differences
4 in measure peaks kind of received scattered neutrons,
5 and some of that error is more about the accuracy of
6 the fit of the peak to the data. And so they plot how
7 well they're able to predict the peak, the tip of the
8 peak based on the normal distribution of the data that
9 they have. And so that's what some more of those
10 error bars are about, and it's not about, you know,
11 comparisons to other measurement techniques and that
12 sort of thing.

13 So, you know, in true measurement data
14 sense, the error data is pretty small. But it doesn't
15 account for the bigger problems of reference specimens
16 and that sort of thing.

17 MEMBER SHACK: Yes. I was going to say
18 that's probably true if the material actually looked
19 like what they assumed when they made the measurement.
20 It's the difference between what the material really
21 is and what they assumed in making the measurement and
22 interpreting it.

23 MR. BROUSSARD: As Dave mentioned, the
24 problems with the diffraction techniques, one problem
25 with the diffraction techniques is the large grain

1 sizes of weld materials versus kind of a fine-grain
2 base material. It does cause some problems when you
3 have kind of large and irregular sized grains in these
4 weld materials and very kind of oriented type grains,
5 as well.

6 MR. BENSON: Okay.

7 CHAIR ARMIJO: And it's a cascade on top
8 of that. So you have a variability in composition as
9 the material solidifies, so what's your lattice
10 parameter --

11 MR. RUDLAND: Well, and that was one of
12 the things we found out that I think Mike is going to
13 touch on is that the lattice, the d-zero unstressed
14 lattice is spatially dependent on welds. I mean, it's
15 very spatially dependent, so it becomes difficult to
16 use these kind of processes.

17 MR. BENSON: Okay. On Slide 25, we look
18 at some of the deep hole drilling measurements, and
19 here we're showing residual stress versus depth
20 through the cylinder, this is for the cylinder
21 specimens. And we've done, I've shown two graphs: one
22 through the weld center line and one through that weld
23 repair that we had mentioned. Here we're seeing
24 smooth trends and more reasonable magnitudes of the
25 data, so one of our general conclusions is we like the

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1 strain relief-based measurements better. And here
2 shows contour-based measurements.

3 CHAIR ARMIJO: Mainly, because they're
4 kind of integrating over bigger areas and all this
5 variability or scatter disappears. But these are
6 destructive, right?

7 MR. RUDLAND: They're destructive.

8 MR. BENSON: Yes. So on Slide 26 -- I
9 won't dwell on some of these slides. This is just to
10 show you that the data is there. Again, we're getting
11 reasonable magnitudes with the contour method, and
12 Slide 26 was a plate specimen. Slide 27 shows data
13 for the ring specimen.

14 So if there are no specific questions,
15 I'll move on. I won't dwell on Slide 28. It just
16 shows some example neutron diffraction data. We're
17 going to come back in a few slides and talk more about
18 the neutron diffraction, but this data is there.

19 Okay. So for a moment, I'm going to shift
20 gears to the finite element modeling. And for the
21 techno jargon here with the modeling is sequentially-
22 coupled thermal-mechanical model. That just means
23 that there's two separate finite element jobs: one
24 where we're calculating the temperature distribution,
25 and then the second finite element job reads in that

1 temperature distribution and calculates the stresses.

2 Up to now, we've only considered two-
3 dimensional models. And so for the case of the ring
4 specimens, that means axisymmetric. And so in these
5 2D models, the true nature of the moving heat source
6 is not modeled; and so, for a given weld pass, and the
7 associated heat input it's applied along the entire
8 surface of the part in one instant in time in the
9 model. So it's a simplification.

10 And we mentioned earlier the laser
11 profilometry readings. We use those to help define
12 the weld pass geometry.

13 You also have to provide thermal and
14 mechanical properties as a function of temperature.
15 Strain hardening law is something we're going to talk
16 about a lot during these talks. It turns out to be an
17 important modeling choice.

18 So there are several different strain
19 hardening laws that you might have seen applied in the
20 documentation. There's elastic-perfectly plastic,
21 isotropic hardening, kinematic hardening, and mixed.
22 And in the isotropic hardening, the yield surface
23 expands, but the yield point in tension is always
24 equal to the yield point in compression. And then
25 kinematic hardening yield surface translates, and so

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1 you use that symmetry in the yield point.

2 We also have a heat input model. At the
3 NRC and the models we do, we've adopted this Goldak
4 model. We have papers on that, if you're interested,
5 and the technical details. But it's programmed in as
6 a user subroutine that gets linked in with the finite
7 element modeling and applies the heat at each weld
8 pass. And we can tune that heat input model to match
9 the thermocouple measurements as close as possible, so
10 that's how we use the thermocouple data in the model.

11 Okay. So Slide 31 is somewhat of a roll-
12 up of the different modeling and measurement results.
13 It's somewhat of a busy slide, but I'll just hit a few
14 main points here. First of all, we'll talk about the
15 neutron diffraction. Neutron diffraction is in the
16 blue lines. This is about the worst-case scenario of
17 the neutron data that we got. Not all the neutron
18 data looked this bad, but this is quite scattered. In
19 fact, in the next slide, I'm going to show some nicer
20 looking neutron data. But this just shows that,
21 potentially, it can be really bad.

22 And for the modeling results, this is a
23 bit of a strange result in that the Model B and the
24 Model C, which are the red X's and the red solid
25 squares, have the same hardening law, but you're

1 getting in very large differences in the results. And
2 it turns out that that results from the fact that you
3 have these relatively small wall thickness in these
4 small specimens. And it turns out that shrinkage
5 effects become really important, and the assumptions
6 that the modelers make have a bigger effect on the
7 results. Generally, however, what you're going to see
8 is that, if a modeler chooses this same hardening law,
9 that the results are going to be much less scattered.

10 CHAIR ARMIJO: Why are this FEA Model B
11 and FEA Model C so irregular in comparison to Model A?
12 Model A looks like nice, smooth, everything is great.
13 The other one is bouncing around all over the place.
14 Is there a good reason for that?

15 MR. RUDLAND: Typically, in isotropic
16 assumptions, you end up with a lot more jumpiness in
17 the data due to, depending on the size of the weld
18 size. So as you go from one weld bead to another, you
19 have a lot of cyclic history that's happening and
20 you'll end up with a lot more jumpiness in the
21 analysis results. But you're not going to see in
22 something where you have an elastically-perfect
23 plastic but you don't have that hardening going on
24 that occurs in each of the thermal cycles. So that's
25 usually why it's a little bit more choppy than in the

1 elastically-perfect plastic.

2 Why the two analysis results are so
3 different between the two isotropic cases are the
4 points that Mike was making. These particular Phase
5 I specimens were a little bit difficult to analyze
6 because they were not just weld specimens, they were
7 plates that were clamped together and welded, and so
8 you had all that restraint that you had to model, and
9 some modelers chose not to model the entire constraint
10 geometry. They chose a different way to do it, and
11 that affected the results.

12 MEMBER SHACK: But even in your Phase IV,
13 you have two kinematic models that give you very
14 different results.

15 MR. RUDLAND: A lot of it comes down to
16 modeling choices. And so what we tried to do in Phase
17 II, which Mike will get to, is try to systematically
18 figure out what those choices were or what the items
19 were that caused these differences.

20 MEMBER SHACK: Do we have agreement now on
21 how to do it so that if you did Phase V you would --

22 MR. RUDLAND: We're learning more and more
23 all the time. Yes, we're learning more and more.
24 Does somebody want to say something?

25 MEMBER SHACK: Well, Phase IV didn't

1 include the elastic-perfectly plastic model either.
2 I'm just wondering why. It seemed to be running along
3 with the others. I assume it's a lot easier to run.

4 MR. RUDLAND: Well, again, it was the
5 modeler's choice. Again, remember, these things are
6 not necessarily run in series, so Phase IV didn't
7 happen at the very end. Phase IV was just a different
8 geometry, and so it was actually done at the same
9 time, I think, Phase I was going on. Phase II and III
10 happened later.

11 MEMBER BROWN: Well, I thought you were
12 using Phase I to come up with your measurements, to
13 validate some of the measurement techniques, so you
14 did the test on Phase IV before you had your
15 measurements? There had to be some series.

16 MR. RUDLAND: Yes, the purpose of, we
17 started with Phase I before anything else, and the
18 purpose of Phase I was to try to begin to learn where
19 the issues were and the learn the process and develop
20 things on a simple basis with supposedly simple
21 specimens. I think, in hindsight, we probably should
22 have chose some different things. For instance, the
23 pipes that we chose I think were a little too thin-
24 walled, so we had a lot of axial deformation that we
25 probably should have stayed away from because it's not

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1 really relevant to what we were trying to do in the
2 nuclear type of stuff. The clamped plate thing caused
3 some issues, also.

4 So, in hindsight, we probably should have
5 done things a little different, but the purpose from
6 the beginning was that we were trying to use Phase I
7 to learn as much as we could. The Phase IV stuff
8 started because there was a regulatory need to work on
9 optimized weld overlays, and so we started that soon
10 after this because there was a regulatory need to get
11 that work done so that we could make a regulatory
12 stance on the optimized weld overlays.

13 MR. COLLINS: Yes, that was a mitigation
14 technique which was being put forth by industry and
15 actually is in place in one particular plant at this
16 point.

17 MR. RUDLAND: So there was a different
18 driver for that, so it kind of got pushed up in the
19 schedule because of the need, the regulatory need for
20 that.

21 MR. COLLINS: But one of the key things I
22 thought you took from this was the deep hole drilling.
23 The incremental deep hole drilling was at least giving
24 you some consistent results through the thickness of
25 the material versus what you were looking at from

1 other items and, at least when you were looking at the
2 finite element model, you were seeing the contours be
3 similar as far as for this part. So it was giving you
4 at least something of a basis for why we continue to
5 move forward with the deep hole drilling, right?

6 MR. RUDLAND: That's correct. And what we
7 learned here again was how spatially dependent d-zero
8 was, which is one of the reasons why the results were
9 so low. As I remember, from this particular first set
10 of plates, we just assumed d-zero was constant through
11 the weld, and that caused some of the issues that we
12 saw with the neutron diffraction measurements.

13 MEMBER BLEY: I'm sorry. Say that last
14 thing again.

15 MR. RUDLAND: For the d-zero measurement,
16 which is the unstressed lattice spacing, we assumed it
17 originally was not very spatially dependent. But what
18 we found out through the course of this study was that
19 it was very spatially dependent and that we needed to
20 measure that a lot more accurately as a function of
21 the position of the weld.

22 MEMBER BLEY: And that you thought that
23 was part of the reason that neutron diffraction was --

24 MR. RUDLAND: Yes.

25 MR. BROUSSARD: Actually -- this is John

1 Broussard again. Those neutron diffraction results
2 that you're seeing are kind of at the end of trying to
3 get the spatially-dependent d-zero measurement.
4 That's factored in. When we didn't do that, the
5 results were actually --

6 MR. RUDLAND: A lot worse.

7 MR. BROUSSARD: I hate using terms like
8 good and bad, but they were certainly a little more
9 difficult to interpret and they improved the --

10 MEMBER SHACK: This is easy --

11 MR. BROUSSARD: The original ones were
12 certainly, when you're showing minus four or five
13 hundred mPA in all three stress directions, that's a
14 little bit harder to interpret definitely. Like I
15 said, I try to shy away from good and bad because
16 they're all doing the best they can to get the
17 measurement data, and it's more just based on
18 difficulty of getting, all of these measurement
19 techniques, as you've seen, are all based on some kind
20 of a transformation. You're measuring a strain level,
21 you're measuring a displacement to bring it to strain,
22 and then you can bring that into stress. And a lot of
23 that trouble comes from doing that.

24 MEMBER BLEY: Back to Bill's earlier
25 comment about the little error bars on that early

1 picture of neutron diffraction results, I take it
2 that's because they do some simple statistics to do
3 the error bars, rather than consider all the
4 uncertainty that they're looking at.

5 MR. RUDLAND: That's right. They're doing
6 -- the uncertainty that they have is on a particular
7 measurement that they're taking, like John had pointed
8 out. You know, on the peaks, how well they could fit
9 the peaks of the diffraction.

10 MEMBER BLEY: So a tiny part of the
11 uncertainty really pretty much.

12 MR. RUDLAND: You know, and I'm still not
13 convinced that we fully understand what's going on
14 with d-zero with neutron diffractions within these
15 welds because, again, we tried in a couple of cases to
16 take a very fine measurement to d-zero, and it was so
17 spatially dependent that it becomes difficult, even
18 when you're measuring in a two millimeter-by-two
19 millimeter block or something for neutron that we're
20 actually getting the proper d-zero to use.

21 CHAIR ARMIJO: I guess I'm more
22 comfortable with experimental variability, but then
23 when I see this model, particularly FEA Model B, it
24 has all these discontinuities, and that's just
25 calculation.

1 MR. RUDLAND: And you'll see that in a lot
2 of the results --

3 CHAIR ARMIJO: Why does it do that?

4 MR. RUDLAND: Again, you'll see that in a
5 lot of the results. Well, you may not be seeing it in
6 details in Phase II, but in the Phase II results a lot
7 of the isotropic hardening results are like that where
8 we have a lot of almost sawtooth behaviors that,
9 again, result from the cyclic occurrence that's
10 happening within these weld beads that cause --
11 remember, there's no shifting of this field surface,
12 so you've got a lot of up and down that's going on
13 within the weld bead.

14 MEMBER BROWN: How many layers was it?

15 MR. RUDLAND: It depends on the size of
16 the weld. This one here had maybe, these had like
17 seven to --

18 MR. BROUSSARD: This specimen is the
19 cylinder specimen. It only had seven weld beads.

20 MR. RUDLAND: Seven weld beads.

21 MR. BROUSSARD: And I think that's what
22 you're seeing in some of this postprocessing of the
23 results. Each bead is a big chunk of that cross-
24 section, which is not necessarily characteristic of
25 what we have in primary systems where we have, you

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1 know, 40 to 50 --

2 MR. RUDLAND: But even in the analysis of
3 40, you'll see the same kind of waviness. It just
4 might not be to this particular extent because --

5 MR. BROUSSARD: You see some of those
6 discontinuities in this. They're just kind of
7 magnified because each bead is a big cross section.
8 As you post-process along there, you kind of get
9 across the layer of that weld, so it kind of jumps up
10 and down.

11 MEMBER BLEY: Back to what Mike talked
12 about earlier, the deep hole drilling technique, does
13 that also require use of finite element to back out
14 what the stresses were? You're getting a pressure
15 differential. How do you turn that into the --

16 MR. RUDLAND: Well, they use it to
17 develop, they use it to measure the change in the
18 displacement within the hole. And then they use that
19 --

20 MEMBER BLEY: So they're actually doing
21 that for the displacement --

22 MR. RUDLAND: That's right. But what they
23 use the finite element for is they use the finite
24 element to help them correct for any added plasticity
25 that occurs from the drilling process.

1 MEMBER BLEY: Oh, so they do that. Okay.

2 MR. RUDLAND: They do that. They've come
3 up with corrections, or what they've done is they've
4 used finite elements to refine their technique. So
5 now what they do is they, instead of drilling all the
6 way through, they drill partial, do a measurement, do
7 a partial, do a measurement. And they drill
8 incrementally instead of all the way through in one
9 shot. And they develop --

10 MEMBER SHACK: But they still have to make
11 assumptions about how to turn those displacements into
12 stresses.

13 MR. RUDLAND: They do, they do.

14 MEMBER SHACK: And they actually have a
15 fairly simple-minded way to do that in terms of just
16 cutting it into sheets until they start doing the
17 corrections. Then the things get more . . .

18 MEMBER BLEY: So the contour and the deep
19 hole drilling are at least smooth results. Is neutron
20 diffraction always a difficult thing to control? I've
21 never, I've never done it.

22 MR. RUDLAND: For the cases where you're
23 in a homogeneous type of material that has equi-axed
24 grains, it's not. It's very easy. It's much easier.
25 But these welds -- especially in these similar metal

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1 welds because you've got grains that are growing in
2 the main weld, and then in the butter they're actually
3 growing in the opposite direction. So that
4 complicates things even more.

5 MEMBER BROWN: It looks like the elastic-
6 perfectly plastic curve bounds your measurements in
7 all the cases in these particular thing, whereas the
8 other ones bounce back and forth a little bit.

9 MR. RUDLAND: I would hold off --

10 MEMBER BROWN: No, I'm not drawing one.
11 My question is is that when you see the later results
12 on your later testing on the bigger components? Do
13 you all try to address whether any of these models --

14 MR. RUDLAND: We've seen that the elastic-
15 perfectly plastic is usually very similar to the
16 isotropic type of hardening behavior.

17 MEMBER BROWN: Yes, but isotropic, in this
18 case, goes up and above and below your actual
19 measurements. Regardless of which one you believe, it
20 doesn't bound them.

21 MR. RUDLAND: That was kind of the, I
22 mean, the point I was trying to make is that, in the
23 future analyses that you'll see in a second, the
24 elastic plastic gives similar results to the isotropic
25 hardening, minus the waviness. And it's going to all

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1 depend on, it depends on a lot of things. Again, the
2 elastic-perfectly plastic is a modeling choice, and
3 the modeler has to be able to choose what is the yield
4 strength of that material, right? So they've got to
5 go back to the strain hard material and say, okay,
6 where am I going to pick that yield strength? Do I
7 look at flow stress, do I pick some number smaller or
8 larger than the flow stress, and what's my rationale
9 for that? That can lead to a lot of uncertainty
10 because it becomes a modeling choice.

11 MEMBER BROWN: Yes, but you've got to make
12 choices with the isotropic.

13 MR. RUDLAND: You've got to make a little
14 bit less choices, but you do have to make choices
15 still. That's right. I mean, you have the stress
16 strain curve that you've developed from experiments,
17 and there's uncertainty on that. But you use that
18 directly, along with its hardening behaviors directly.

19 MEMBER SHACK: Yes, but then you're making
20 assumptions about how much relaxation occurs.

21 MR. RUDLAND: Right. Well, all of
22 modeling is assumption, right?

23 MEMBER SHACK: All of the --

24 MR. RUDLAND: And that's really what we're
25 trying to get to. I mean, the same with the kinematic

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1 hardenings. It's the same way. I mean, the
2 assumptions of how the yield surfaces evolve, and it's
3 all assumptions right there. I mean, it's not
4 necessarily true that these yield surfaces just expand
5 or just translate. You know, they do a little of both
6 and . . .

7 MEMBER BROWN: Well, I just kind of
8 thought the object here was to try to come up with
9 modeling methodologies that would give you confidence
10 that would bound what you get in your --

11 MR. RUDLAND: That's what we're trying to
12 do.

13 MEMBER BROWN: -- actual measurements.

14 MR. RUDLAND: That's what we're trying to
15 do.

16 MEMBER BROWN: And you've done it on your
17 small specimens, and then you're going to do it on the
18 bigger components, and you'd like to see if you still
19 get a result where you've got a model approach through
20 a variety of weld whatever assumptions you make. You
21 still got to make assumptions. If it bounds them all,
22 then you get a little bit of confidence that it might
23 be less conservative than the other methodology you're
24 using today.

25 MR. RUDLAND: And what you'll find out on

1 the thicker welds, though, is that the isotropic
2 doesn't necessarily bound because what it will do is
3 it will bound, but it will bound in compression very
4 conservatively also, which could lead, again, like we
5 talked about earlier, to crack --

6 MEMBER BROWN: But that's what this does
7 in one of the cases, also. In one of the isotropic
8 ones, it bounds, doesn't bound all of your data. It's
9 more compressive than it is tensile.

10 MR. RUDLAND: Right, right, which can be
11 non-conservative from flow growth --

12 MEMBER BROWN: Yes.

13 MR. RUDLAND: And so we have to try to use
14 those things and balance what's the best approach to
15 use, and that's what we're doing through the course of
16 the project.

17 MR. COLLINS: But I appreciate your
18 original observation.

19 MEMBER SCHULTZ: And what are the
20 differences, once again, in the models? Like in the
21 Model B and C, what are the differences in those
22 applications? Is it --

23 MR. RUDLAND: I believe the difference is,
24 and, Mike, you can correct me if I'm wrong, are in the
25 choices the modelers made in how to model the

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1 restraint of the plate. That's one of them because
2 the plates are restrained, and John may have a comment
3 on this. I'm not sure if I --

4 MR. BROUSSARD: Yes, this is cylinder data
5 here.

6 MR. RUDLAND: Oh, this one is cylinder
7 data.

8 MR. BROUSSARD: Yes, so the differences
9 between those two modelers was that the, we talked
10 about how with this fairly thin wall cylinder you get
11 kind of a change in the weld group geometry as each
12 weld pass is deposited, and it's a lot bigger than
13 what you really have in a normal dissimilar metal
14 weld. It's all magnified. And so you wind up with
15 some modeling assumptions, and the two different
16 modelers use some different modeling assumptions on
17 the size of each particular weld. And because each
18 weld bead is a big chunk of the cross-section, you
19 get, it kind of magnifies differences that aren't
20 necessarily present. So that's why we did this Phase
21 I, and then we kind of got some of these results and
22 scratched our heads about them, and we said, you know
23 what, we're not dealing with seven-pass welds in our
24 particular issue, you know, in the components, in
25 these primary system components; let's kind of table

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1 this and move on to thicker wall components where
2 there's significant numbers of weld beads and see if
3 some of these differences still exist or if it maybe
4 improves things a little bit.

5 MR. RUDLAND: Yes. Just to build on that
6 a little bit now that this is a misprint on this slide
7 that it's a plate specimen. You know, the original
8 design of the bevel was used, in some cases, for
9 developing the finite element model. However, due to
10 the amount of weld beads placed, the shrinkage was
11 great. And so by the time you got done, the weld
12 bevel geometry was a lot smaller than it was in the
13 original design because of that shrinkage. So you've
14 got to make an assumption as a modeler: do you use the
15 original weld bevel or do you use the final weld bevel
16 size when you're doing your model? And that may be
17 the difference between, I'll have to go back and check
18 to make sure, but those assumptions can have a big
19 difference when you're talking about only a seven
20 weld, seven-bead weld.

21 MR. FENG: Can I make a comment? This is
22 Zhili Feng from Oak Ridge National Lab. I'm working
23 with both the NRC and EPRI on this project, though
24 mostly from the research side of the activity. And
25 this is certainly something we need to do a lot more

1 study on to that to find out what happened because
2 some of the assumption is probably we had a lot of
3 good experience on carbon steels, whereas the strength
4 hardening behavior of material is not that great. But
5 we move on to standard steel and nuclear alloys,
6 there's a huge strain hardening behavior, and we
7 probably didn't look that carefully, from a research
8 point of view, past.

9 Now we are doing a lot of measurement to
10 really quantify what is a strain hardening behavior in
11 those electrodes because this situation where the weld
12 couldn't from weld temperature to room temperature.
13 At the same time, we have this strain case going on
14 that caused some deformation, and those deformation
15 behavior will influence the strain hardening law. So
16 those are things that we are working today very
17 closely with NRC and EPRI.

18 I also want to comment on this jumpiness
19 of the prediction. To some degree, that is probably
20 real because when they make a weld they are down to
21 like a seven pass at the same time. When they make a
22 one pass, that cool down to room temperature, and we
23 put on the second pass and the third pass. When it
24 goes through this process, it actually different weld
25 process see different deformation behavior. So that

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1 you may see some in those kind of situations, either
2 as a sudden pass and maybe a bigger pass. So it's
3 probably going to have a very smooth curve. Smooth
4 curve doesn't mean it has a good result.

5 And, lastly, I want to talk about the
6 neutron diffraction because Oak Ridge National Lab has
7 a neutron facility. The error bar we talked about
8 before is basically a curve of a peak, so when you
9 measure a lattice spacing change at, say, on the
10 stress in a weld, you have a diffraction peak. You
11 fit that. You say maybe my fit is not very good. You
12 have some uncertainties. Then the measurement also
13 require a d-zero measurement where those kinds of
14 uncertainty, peak fit uncertainty does not account for
15 those change. I think d-zero we'd probably see a
16 better comparison. When we do some other treatment of
17 the d-zero, we see a better comparison with some of
18 the model results and also with deep hole drilling and
19 contour measurement results.

20 Each measurement at a certain set of
21 parameters assumptions in welding that, if we do not
22 consider that carefully, we may run into an issue. If
23 we do that right, hopefully we can have a better
24 result later on.

25 MR. TREGONING: It's Rob Tregoning from

1 the staff, at the risk of piling on, because I think
2 you've had a lot of discussion. But I just want to
3 put some perspective into this, and I think this slide
4 just beautifully encapsulates this. Normally, when
5 you do a computational analysis, you have a way,
6 typically, to calibrate them using measurements. And,
7 usually, we have very little uncertainty about those
8 measurements. What this slide I think really
9 encapsulates in this program is, in this case, we
10 don't know what the truth is in terms of the
11 measurement. It's not simple to do the measurements.
12 There's as much uncertainty in the measurements as
13 there are in the theoretical predictions.

14 Normally, when you see weld residual
15 stress programs, you're lucky if they have a
16 measurement to compare with the theory that they do.
17 You never see multiple measurements like this done in
18 such a systematic way. Typically, they'll make
19 assumptions on models. They won't systematically and
20 parametrically vary them, as we've done here, to look
21 at the influence of those assumptions. So, to me,
22 that's really the uniqueness of this particular
23 program, compared to -- look, we've been looking at
24 weld residual stress modeling now for 25 years or 30
25 years or so, but none of them have really tried to

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1 understand uncertainty and variability and the effects
2 that those things can have, ultimately, on your crack
3 predictions, which is the ultimate end goal. This
4 program is singular and unique in that aspect, and I
5 think that's really the focus.

6 So I think a lot of these things we're
7 trying to understand, but we need to take into
8 consideration really how seminal this program is and
9 its uniqueness and the fact that it's trying to
10 investigate these things from a fundamental level.
11 And if it didn't have such an impact in regulatory
12 space, this wouldn't be needed. But we've seen that
13 it is, so we're really in a different regime than
14 we've been in the past.

15 So I think we're going to see a lot more
16 results, but I think those similar conclusions are
17 going to carry through from result to result that,
18 yes, you have to interpret all of these results very
19 carefully, given what you know about how the weld was
20 down, how the measurements was done, and how the
21 modeling was done. And it really takes that
22 systematic and complex study to understand what you're
23 seeing at the end of the day.

24 MR. RUDLAND: Okay. We've spent a lot of
25 time on this particular slide, and there's a lot more

1 similar slides to come uphill.

2 CHAIR ARMIJO: Okay.

3 MR. BENSON: So on the next slide, this is
4 just in defense of neutron diffraction. It shows
5 that, in some cases, the neutron data can compare well
6 with the model results.

7 MEMBER BLEY: What's the three curves?

8 MR. BENSON: Yes, the bottom here --

9 MEMBER BLEY: Oh, there we go.

10 MR. BENSON: Red is the measurements.

11 MEMBER BLEY: I couldn't find it. Sorry.

12 MR. BENSON: Yes, so two measurements:
13 neutron and contour. So, in any case, I won't dwell
14 on that, but we just wanted to make sure we gave a
15 fair pictures of the neutrons.

16 CHAIR ARMIJO: Is this on the rings or the
17 --

18 MR. BENSON: This was a plate specimen.
19 It's correctly labeled in this slide.

20 CHAIR ARMIJO: Okay. So this is a plate,
21 which presumably is simpler.

22 MR. BENSON: Well, that's true. Yes, yes.

23 CHAIR ARMIJO: It turned out not to be.

24 MEMBER SHACK: Well, I think one of the
25 messages is the less weld you measure the better you

1 do.

2 MR. RUDLAND: If we have no weld, we do
3 really good.

4 CHAIR ARMIJO: Or just one weld.

5 MR. BENSON: Okay. So we talked a lot
6 about the x-ray and the neutron data and the d-zero
7 issues, texture and grain size. We've all talked
8 about that. But, in general, we sort of set the
9 diffraction techniques aside and focused more on the
10 strain relief-based techniques. But even here, the
11 near surface results did not appear reasonable, in our
12 view. But for both measurements, we feel like there's
13 less experimental difficulties for the strain relief-
14 based techniques.

15 MEMBER BROWN: The bulk measurement is the
16 contour measurement?

17 MR. BENSON: Bulk just means it's farther
18 through the thickness of the measurements. So things
19 like deep hole drilling and contour measurement,
20 that's what I'm referring to.

21 And then I'll just conclude Phase I. We
22 focused on simple weld geometries here and --

23 MEMBER SHACK: You better put that one in
24 quotes.

25 MR. BENSON: Yes. Near surface stress is

1 experimentally problematic. In general, we liked the
2 mechanical strain-relief techniques. And agreement
3 between the models and experiment does seem feasible.
4 And at this stage, we also recognize that there's a
5 possibility for modeling uncertainty. In particular,
6 the hardening law is going to be an important modeling
7 choice.

8 Okay. So any remaining questions on Phase
9 I?

10 MEMBER BLEY: Just one quick one. You
11 didn't show us any x-ray diffraction.

12 MR. BENSON: I did.

13 MEMBER BLEY: You did. Was it on some of
14 those curves?

15 MR. BENSON: It was --

16 MEMBER BLEY: Well, just briefly. You
17 don't have to go find it.

18 MEMBER SHACK: It's only surface remember.

19 MEMBER BLEY: I know it's only surface,
20 but, if surface is where we're most interested, how
21 does it do? How does it do?

22 MR. BENSON: That was the data that was
23 not symmetric.

24 MEMBER BLEY: Oh, okay.

25 CHAIR ARMIJO: That was x-ray?

1 MEMBER BROWN: Slide 23, one of the curves
2 and one data point. And then Slide 24 says x-ray
3 diffraction residual stress, so I presume that was x-
4 ray.

5 MR. BENSON: That's right.

6 CHAIR ARMIJO: So it's the same material
7 on both sides of the weld of zero, right?

8 MR. BENSON: Yes.

9 CHAIR ARMIJO: But you have tensile on one
10 side and compressive on the other.

11 MEMBER SHACK: But, again, it needs d-
12 zero, I mean, like all of these lattice methods, so
13 it's going to have --

14 MR. RUDLAND: The x-ray diffraction is
15 also very sensitive to the surface finish. You have
16 to spend a lot of time preparing the surface. And if
17 you don't do that properly, of course you get a --

18 CHAIR ARMIJO: Sure, sure. But going back
19 to that 24, to make sure I understand what I'm looking
20 at here, zero is the center line of the weld. How far
21 is the weld metal? Does it go out to plus or minus
22 0.4? Is it all weld metal from -- where does the
23 plate start?

24 MR. BENSON: We can go back to --

25 MR. BROUSSARD: I'm pretty sure that that

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1 is, you know, that the edges of those points are all
2 the way up -- you know what, Mike? If you find that
3 extra cross-section that shows the neutron diffraction
4 lines, the x-ray diffraction points are at the top of
5 the neutron diffraction. Yes. So those are the seven
6 points you see. At the top of each of those columns
7 of neutron diffraction is where the extra --

8 CHAIR ARMIJO: Okay. So the only, so
9 these are all in the weld bead itself or weld bead --
10 so in weld metal it goes from compression to tension
11 on either side.

12 MR. RUDLAND: And these were on the OD.
13 These were our OD measurements because this was a
14 groove weld and not a butt weld, and so there's no
15 weld on the ID.

16 MR. BROUSSARD: That's right. It's all on
17 the top surface of the weld there. So as you go
18 across the top surface, we did these at numerous
19 axial, at a couple of different axial locations, so
20 along the length of the weld. And we got variability
21 at the same location at different axial positions,
22 even though it was a fairly continuous weld. So we
23 did try our best to follow best recommended practice
24 on these. We electropolished down to I think 15
25 microns to eliminate any very, very surface finish

1 effects and that sort of thing. Obviously, these
2 welds, you can tell, were not ground afterwards or
3 anything like that. They were left in the as-welded
4 condition. We tried to remove surface contamination
5 and that sort of thing.

6 Again, not wanting to call, to judge
7 measurement techniques, that wasn't the goal of this,
8 but we did get less consistent results with this one-
9 time application of x-ray diffraction. It doesn't
10 mean that all x-ray diffraction, as a technique, is
11 bad or that it couldn't be used in weld metal, but
12 maybe a little bit more research should be and a
13 little more care should be taken.

14 CHAIR ARMIJO: If you plotted the data for
15 those neutron diffraction measurements at the bottom
16 plate where there's been no melting, no face change,
17 right? The seven measurements down at the bottom of
18 the plate, were they very consistent?

19 MR. RUDLAND: Those measurements were
20 never taken. Again, though, the issue with these
21 plates were in these restraining fixtures, so it
22 wasn't accessible for x-ray.

23 MR. BROUSSARD: We didn't measure the
24 bottom side of that plate. Oh, the neutron
25 diffraction?

1 MR. RUDLAND: Oh, the neutron. Yes, yes,
2 yes.

3 CHAIR ARMIJO: You know, I'm just trying
4 to say, if you're measuring a part of the specimen
5 that didn't melt, there was no face change, was the
6 neutron diffraction pretty good?

7 MR. BROUSSARD: Yes, yes. The answer is
8 yes, particularly at the bottom side of those edge
9 lines where you're deep into the base material and
10 where you're basically kind of doing elastic
11 deformation caused by the welding. The models and the
12 neutron diffraction did agree pretty well out of those
13 locations, and the measurement data was not bad.

14 CHAIR ARMIJO: Thank you.

15 MR. BENSON: Okay. So Phase II now?

16 MEMBER BLEY: Are we taking a break, Sam?

17 CHAIR ARMIJO: We were supposed to take a
18 break at 11, but we might just choose to do it now,
19 take about 15 minutes. Come back at 10:40. Okay.
20 Now would be a good place to stop.

21 (Whereupon, the foregoing matter went off
22 the record at 10:24 a.m. and went back on
23 the record at 10:40 a.m.)

24 CHAIR ARMIJO: Let's try and get back in
25 session, please. Okay. So, Mike, I think we have a

1 quorum, so there's no problem. Please go ahead.

2 MR. BENSON: All right. So let's get into
3 Phase II. In Phase II, there are actually two
4 separate mockups, and we're only going to talk about
5 one in this presentation, the Phase IIa mockup. And
6 then it's meant to be a prototypic pressurizer surge
7 nozzle, so that's the geometry we're looking at.
8 Phase IIa consisted of finite element round robin
9 study that was double blind, so the measurers and the
10 modelers didn't talk to each other. And the
11 objectives of Phase II were to validate weld residual
12 stress modeling with experiment and to assess modeling
13 uncertainty.

14 Slide 37 just gives you an idea of what
15 the mockup looked like. I think the wall thickness of
16 the pipe was about an inch and a half.

17 CHAIR ARMIJO: Mike, Mike, just a quick
18 question. What kind of information did the modelers
19 get, as far as, you know, the details of the weld
20 procedures, numbers of passes, heat inputs, all that
21 sort of stuff? Did they get that kind of detail?

22 MR. BENSON: We're going to talk a little
23 bit about how we provided some of that information,
24 but definitely, at the very beginning, they definitely
25 had all the weld geometry. Some of the other

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1 information we held from them and then provided as
2 they went along. So we'll talk about that.

3 MR. RUDLAND: We put together a pretty
4 comprehensive modelers' package. For instance, for
5 like the laser profilometry, we gave them Excel files
6 that had the actual shapes of the weld beads, and we
7 gave them the welding records and all that kind of
8 good stuff. So they all of those kinds of
9 information. Things that Mike is talking about are
10 things like properties and thermocouple readings. We
11 kind of held back to see whether or not it would
12 affect the uncertainty by giving them those things.

13 MR. BENSON: Okay. And then for
14 measurements, we used incremental deep hole and deep
15 hole drilling. And the measurements were taken before
16 and after the stainless steel closure weld because
17 that closure weld can affect the stress at the
18 dissimilar metal weld location, so we wanted to
19 investigate that effect.

20 On Slide 39, we show the measurement
21 results, both before the stainless steel closure weld
22 and after. And you can see these are axial stresses
23 plotted versus distance from the ID, and you can see
24 that close to the ID, as close as we could get, given
25 the measurement technique, the deep hole drilling

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1 measurements did show that the stresses decrease after
2 the closure weld for this particular geometry. But it
3 turns out that the safe-end length can be an important
4 parameter, so it's not necessarily guaranteed that
5 every weld configuration will show this. But in this
6 case, it did.

7 MR. RUDLAND: I'm sorry, Mike. I'm not
8 sure if you pointed this out, but the DHD measurements
9 were at 90 -- these were 180 degrees from each other.

10 MR. BENSON: Right. Two separate
11 measurements that you're seeing there on the slides.

12 CHAIR ARMIJO: Okay. And after you did
13 the closure weld, you put the ID into compression or
14 near compression, and that's the good news there.

15 MEMBER SHACK: At least for the axial
16 stresses.

17 CHAIR ARMIJO: The axial but not the hoop.

18 MEMBER SHACK: Yes, that's one of the
19 things that's quite different about the pipes I used
20 to do where they were pretty bisymmetric. But here
21 it's not.

22 MR. RUDLAND: It's definitely not.

23 MEMBER SHACK: I was going to ask do you
24 see a difference in the field? I mean, this would
25 suggest you'd see more axial cracking than you would

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1 hoop cracking, and is that --

2 MR. COLLINS: That's generally what we see
3 in the field. We've seen a number of axial flaws. We
4 have seen some circumferential flaws, and a lot of it,
5 when we go into the modeling of it, we are looking for
6 the length of that safe-end because how far away that
7 safe-end weld is identifies that as far as when we go
8 into modeling ahead of time. But the operational
9 experience is also seeing a difference when they don't
10 even have that weld there, when they have some other
11 type of geometry there.

12 MR. RUDLAND: And I think we haven't had
13 a leaking circumferential crack, have we? But we've
14 had leaking axial cracks.

15 MR. COLLINS: Right. I don't believe
16 we've had a circumferential crack.

17 MR. BENSON: And Slide 40, we just mention
18 the number of participants and the organizations who
19 participated in the finite element round robin study.
20 And I'll just point out we have some EPRI contractors
21 and some NRC contractors, and we also have some
22 international participants.

23 MR. RUDLAND: And I do want to point in
24 that that the NRC staff themselves also had, also
25 participated.

1 MR. BENSON: And Slide 41 shows model
2 geometry with a mesh. That just gives you an idea of
3 how these models look. And down at the bottom, you
4 can see that the mesh gets coarse away from the
5 welding areas, and then at the top we refined the mesh
6 near where the weld passes are. And on this slide, we
7 just show the type of steps that we go through in
8 these models. Your first model with the butter
9 passes, and then you can model a heat treatment if you
10 want to. Sometimes, it's neglected. And there's a
11 machining process for the butter. Then you add your
12 stainless steel safe-end, and then you can start
13 modeling your dissimilar metal weld passes.

14 And then for the Phase IIa, there was
15 actually simulated repair. In the actual mockup, they
16 machined out a groove and replaced it with filled in
17 weld metal. So you can also simulate that process
18 with your model.

19 Slide 43 talks about, gets to the question
20 that Sam asked: what type of information did we
21 provide the modelers and how did we provide it to
22 them? So, first of all, we postulated that the main
23 sources of uncertainty might be welding heat input and
24 material properties. And so we decided to do three
25 analysis stages. In the first stage, we do not

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1 provide any thermocouple data or material property
2 data. In the second stage, we provide that
3 thermocouple data so they can tune their heat input
4 models. And then, in the last stage, we provide
5 material property data so everyone is using the same
6 material properties. And the hope is, or the hope was
7 that, as modelers got more information, that the
8 modeling uncertainty would decrease. And we also
9 modeled before and after the stainless steel closure
10 weld.

11 And then on Slide 44, we show some of our
12 results. This is for pre-stainless steel closure
13 weld. On the left, we have no material properties and
14 no thermocouple data provided to the participants, and
15 then on the right side we show the results when they
16 had both material and thermocouple data. And what we
17 show here, these are axial stresses, distance from the
18 ID. We show that the modeling uncertainty is the
19 same, even though we provide the modelers more
20 information. So that was a disappointing result.

21 Some good news here is that at least the
22 average of all the models seem to agree reasonably
23 well with the experiment, so we were happy with that
24 result.

25 MEMBER BLEY: So do you know why providing

1 the additional data didn't affect them? Did they
2 already have similar information in their models, or
3 did they account for those kind of things?

4 MR. BENSON: To a certain extent, we
5 think, at least in this slide, we're showing a variety
6 of hardening laws. So some of the differences between
7 the hardening laws is washing out some of that
8 uncertainty. That's one conclusion. There may be
9 some others.

10 MR. RUDLAND: You know, there's two
11 different types of uncertainty that we're dealing with
12 here. There is modeling uncertainty that's driven by
13 modeling choice, and then there's the weld variation
14 uncertainty. And so by taking the thermocouple and
15 the material properties, we're trying to hit at the
16 weld uncertainties, thinking that was driving the
17 problem. What's really driving the problem is the
18 choice that the modelers are making.

19 MEMBER BLEY: That's not surprising.

20 MR. RUDLAND: Yes, I didn't think it would
21 be. We didn't think, at the beginning, that it was
22 going to be as big a difference in the uncertainties,
23 but it seems to be totally driving the problem. And
24 so we --

25 MEMBER BLEY: They did actually use the

1 data you gave them?

2 MR. RUDLAND: They did use the data.

3 Well, you know, most of these modelers have their own
4 databases of material properties.

5 MEMBER BLEY: That's what I'm saying.
6 They didn't just look at it and say that's about like
7 what we're already using?

8 MR. RUDLAND: I know they used this, you
9 know. And they tuned their heat models based to the
10 actual thermocouple measurements --

11 MEMBER BLEY: Okay, okay.

12 MR. RUDLAND: -- and it didn't make that
13 much of a difference. Especially for these types of
14 welds that are very thick, it didn't make that much of
15 a difference.

16 MEMBER SCHULTZ: And that is, we're
17 looking at, at least to what we can tell by looking at
18 these plots, the aggregate of information here. You
19 look individually at the differences from one modeler
20 to one modeler, same modeler?

21 MR. RUDLAND: Well, we're going to get to
22 that --

23 MEMBER SCHULTZ: Oh, okay.

24 MR. BENSON: Yes, this slide shows just an
25 example from one modeler --

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1 MEMBER SCHULTZ: All right. Thank you.

2 MR. BENSON: -- going through the
3 different analysis stages. And we just plot the data
4 a little differently, but, yes, the conclusion is the
5 same. Just adding the additional information didn't
6 change the results that much.

7 MR. TREGONING: Rob Tregoning, NRC staff.
8 So, yes, it's comforting because you don't have those
9 in a real problem.

10 MR. BENSON: On Slide 46, I've just
11 separated out at least the hardening law issue that we
12 sort of talked about. On the right-hand side, we have
13 just the isotropic hardening results, and then on the
14 left-hand side the kinematic hardening results. You
15 know, just one observation. If you look at the ID
16 location, at least, the isotropic hardening sort of
17 takes up four- to six-hundred range, and the kinematic
18 takes up the two- to four-hundred range. So to a
19 certain extent, just this hardening law issue is
20 exacerbating the uncertainty issue.

21 And then on Slide 47, we're just showing
22 the results both pre-stainless steel closure weld and
23 then after the stainless steel closure weld. And
24 these, again, are axial stresses.

25 MEMBER SHACK: Just going back to the last

1 one, at least not intuitively, which one of those is
2 the most conservative one from a crack propagation
3 point of view? You initiate faster, but you might
4 stop the crack.

5 CHAIR ARMIJO: The worst case, I see the
6 one on the left, though.

7 MEMBER SHACK: But it's pretty
8 conservative there halfway through.

9 CHAIR ARMIJO: Halfway through, yes. But
10 they're both about halfway through where they got
11 compressive --

12 MEMBER SHACK: The other one gets much
13 more, I mean it's much more compressive earlier.

14 CHAIR ARMIJO: Okay. And these are axial
15 stresses.

16 MEMBER SHACK: I mean, they can do the
17 computation. It's not intuitively obvious looking at
18 them.

19 MR. RUDLAND: Right. There's this spot
20 also where it crosses through the S axis, crosses
21 zero. Also, it's very sensitive in the calculation.
22 So where that crosses makes a big difference in the
23 crack course predictions. Of course, the farther
24 right you are, the more tension you have, right? So
25 it's actually better there.

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1 MR. BROUSSARD: That effect was looked at
2 in MRP-287. There is an Appendix A where they took a
3 few different through wall stress distributions and
4 then did the K calculation for that for a given size
5 flaw, and you do see some of that. And sometimes the
6 K kind of stays the same, and other times the K kind
7 of falls off, depending on what the through wall
8 stress distribution looks like.

9 MR. BENSON: So if we're done there, Slide
10 47 is just comparing the modeling and measurement
11 results for two cases, both before and after the
12 stainless steel closure weld. And it is kind of nice
13 that the models also captured fairly well this effect
14 of a stainless steel closure weld.

15 MR. COLLINS: To highlight it once again,
16 the surface type like stresses, if you look on the
17 surface including the stainless steel weld, you've got
18 from tension down to compression. So another reason
19 for the need for this or to refine that is to have
20 that better understanding of how much we can say there
21 is the potential for initiation versus this is a
22 relatively well protected initiation site.

23 CHAIR ARMIJO: This is also a function of
24 the length of the stainless steel --

25 MR. COLLINS: Distance from how far it is

1 away from this --

2 MR. RUDLAND: Yes, the length of the
3 stainless safe head directly affects its bending
4 problem. So it's a function of that length, and it's
5 actually R/T ratio.

6 CHAIR ARMIJO: There could be a preferred
7 length to make sure you're always in compression if
8 you were building a new component.

9 MEMBER SHACK: Optimized safe-ends.

10 MR. COLLINS: I think NRO, going back to
11 the Vogtle issue, I think NRO has talked to, raised
12 that issue with them.

13 MR. RUDLAND: The issue also, the only
14 issue is that the safe-end length is sometimes used to
15 help make up some tolerance differences when they're
16 out in the plant. So it's --

17 CHAIR ARMIJO: Make it up some other way.

18 MR. RUDLAND: That's right. So they cut
19 them long, and then they bring it back to however long
20 they need it, you know, before they do that stainless
21 steel --

22 CHAIR ARMIJO: I know, but that may not be
23 the smartest thing to do.

24 MEMBER BROWN: So you've got two
25 incremental deep hole drilling sets, and they're done

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1 for both of these circumstances. Are they in
2 different places? I mean, how do you -- okay. So you
3 do them at different locations --

4 MR. RUDLAND: These two are 180 degrees
5 apart.

6 MEMBER BROWN: Okay, all right.

7 MR. RUDLAND: And, actually, there's been
8 --

9 MEMBER BROWN: And they map pretty well.

10 MR. RUDLAND: They map pretty well. And
11 there's some additional measurements that are being
12 made right now I believe. There's contour
13 measurements being made. We don't have the results
14 completed yet.

15 MR. BENSON: That's right, on this same
16 nozzle that we're talking about here.

17 CHAIR ARMIJO: So additional incremental
18 deep hole drilling?

19 MR. BENSON: It's not deep hole drilling.

20 MR. RUDLAND: The contour method.

21 CHAIR ARMIJO: Contour method.

22 MEMBER SHACK: We're going to really slice
23 it up.

24 MR. RUDLAND: Really slice it up, yes.

25 MEMBER SHACK: I mean, the nice about the

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1 deep hole is you can do the pre-stainless steel weld
2 and still be able to do it --

3 MR. RUDLAND: You can't do that with
4 contour.

5 MEMBER SHACK: You can't do that with the
6 contour.

7 MR. BENSON: Okay. So in Slide 48, we
8 talk about sensitivity studies that were performed
9 with the models.

10 MR. RUDLAND: By single analyst.

11 MR. BENSON: By single analyst, yes. And
12 in this case, if we look at, say, the blue line, which
13 is kinematic hardening pre-stainless steel weld, and
14 the green line is isotropic hardening, you can see
15 just by varying the hardening law we get fairly large
16 differences.

17 CHAIR ARMIJO: If that was real hardening,
18 if that was real hardening, would you be able to
19 detect it with microhardness measurements?

20 MR. RUDLAND: You should be able to detect
21 the hardness level. I would think so, if you're able
22 to find enough measurements.

23 CHAIR ARMIJO: Have you tried it?

24 MR. RUDLAND: No, because, in reality, the
25 materials aren't isotropically hardened. You know,

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1 it's some place in between kinematic and isotropic
2 hardening, so it's going to be probably closer to the
3 smoother curve than it is the jagged curve because it
4 really isn't isotropic hardening.

5 MR. BROUSSARD: There's been a little bit
6 of microhardness measurements. I think I may have
7 even put it in the MRP-316. Maybe did one
8 microhardness in one of the plate cross-sections, I
9 think. And it's been done by a few other researches,
10 so there is some data out there, but we haven't fully
11 integrated that --

12 CHAIR ARMIJO: Well, was it smooth, or did
13 it indicate this significant variability?

14 MR. RUDLAND: Yes, I don't know. Could
15 you see the weld-by-weld variations in hardness? I
16 don't know --

17 MR. FENG: We just finished a measurement
18 of microhardness, and it had actually a pretty good
19 correlation with strain distribution model in the
20 weld. I will send some of the data to you probably
21 next couple of weeks.

22 CHAIR ARMIJO: Okay. So we'll see that
23 later.

24 MR. BENSON: And this slide just shows
25 sensitivity studies with heat input, and the slide is

1 really busy. But the easiest way to look at it, I
2 found, was to pick out this orange line here, which is
3 baseline post-stainless steel weld, and then this red
4 line here at the bottom which is 25 percent of the
5 heat flux of that baseline. And by varying that heat
6 input, you can have some significant effect also on
7 the results.

8 So this is just two examples of
9 sensitivity studies that were performed. Others were
10 performed also to try to understand what might be the
11 potential sources of uncertainty that we're getting.

12 CHAIR ARMIJO: Okay. I'm just trying to
13 say, is the high heat input weld the worst case or on
14 the ID as far as residual stress?

15 MR. BENSON: So higher --

16 CHAIR ARMIJO: Your green is -- you've got
17 too many colors for me.

18 MR. BENSON: Yes, yes. So if we pick out
19 --

20 CHAIR ARMIJO: Your highest heat input is
21 what? The purple line, the blue?

22 MR. BENSON: Highest input is blue and
23 red. Excuse me, it's not red. It's this pinkish
24 color. So it's kind of going along through here.

25 MEMBER BROWN: The light blue is the

1 highest input, is the highest heat flux?

2 MR. BENSON: Yes, light blue is one and a
3 half for the pre-stainless steel case.

4 MEMBER SHACK: It looks like the half heat
5 flux is the worst.

6 CHAIR ARMIJO: Yes, which is kind of
7 interesting.

8 MR. RUDLAND: Right at the ID you mean.

9 MR. BENSON: It's the green right here,
10 yes, yes.

11 MEMBER SHACK: And it just may be that
12 you're not relieving as much of the stress that you
13 put in.

14 MR. RUDLAND: That's going to be weld bead
15 size dependent also.

16 MEMBER SHACK: Yes, right.

17 MR. RUDLAND: Especially at the ID. But,
18 typically, the higher the heat flux, the higher the
19 stress in that particular bead.

20 CHAIR ARMIJO: Yes, but this assumes the
21 same low heat input for every pass, right?

22 MR. RUDLAND: Right. It assumes the same
23 heat flux for every pass in this particular
24 sensitivity study, yes.

25 CHAIR ARMIJO: So that could make sense,

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1 just there's no stress relaxation and --

2 MR. RUDLAND: Because if you look, on
3 average, the blue line is the highest line, the light
4 blue line. This line here is typically the highest
5 line right through here. It has the highest heat
6 flux.

7 MEMBER BROWN: Pre --

8 MR. RUDLAND: Pre-stainless steel, right.
9 Because by the time you compress it, you're moving
10 things around anyway. So it probably doesn't matter
11 as much.

12 MR. BENSON: So just some observations
13 from the Phase II work. Modeling and measurement
14 results do show some reasonable agreement in magnitude
15 and shape. There is significant model to model
16 variability. And providing thermocouple and material
17 property data did not reduce that variability.

18 We're also beginning to identify certain
19 areas of uncertainty. For welding uncertainty, we're
20 talking about things like process sequence, arc
21 efficiency, and material properties. For modeling
22 uncertainty, it can be choice of hardening law, which
23 we saw a huge effect on. And also finite element
24 details, like mesh density and how you post-process
25 the results.

1 So that's Phase II. In Phase III, we're
2 looking at actual components that were fabricated for
3 intended service. And this case was also a
4 pressurizer nozzle, safety and relief pressurizer
5 nozzle. And the finite element round robin is not as
6 extensive as the Phase II case, but we did get some
7 results from different modelers. And, again, we're
8 trying to validate modeling and experiment and assess
9 modeling uncertainty.

10 And we sort of talked about earlier using
11 the contour method is a completely destructive method.
12 So if you want to get at this effect of the closure
13 weld, you have to have two different specimens and two
14 different mockups. So that's what was done here. And
15 also these mockups were smaller than Phase IIa
16 mockups. The outer diameter in the Phase III was 200
17 millimeters, as compared to 350.

18 And, you know, I'm not going to spend a
19 whole lot of time on the slide. The results, they
20 tell the same story as the previous results. We're,
21 more or less, in the right ballpark between the models
22 and experiment, but there's uncertainty there.

23 MR. RUDLAND: And I'll make one point is
24 that, again, with this Phase III we knew nothing about
25 these welds. We knew nothing about the weld processes

1 for these welds at all. We were able to check the ID
2 to see if there were some kind of repairs, but you
3 will notice that the deep hole drills on certain parts
4 of the wall thickness were different. Again, these
5 were done at 180 degrees from each other. You'll see,
6 if you look at the solid circle dots, there are some
7 differences, again indicating that something is going
8 on in that particular part, which isn't incorporated
9 into the residual stress models because we just don't
10 know what's there.

11 MEMBER SCHULTZ: The question in Phase II
12 moves to Phase III chronologically or --

13 MR. RUDLAND: No, no, they were done
14 mainly in series. So what we did was we started Phase
15 II and Phase III started after Phase II was started
16 but not after it completed. So we used the same types
17 of modeling techniques because we wanted to see if
18 scatter was different using the same modeling
19 technique between a very well-prepared weld and a weld
20 taken for service.

21 MEMBER SCHULTZ: So we just went through
22 some lessons learned from Phase II. They were not
23 particularly applied for Phase III?

24 MR. RUDLAND: Because they curve, those
25 lessons learned are learned after, were learned after,

1 yes. So, in case, if you were able to read this,
2 you'd see that some, again, used isotropic and some
3 used kinematic in their analyses.

4 MEMBER BROWN: I'm sorry. I didn't mean
5 to interrupt you, Steve. But where's the measured
6 data? Is that the dots?

7 MR. RUDLAND: Yes.

8 MEMBER BROWN: So the Vegter nozzle two
9 hoop and the --

10 MR. BENSON: And the hill, which is the
11 solid lines, those are the contour measurements.

12 MEMBER BROWN: Oh, okay.

13 MR. BENSON: And the dots are the deep
14 hole drilling measurements.

15 MEMBER SHACK: Who assumes axisymmetry and
16 who doesn't here?

17 MR. RUDLAND: I don't think there was a
18 single modeler that made the choice to use three-
19 dimensional modeling. They all used --

20 MEMBER SHACK: All used axisymmetric.

21 MR. RUDLAND: -- axisymmetric. We
22 allowed, at least for Phase II, we allowed in the
23 package for them to do that if they wanted to.

24 MEMBER SHACK: It's just that axisymmetry
25 becomes more problematic as the nozzle gets smaller,

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1 and this is, like, what? An eight-inch nozzle and you
2 bound to it, yes.

3 MR. RUDLAND: Again, the choice, from the
4 modeler's perspective, was that it's a lot more costly
5 when you have to do those types of analyses, right?
6 So . . .

7 MR. BENSON: Okay. So, yes, similar
8 observations from the Phase IIa. We're in the right
9 ballpark, but there's modeling uncertainty.

10 MR. RUDLAND: And no difference really in
11 the uncertainty when going from a well-controlled weld
12 to a, you know, a shop weld that was made for service.

13 MR. BENSON: So Phase IV was also an
14 actual component intended for service. It was a cold
15 leg nozzle from a canceled plant. But there was one
16 additional objective here that we've alluded to, which
17 was assessing the effectiveness of weld overlay
18 process. And, in particular, we looked at this
19 optimized weld overlay process, which is a thinner
20 amount of weld material applied on the OD. This just
21 shows before and after photographs.

22 CHAIR ARMIJO: How many passes is that to
23 get there?

24 MR. COLLINS: It goes to less than a half
25 an inch of weld material on top, whereas a full

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1 structural weld overlay would be over the half-inch.

2 CHAIR ARMIJO: But it's a continuous weld?

3 MR. COLLINS: There's a couple of
4 different ways of doing it. It has been done to speed
5 it up, double up. There are different ways of doing
6 it, and those go into some of the modeling problems
7 that were looked at in a different analysis than this.
8 It was the actual validation for the whole program,
9 which was done by -- who was that done by? For the
10 weld overlay stuff. For the weld residual stress.

11 MR. RUDLAND: Vegter did most of that.

12 MR. COLLINS: I meant the calculations of
13 the NUREG reports that we have for the -- yes,
14 Battelle had modeled the different ways of doing the
15 welding on the particular item. This one, I don't
16 know if you guys knew, you knew how the weld overlay
17 was, how the weld overlay was put on but not the
18 initial, as much about the initial welding processes.

19 MR. RUDLAND: But I believe this was
20 automated continuous welding for the overlay for this
21 particular model.

22 MEMBER BROWN: What's the difference
23 between optimized weld overlay and non-optimized?

24 MR. RUDLAND: Weld structural overlay is
25 designed to basically replace the load-carrying

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1 capacity of the undersized weld. So the weld
2 underside is degraded for some reason, and they put
3 the overlay on with sufficient thickness to satisfy
4 Section III, ASME Section III. The optimized is not.
5 The optimized is thinner, takes credit for some of the
6 weld, still provides enough residual stress mitigation
7 to satisfy the mitigation of the PWSCC.

8 MEMBER SHACK: It's optimized to give them
9 good residual stresses.

10 MR. RUDLAND: Good residual stresses but
11 less weld.

12 MEMBER BROWN: But it makes the pipe
13 fatter in the areas of the weld; is that what it does?

14 MR. RUDLAND: It makes the pipe fatter.
15 The optimized --

16 MEMBER BROWN: Bigger through walled --

17 MR. RUDLAND: Yes, the thickness is
18 larger.

19 MEMBER BROWN: The thickness is larger.

20 MR. COLLINS: With crack-resistant
21 material.

22 MR. RUDLAND: Right. So they use a
23 different material here than what's in the weld. They
24 use a material that's got a higher resistance to
25 PWSCC. So if the crack, for some reason, does make it

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1 all the way through the susceptible weld, it's going
2 to not --

3 MEMBER BROWN: Even though it's on the
4 external surface.

5 MR. RUDLAND: That's right.

6 MEMBER BROWN: Okay, thank you.

7 MR. BENSON: And on Slide 59, we show some
8 contour plots from the measurements on axial stresses,
9 and we can look at the results after the DM weld and
10 then after the stainless steel closure weld and then
11 after the overlay is applied. And we're going to look
12 at stress profiles through the center of the DM weld
13 in these coming slides.

14 And this shows axial stresses. And what
15 we show here is that the stainless steel closure weld
16 actually causes the stresses to decrease relative to
17 prior to. And then the weld overlay shows, at least
18 according to the model, a small increase, but still
19 you're close to zero near the ID.

20 And then this is just a different way of
21 looking at the data. We're showing the ID stress as
22 we go along the length of the component and similar
23 conclusions to the last slide.

24 And then so we were looking at axial
25 stresses in the previous two, but on Slide 62 I've

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1 just shown the hoop stresses. And there's actually a
2 much more beneficial effect, according to our models,
3 on the hoop stresses after the optimized weld overlay.

4 CHAIR ARMIJO: And those are the ones that
5 generate the kind of cracks you're seeing, right? The
6 actual cracks? Hoop stresses?

7 MR. BENSON: Yes.

8 CHAIR ARMIJO: Okay. So it's unfortunate
9 then that you get better compression there.

10 MR. COLLINS: We have a requirement for
11 the optimized weld overlay of ensuring that you have
12 a maximum 10 ksis on the ID surface. So we want
13 modelers, in their design, to have a design of the
14 thickness of the optimized weld overlay --

15 CHAIR ARMIJO: You had at least 10 K
16 compression?

17 MR. BENSON: No.

18 MR. RUDLAND: 10 K tension.

19 MR. BENSON: 10 K tension.

20 CHAIR ARMIJO: Less than 10 K tension. So
21 you will accept some tension on the ID?

22 MR. RUDLAND: There is a lot of debate and
23 discussion on what the level of stress is needed for
24 SCC initiation and --

25 CHAIR ARMIJO: You can dance around that

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1 forever. You know, if you go into compression, you've
2 answered the question, you know, assuming you're
3 taking care of uncertainties. But this idea of
4 saying, well, it's not tensile enough to initiate a
5 crack --

6 MR. COLLINS: But you can also see the
7 other uncertainties that are in here, but that was
8 kind of the reason why you see some of these are a
9 little bit higher, even on the previous slide.

10 MR. RUDLAND: The decision, I think, was
11 made based not only on the stress but also on the fact
12 that there is a resistant material on the other side
13 of the pipe.

14 CHAIR ARMIJO: Yes, sure, sure.

15 MEMBER SCHULTZ: What constitutes the
16 definition of the optimized weld overlay?

17 MR. RUDLAND: It just has a smaller
18 thickness. It's optimized in thickness to be able to
19 give us the appropriate residual stress on the ID
20 surface.

21 MR. COLLINS: It actually, in the
22 calculation for holding the integrity of the pipe, it
23 uses the outer quarter thickness of the material of
24 the Alloy 82/182 material that would still be
25 susceptible to cracking to go into those calculations,

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1 whereas the full structural weld overlay doesn't use
2 that outer material.

3 MR. RUDLAND: It takes no credit for the
4 original weld.

5 MEMBER SCHULTZ: Thank you.

6 MR. BENSON: And then on this slide we
7 show the measurement and modeling results. These were
8 deep hole drilling and incremental deep hole drilling
9 results. And so Slide 63 were axial stresses and then
10 hoop stresses on 64.

11 So observations for Phase IV work.
12 Modeling and measurement results did show improvement
13 of the residual stresses at the ID location after
14 optimized weld overlay was applied, and modeling
15 uncertainty still exists but general agreement between
16 models and measurements.

17 And then we'll wrap up this talk. We
18 wanted to start out with what we think we've
19 accomplished in this work. We performed double blind
20 weld residual stress modeling validation using
21 prototypic nuclear components. We've also seen the
22 beneficial effect of weld overlay, optimized weld
23 overlay by modeling and experiment, and this actually
24 led to input into the safety evaluation report on
25 that.

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1 And sources of uncertainty have been
2 identified. These include things like weld
3 uncertainty, process details, and material properties;
4 and then, for modeling uncertainty, hardening law and
5 then certain finite element details. And so what we
6 hope in going forward is that we can take lessons
7 learned from this work and begin to reduce that
8 modeling uncertainty that we're seeing.

9 And then what are the opportunities for
10 improvement? There are no procedures in place
11 currently to reduce modeling uncertainty. There's
12 some sources of uncertainty that aren't well
13 quantified, and so we want to do additional
14 sensitivity studies with the models. And then no
15 current acceptance criteria for weld residual stress
16 input is in place.

17 CHAIR ARMIJO: Is there intent to
18 establish by the staff?

19 MR. RUDLAND: That's the next little
20 presentation. We've got seven slides or something on
21 what our plans are moving forward.

22 MEMBER SCHULTZ: I'd like to bring it up
23 here. I'm struggling with the concept of saying that
24 what we're looking at here is modeling uncertainty
25 versus what I saw earlier that I appreciated, which

1 was variability in the results of the modeling. The
2 modeling uncertainty seems, to me, to be the strict
3 comparison of the models of the data, and we saw many
4 graphs or displays that showed the variability. And
5 some of the models were, I presume, good in comparison
6 to the data, and some were poor. But that doesn't
7 mean that what I'm looking at is model uncertainty.
8 I'm looking at the variability in the model, and I'd
9 have to pour into the capacity of one particular model
10 to identify its uncertainty versus the inability of
11 the modeler or the inability of the model to
12 effectively match the data. It's a little different
13 than --

14 MR. RUDLAND: Yes, and that's a good
15 point. I think we've kind of lumped those things
16 together. I mean --

17 MEMBER SCHULTZ: Yes. I'd use caution
18 there because, as we go forward with this, it's
19 important to recognize that.

20 MR. RUDLAND: That's a good point. The
21 analysis, at least in the round robin, the mean value
22 matched the experiments pretty well. So from a mean
23 standpoint of all of the analysis, we have little
24 model uncertainty, I suppose, because the mean value
25 matches the experiments rather well. And it's really

1 that scatter from the individual modelers --

2 MEMBER SCHULTZ: Correct.

3 MR. RUDLAND: -- that we're concerned
4 about. And we've lumped it into the term uncertainty,
5 but you're right that there really is a separation
6 between those two. We probably should take that
7 better into account.

8 MR. COLLINS: When we did those, when a
9 licensee provides us a weld residual stress
10 calculation, we're informed by some of this work to
11 ask those initial questions NRR has, as far as
12 requests for information from the licensee, if it's
13 not already in the document, to better understand how
14 they came up with their weld residual stress and
15 inform us with these. And then I guess maybe
16 sensitivity studies, as identified there, we'll try to
17 develop with a range to look how much of an impact
18 some of these things which we have uncertainties in
19 the answers coming back from the licensee that are
20 feeding into these questions. So I guess we do use
21 uncertainty maybe a little bit too much but --

22 MEMBER SCHULTZ: Well, it's all, as you
23 say, it's all good information. And given that a
24 modeler is giving you a one-of-a-kind analysis, then
25 it does, as you appropriately picked the word, inform

1 you as to what confidence one may have at this point
2 in time related to that prediction.

3 MR. RUDLAND: All right. So if I look at
4 it this way, if I say that the finite element method
5 to model uncertainty has much smaller modeling
6 uncertainty than the individual analyst scatter in
7 representing that particular modeling result. I think
8 that's what you're saying, right? So we have to
9 understand that scatter from the individual modelers
10 --

11 MEMBER SCHULTZ: That's right.

12 MR. RUDLAND: -- differently than actually
13 saying that the model itself of using finite element
14 to predict residual stress. That uncertainty may be
15 small.

16 MEMBER SCHULTZ: And we know something
17 about what's causing that.

18 MR. RUDLAND: Right.

19 MEMBER SCHULTZ: But it's multi-variable.

20 MR. RUDLAND: Right, right, right, right.

21 MEMBER SCHULTZ: So there's several
22 considerations to continue to explore --

23 MR. RUDLAND: Yes, thank you.

24 MR. BENSON: Are we ready to move on to
25 the last talk?

1 CHAIR ARMIJO: Yes, yes.

2 MR. BENSON: Okay. So for our final talk,
3 this is a short talk, more or less, we're going to
4 talk about what we plan going forward. But we will
5 spend a brief time to recap what the current
6 accomplishments are and describe the knowledge gaps,
7 and then we'll introduce the potential future
8 activities that are currently planned.

9 So modeling uncertainty right now is, what
10 we're calling modeling uncertainty is uncomfortably
11 large. But sources of uncertainty have been
12 identified, such as the choice of hardening law. And
13 despite large analyst scatter, the axisymmetric finite
14 element models do seem to show agreement with the
15 measurements. So that's sort of the three main
16 points.

17 CHAIR ARMIJO: Michael, you don't mention
18 here in your summary of whether you've reached a
19 conclusion that measurements using the deep hole
20 drilling or incremental deep hole drillings appears to
21 be satisfactory or the best thing you've come up with.
22 You've not reached that conclusion yet? It looked to
23 me like that's --

24 MR. BENSON: Yes. You're right, Sam. Our
25 essential conclusion was things like contour

1 measurement and deep hole drilling measurements are
2 the ones we're going to stick with.

3 CHAIR ARMIJO: Okay.

4 MR. COLLINS: But we're still doing more,
5 right? I mean, trying to do some more --

6 MR. RUDLAND: That's what I understand.
7 And, again, there's a lot -- like John Broussard
8 pointed out earlier, it's not that those are bad
9 measurements. It's just that I think more research
10 needs to go to be able to understand their effects in
11 these types of welds.

12 CHAIR ARMIJO: Yes. But the point I want
13 to make is that measurements, reasonably reliable
14 measurements are available, and you've used them. And
15 it's these two destructive techniques, but, you know,
16 they're consistent. In the models, they're
17 consistent.

18 MR. RUDLAND: Except for at the surface,
19 where I think that's where the issue --

20 CHAIR ARMIJO: Yes, the surface is a
21 different area, and I want to comment on that later.

22 MR. BENSON: So what are the knowledge
23 gaps? First of all, commonly accepted procedures for
24 developing a weld residual stress input to a flaw
25 evaluation are lacking. And criteria are needed for

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1 weld residual stress acceptance and validation. No
2 measurement data currently exists for various other
3 weld geometries that we haven't looked at, such as J-
4 groove weld. And the effect of partial arc repairs
5 cannot be captured with axisymmetric models. So
6 typical repairs in the field or certain portion of the
7 circumference, we can't model that effect with the
8 axisymmetric models.

9 And so moving on to Slide 5, where we
10 actually start to list out some of the joint research
11 activities we're planning with EPRI right now. I
12 mentioned earlier that we are in the course of
13 developing a new MOU addendum for WRS research. We
14 alluded to this some. The Phase IIa mockup that you
15 saw data from already, there are additional
16 measurements that, they're probably completed by now.
17 They may be analyzing the data at this point. But the
18 contour and slitting measurements are ongoing on the
19 Phase IIa mockup. And then there's this --

20 MEMBER SHACK: But how do you compare
21 those two? I mean, you get a lot more displacement
22 measurements, obviously, out of the contour system
23 than the setting where you're still depending on
24 strain gauges there or the slitting actually does the
25 --

1 MR. RUDLAND: Strain gauges.

2 MEMBER SHACK: Strain gauges. Okay. So
3 you have far more information, in a sense, from the
4 contour.

5 MR. RUDLAND: Right, right. But the
6 contour gives us, hence the name, you know, contour
7 kind of plots of that. So that's a nice comparison
8 also against the finite element analysis. Sometimes
9 by taking single cuts, you miss the hot spot or
10 something, right?

11 MEMBER SHACK: Right.

12 MR. RUDLAND: So you can do that, but we
13 can also take the contour measurements and make that
14 same cut and compare the through thickness
15 measurement.

16 MEMBER SHACK: It just seems you get a lot
17 more out of the contour.

18 MR. RUDLAND: Agreed.

19 MR. BENSON: So that data is being
20 collected now. And then there's, like we mentioned,
21 there's the Phase IIb mockup, which is pretty much
22 similar to the Phase IIa mockup, except here we are
23 using a manual welding technique. And this mockup is
24 currently in England at Vegter, and they're finishing
25 up deep hole drilling measurements. And then once

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1 that's finished, that nozzle will be shipped to our
2 contractor in California who will do the contour and
3 slitting measurements on that mockup.

4 And we're also in the course of planning
5 finite element round robin with the Phase IIb mockup.
6 And here's where we hope to apply some of the lessons
7 learned and see what we can do about reducing modeling
8 uncertainty.

9 We're also -- another goal of the program
10 is to get a draft of ASME code best practices for weld
11 residual stress inputs to flaw evaluations. We want
12 to look into development of three-dimensional moving
13 arc analysis and development of improved hardening
14 laws, which is some work EPRI has initiated with Oak
15 Ridge National Lab.

16 We're also going to be considering
17 measurements on some of these J-groove weld
18 configurations, such as bottom-mounted instrument
19 nozzles. And then another ongoing topic is weld
20 residual stress inputs for xLPR. And so in that case,
21 we're having three separate modelers, at least three,
22 possibly more, depending on funding, but at least
23 three different modelers who will be independently
24 modeling this same problem.

25 So that will get at modeling uncertainty,

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1 and then welding uncertainty will be assessed by
2 performing sensitivity studies on particular key
3 inputs. So that's the work for xLPR. And then we're
4 also keeping our eye on some international research
5 programs.

6 So with that, I'll just summarize. This
7 will be the last slide that we will have. Weld
8 residual stresses have regulatory significance.
9 They're important to engineering evaluations involving
10 nuclear safety and large uncertainties exist in those
11 inputs.

12 And then just a recap of some of our
13 future activities. We want to validate finite element
14 modeling for different weld geometries. We want to
15 develop codified guidelines for formulating WRS
16 inputs. We'd like to reduce modeling uncertainty and
17 quantify uncertainty through sensitivity studies and
18 also recommend acceptance criteria to the regulators.

19 So with that, that's all we have prepared.

20 MEMBER SCHULTZ: A couple of questions on
21 the future activities. What is the duration you
22 anticipate for this next Memorandum of Understanding
23 with EPRI?

24 MR. BENSON: Yes. Some of the topics went
25 out to the end of 2014; is that correct, Paul? Is

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1 that what you remember? Yes, okay.

2 MEMBER SCHULTZ: And on Slide 7, you
3 indicated you're going to keep your eye on
4 international programs in this arena. What is the
5 extent of those programs and how are you monitoring or
6 participating in what is ongoing in the international
7 programs?

8 MR. BENSON: So there's a program called
9 NET, and it's an acronym. The name is long and
10 complicated; I forget what it is. But I actually
11 visited some of the participants in that program and
12 talked to them some. They are doing residual stress
13 modeling and measurements on more simplistic weld
14 geometries, like the Phase I weld geometries that we
15 talked about. And so we have offered to participate
16 in their modeling efforts and, if we do that, we can
17 then get access to some of the information that they
18 have gained through reports they've produced over the
19 years. So that's one example.

20 MEMBER SCHULTZ: And in the round robins
21 that you're planning in this next segment, are you
22 going to have international participation there?

23 MR. BENSON: Potentially, yes.

24 MR. RUDLAND: We did in the first --

25 MEMBER SCHULTZ: I know in the first. I

1 hope that would continue.

2 MR. RUDLAND: We're hopefully going to try
3 to use the same set.

4 MEMBER SCHULTZ: Good. That's even
5 better. Thank you.

6 MEMBER SHACK: Just a question on this
7 ASME best practices for residual stress inputs to flaw
8 evaluations. Is that going to aim at a best estimate
9 value, or is that going to make Charlie happy and look
10 for what we would consider a conservative
11 deterministic weld residual stress input? Is that
12 something to discuss with the code?

13 MR. RUDLAND: Well, I think, again, I
14 think what we're going to try to do is going to try to
15 come up with a tiered approach where, if the person
16 doing the analysis can spend the time and money to use
17 a, to do a sophisticated validated finite element,
18 they can reduce some of that certainty. But there's
19 going to be options, I think, you know, within this
20 tiered structure where they can use more and more
21 conservative but less and less effort, basically, to
22 satisfy their needs. But, again, using that bottom
23 tier where you need the analysis, it's going to take
24 a while for us to come up with those acceptance
25 criteria and things like that and best practices for

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1 that.

2 MEMBER BROWN: Isn't the answer then --
3 that's a long answer --

4 MR. RUDLAND: That's a long answer.

5 MEMBER BROWN: -- to a short result. In
6 other words, I would have come away with the
7 conclusion that you don't have a basis for
8 establishing a new set of criteria. You still have to
9 stick right now, and the effort to develop a new code
10 of best practices, it would really have to be held in
11 a abeyance until you have a better feel for how you
12 can make these models replicate and you have more
13 confidence in the actual measurement data that you get
14 to make sure that they are giving you something to
15 really validate the model.

16 MR. RUDLAND: Or you put guidance in the
17 code that, again, is conservative in the hopes that
18 you can modify it in the future.

19 MEMBER BROWN: Don't you already have
20 conservative requirements in there now, or there are
21 no requirements --

22 MR. RUDLAND: No. Like I mentioned, early
23 on, there's nothing. There's no guidance at all.

24 MEMBER BROWN: Okay. For weld residual --

25 MR. RUDLAND: Right.

1 MEMBER BROWN: Okay.

2 MR. COLLINS: So we use the flaw
3 evaluation guideline, that initial document, because
4 we got some questionable flaw analysis as it came out
5 that we poked that a little bit more and found
6 questions. So it started to develop this flaw
7 evaluation guideline that came out which has
8 recommendations already on a tiered level to where we
9 ask licensees to come in, assuming like a 50-percent
10 weld, that a 50-percent weld repair has been initially
11 done. If you can't go back and find records or be
12 able to place, that puts a higher significant weld
13 residual stress initially in there in the calculation.
14 Things of those types, like actions, that we're moving
15 forward with outside of the code just when they're
16 coming in for analysis.

17 MR. RUDLAND: Right. And the folks that
18 are on the code are, very much want to be able to
19 develop the procedures so that if you or you or you do
20 analysis you get the same results. If you have
21 ambiguous requirements in the code and let's say you
22 do some kind of analysis, you're not going to get the
23 same kind of results, right? You may get different
24 results based on the assumptions that you made. So I
25 think that the code is going to lean towards more, I

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1 hope lean towards more direct guidance so that it's
2 not ambiguous on what the --

3 MEMBER BROWN: In other words, you mean
4 provide the assumptions --

5 MR. RUDLAND: That's right.

6 MEMBER BROWN: -- be more prescriptive?

7 MR. RUDLAND: Or provide the stress fields
8 that need to be used for a particular job. I don't
9 know if that's where it's going to go, but that seems
10 to be the way the code would want to go to make it
11 consistent between different people doing code
12 analysis. But we'll have to say. I mean, I think
13 that's a little ways off.

14 MEMBER BROWN: When you say a little ways,
15 what does that mean? Ten years?

16 MR. RUDLAND: No, I sure hope not.

17 MR. BROUSSARD: This is John Broussard.
18 I'm the primary whipping boy for developing that
19 appendix. Over the next, over this year and maybe
20 into early next year, we understand there's a need to
21 kind of get these things in place. We're been working
22 on it over the past year, and it's taking form. I
23 think we've agreed on kind of how we want to approach
24 it. The work that's being done on xLPR is going to
25 give us at least some understanding of uncertainty.

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1 And I think if you're comfortable enough with doing
2 the probabilistic analysis, you can use that same kind
3 of thing and just set your upper bound to do a
4 deterministic calculation. That's what that code
5 guidance is aiming towards.

6 MR. RUDLAND: There's also talk from the
7 NRC side of creating a regulation guide on this.
8 However, there's not quite consensus at this point of
9 whether or not that's needed or not, so we're still in
10 discussions on when we want to do that. And in the
11 regulation guide, we'd be specific.

12 MEMBER BROWN: But you'd still have to
13 accept the code, though. You'd still have to agree
14 with its use --

15 MR. RUDLAND: No.

16 MEMBER BROWN: -- if industry made it
17 without the guide, wouldn't you?

18 MR. RUDLAND: No.

19 MEMBER BROWN: You'd let them use
20 something you don't agree with?

21 MR. RUDLAND: No.

22 MEMBER BROWN: I'm trying to phrase this
23 --

24 MR. COLLINS: Like right now, well, I
25 mean, right now it's not in the code. So, I mean,

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1 when we see something come in, usually they're asking
2 for reason, right? They're asking for an extension of
3 an inspection frequency or something of that nature.
4 So we want to have the confidence in whatever they're
5 providing. And, unfortunately, at this point, since
6 we don't have this established criteria out there,
7 there's uncertainty when we go to talk to them about
8 what we need to have. Like, for instance, that tiered
9 level approach, that 50 percent weld repair that's
10 initially in there for their initial calculation. And
11 then if they want to better define their residual
12 stresses, then we have to work through that process.
13 And we look at the sensitivity to how close they are
14 in months to what they're asking for. Do they
15 actually have, are the calculations saying it's 120
16 months and they're only asking for 50 versus does the
17 calculation show 58 months and they're asking for 50?
18 Then we have to better redefine and look at some of
19 the uncertainty analysis.

20 MR. RUDLAND: Whatever the code comes up
21 with has to be, of course, approved by the NRC before
22 it's put into the regulations. So, hopefully, our
23 cooperative effort will allow that review to be
24 possible or positive and quick. I think that's kind
25 of the whole -- and the reason we do these cooperative

1 research programs.

2 CHAIR ARMIJO: I'm trying to think of how
3 this would be used, and I just come up with a
4 hypothetical situation. Somebody comes in to you and
5 he says, "Look, I'd like to extend my inspection
6 frequency on these nozzles. I've already done my NDT,
7 and there are no flaws in it so far. It's a
8 susceptible material. It's not the newest and
9 greatest material, but we don't have any flaws. And
10 I'm making my argument without any residual stress,
11 weld residual stress basis." Do they have a chance?

12 MR. COLLINS: No.

13 CHAIR ARMIJO: Okay. So they'd have to
14 come and tell you, look, we've done the analysis and
15 we're convinced we have a favorable weld residual
16 stress and here's how we did it. And then if you had
17 a position or a criteria, you could accept it or not
18 accept it. But right now nobody can do that.

19 MR. COLLINS: I think that's a pretty good
20 general statement. Even the requirements currently in
21 the code for the various different inspection programs
22 are based upon the idea of a deterministic calculation
23 at some point along the line. There's other factors
24 that feed into, probabilistic and things of that
25 nature have their opportunities. But the base

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1 deterministic calculation, especially for relief
2 requests that come in for, like you were saying, a
3 licensee wanted to change inspection frequency or
4 they've missed coverage and the flaw size might be
5 larger in an area because they can't get full
6 volumetric inspection coverage. Those are things we
7 handle more so on a basis.

8 MR. RUDLAND: And, usually, what's
9 happened in the past is that we'll get these requests
10 and then research will take that into a sensitivity
11 study to make sure that we verify and confirm that the
12 uncertainties are properly handled with the analysis
13 that comes from the industry.

14 MR. COLLINS: And let me clarify, as well.
15 Those are generally more in the active degradation
16 mechanism, like the stress corrosion cracks. Other
17 components that don't have as much, the other methods
18 get weighed a bit more as far as --

19 CHAIR ARMIJO: Yes, those are mechanical
20 kind of things rather than chemical mechanical. Okay.
21 Any other questions from the Committee? Any questions
22 or comments from members of the audience?

23 MR. BENSON: Let me just add one
24 statement. We are working on a NUREG to summarize all
25 this.

1 CHAIR ARMIJO: Okay, great, great. I
2 think we have a bridgeline. I don't know if it's open
3 or if anybody is on it. Is the bridgeline open?

4 MR. NGUYEN: No one said that they were
5 going to call in.

6 CHAIR ARMIJO: No one called in?

7 MR. NGUYEN: Correct.

8 CHAIR ARMIJO: Okay. If no one has called
9 in and we've finished all the presentations, I'd like
10 to thank the staff and EPRI and all the contributors
11 to this work. Very nice work. Very difficult work.
12 And I learned a lot. I look forward to your next shot
13 at this. Thank you very much. With that, we'll close
14 this session.

15 (Whereupon, the foregoing matter was
16 concluded at 11:40 a.m.)

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WRS Validation Program

Accomplishments

Michael Benson
U.S. NRC RES/DE/CIB

**ACRS Meeting of the Subcommittee on
Materials, Metallurgy, & Reactor Fuels
February 6, 2013
Rockville, MD**

Outline

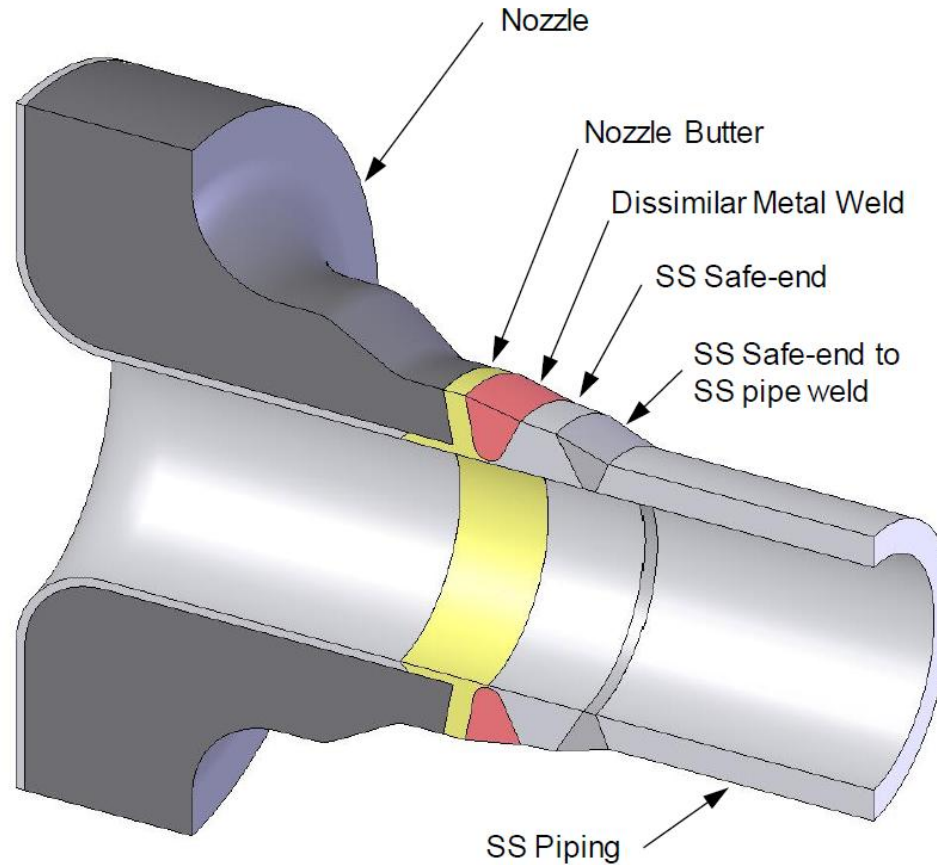
- Overview
- Phase I Work
- Phase II Work
- Phase III Work
- Phase IV Work
- Conclusions

Outline

- Overview
- Phase I Work
- Phase II Work
- Phase III Work
- Phase IV Work
- Conclusions

WRS Validation Program Overview

Dissimilar Metal Weld Geometry



WRS Validation Program Overview

Goals



- Identify, quantify, and minimize sources of model uncertainty
 - Develop reliable and consistent modeling procedures
- Validate WRS models with robust measurement techniques
- Develop acceptance criteria for WRS inputs to flaw evaluations

WRS Validation Program Overview

Memorandum of Understanding (MOU)



- Cooperative research performed under the Nuclear Regulatory Commission (NRC)/Electric Power Research Institute (EPRI) MOU
- Sets forth terms for cooperative research
- Addenda
 - Address specific research topics
 - Extremely Low Probability of Rupture
 - WRS Validation Program
 - Nondestructive Evaluation
 - High Density Polyethylene Piping
 - Environmental Fatigue

WRS Validation Program Overview

Memorandum of Understanding (MOU)



- EPRI
 - Designed/fabricated small-scale specimens and full-scale mockups for WRS measurement
 - Created finite element models

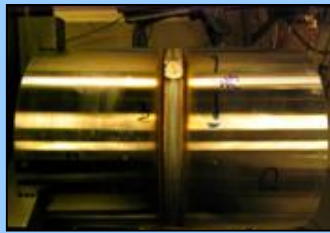
- NRC
 - Created finite element models
 - Organized finite element round robin studies
 - Designed/fabricated a full-scale mockup for WRS measurement

WRS Validation Program Overview

Research Phases

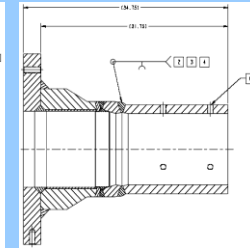
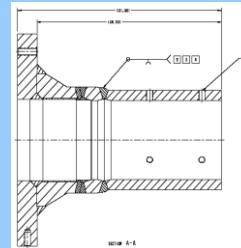
Phase 1 - EPRI

- **Scientific Weld Specimens**
- **Phase 1A:** Restrained Plates (QTY 4)
- **Phase 1B:** Small Cylinders (QTY 4)
- Purpose: Develop FE models.



Phase 2 - NRC

- **Fabricated Prototypic Nozzles**
- Type 8 Surge Nozzles (QTY 2)
- Purpose: Prototypic scale under controlled conditions. Validate FE models.



Phase 3 - EPRI

- **Plant Components**
- WNP-3 S&R PZR Nozzles (QTY 3)
- Purpose: Validate FE models.



Phase 4 - EPRI

- **Plant Components**
- WNP-3 CL Nozzle (QTY 1)
- RS Measurements funded by NRC
- Purpose: Effect of overlay on ID.



Outline

- Overview
- **Phase I Work**
- Phase II Work
- Phase III Work
- Phase IV Work
- Conclusions

Phase I: Scientific Weld Specimens

Overview

- Simple, light-weight specimen geometries
 - Grooved plate
 - Butt-welded cylinders
- Objective
 - To demonstrate/develop WRS measurement and modeling capabilities

Phase 1 - EPRI

•Scientific Weld Specimens

- Phase 1A: Restrained Plates (QTY 4)
- Phase 1B: Small Cylinders (QTY 4)
- Purpose: Develop FE models.



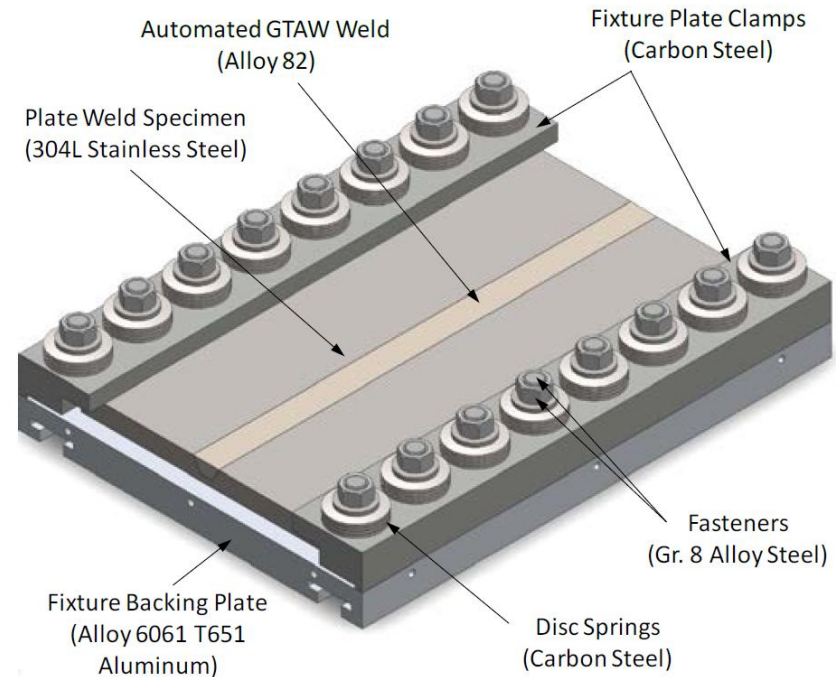
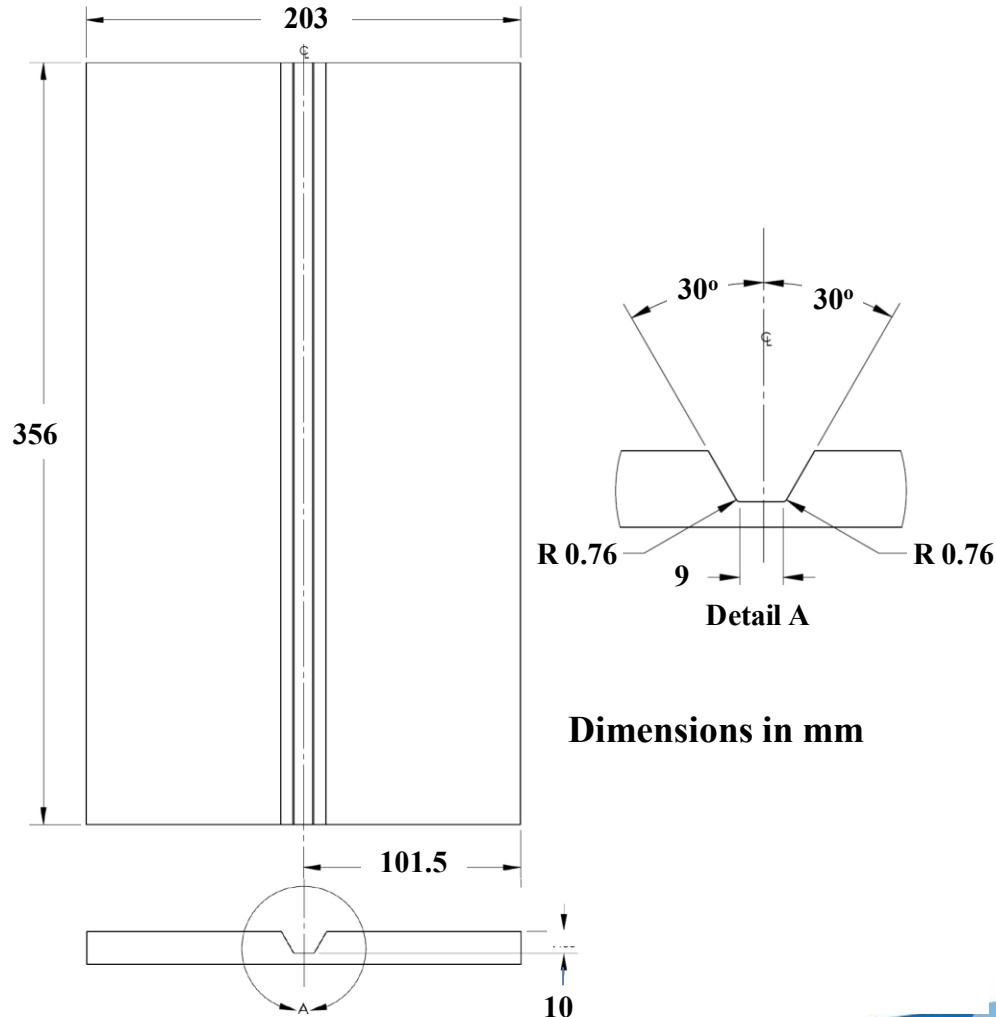
•Fabricated Pr

- Type 8 Surge No
- Purpose: Prototy
- conditions. Valida

Phase

Phase I: Scientific Weld Specimens

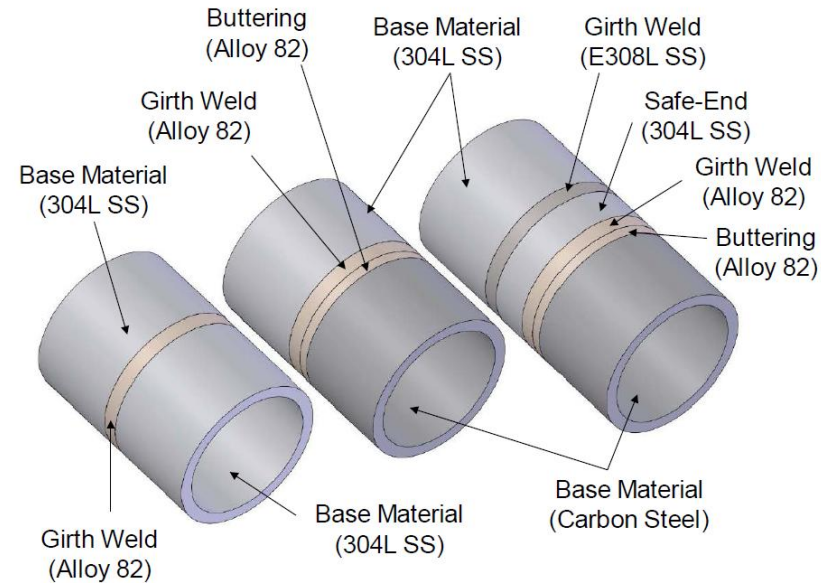
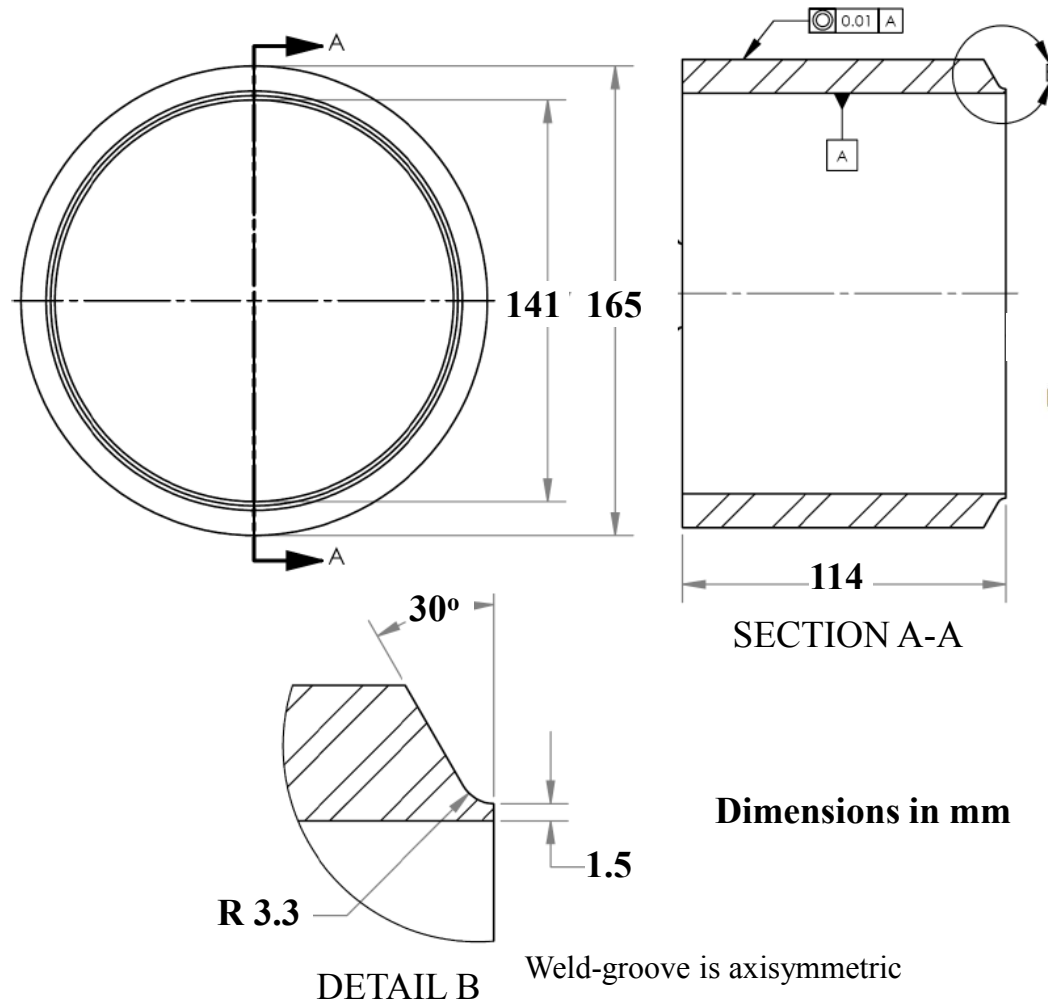
Plate Specimens



Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

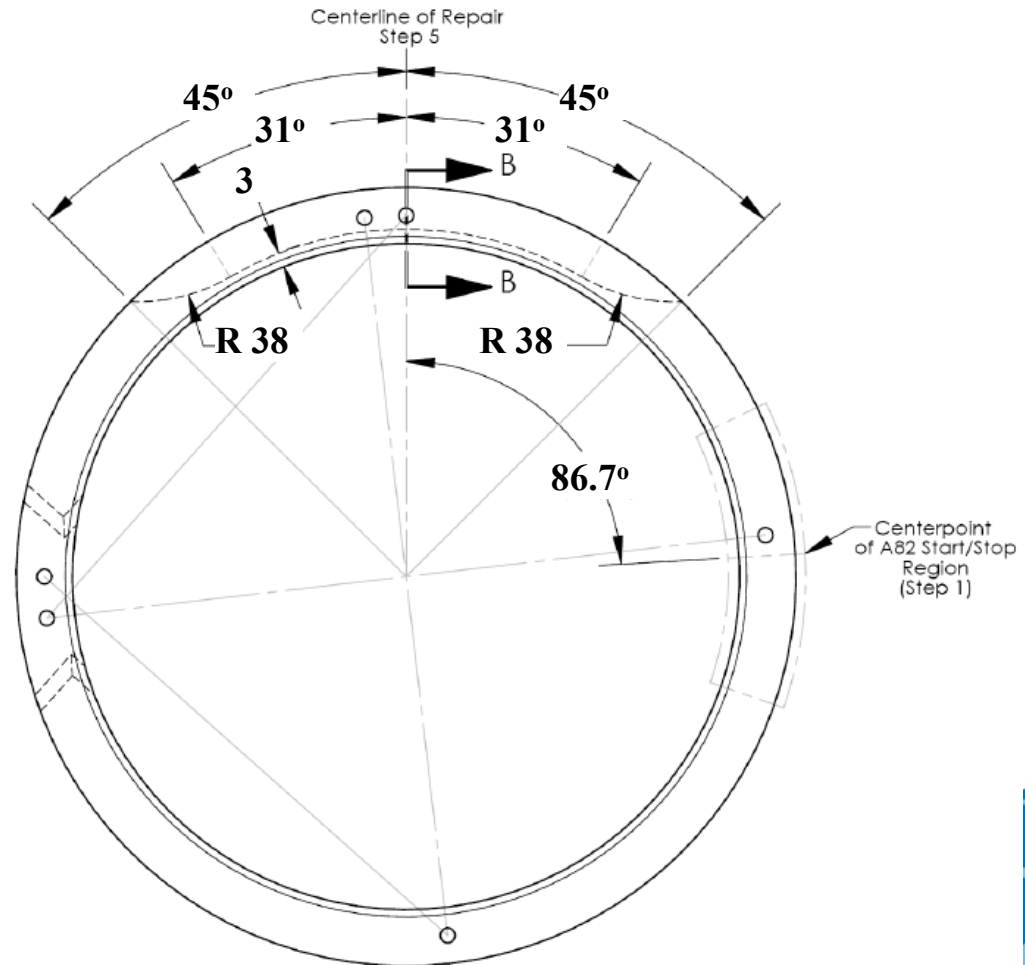
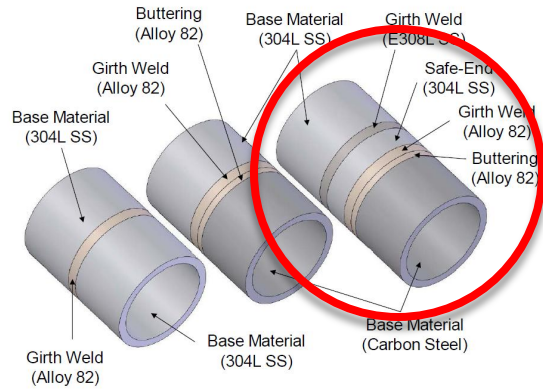
Cylindrical Specimens



Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

Weld Repair

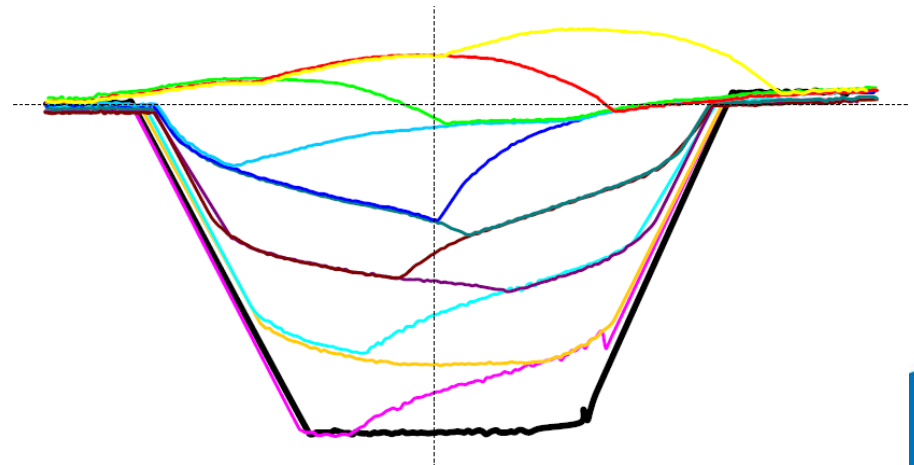
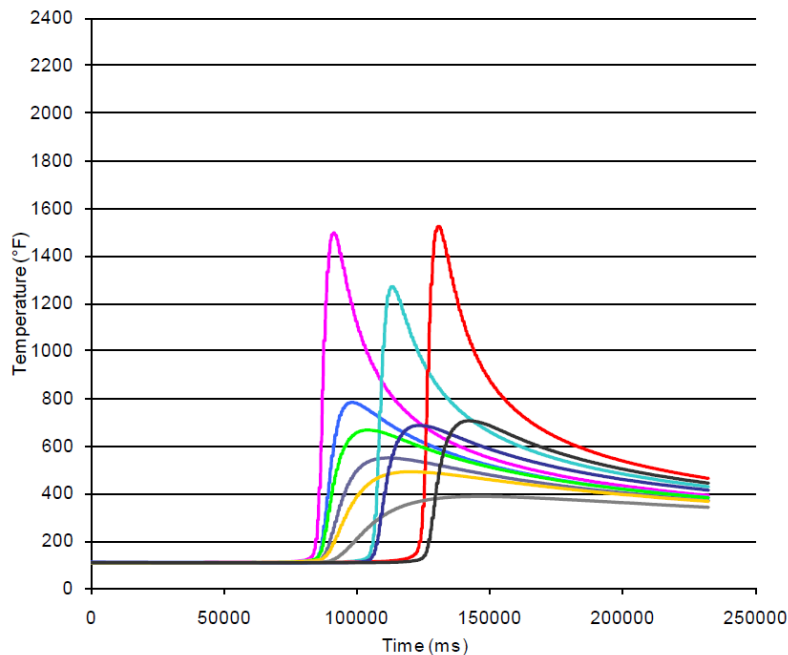


Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

In-Process Characterization

- Thermocouples were spot welded on the specimens to characterize temperature history at different locations
- Laser profilometer was used to measure individual weld beads

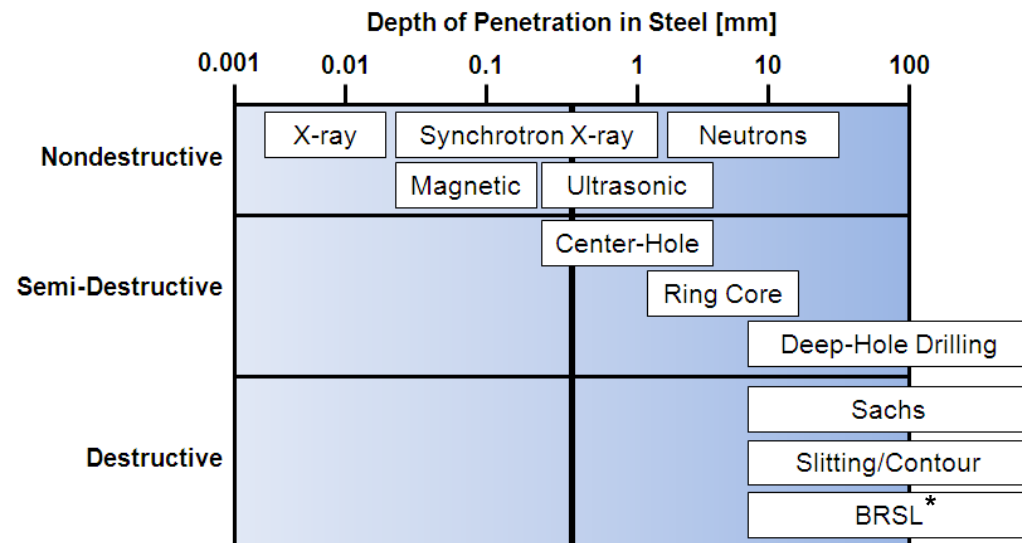


Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

WRS Measurement Techniques

- Neutron diffraction - Oak Ridge National Laboratory
- Contour - Hill Engineering
- X-ray diffraction - TEC
- Surface Hole Drilling - LTI
- Deep Hole Drilling - VEQTER
- Ring-Core - LTI
- Slitting - Hill Engineering



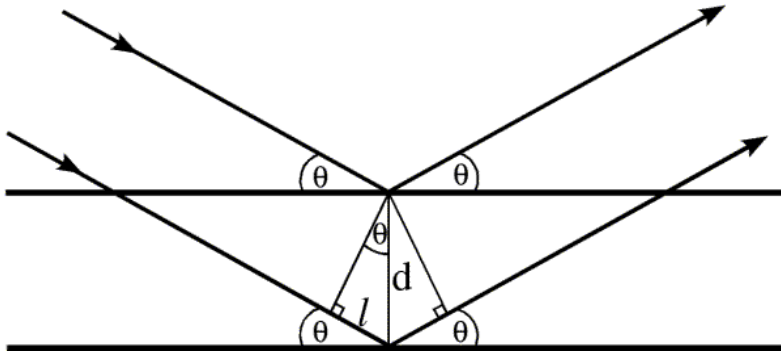
Source: Vecor, Ltd.

* Block Removal and Surface Layering

Phase I: Scientific Weld Specimens

Diffraction Techniques

- Measurement of lattice spacing, based upon the position of diffraction peaks
- Relies upon proper measurement of reference lattice spacing
- X-ray: surface, neutron: bulk



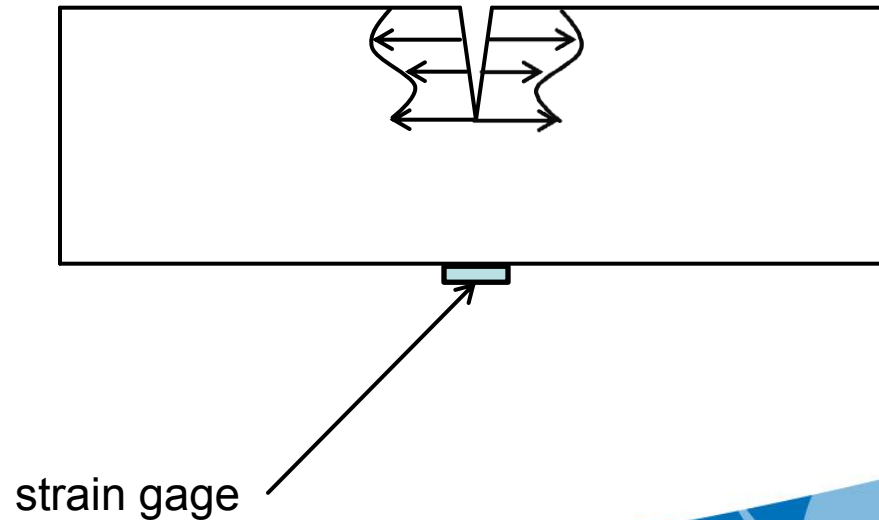
$$\varepsilon_{ii}^{hkl} = \frac{d_{hkl} - d_{hkl,0}}{d_{hkl,0}}$$

$$\sigma_{ii} = \frac{E_{hkl}}{(1 + \nu_{hkl})} \left[\varepsilon_{ii}^{hkl} + \frac{\nu_{hkl}}{(1 - 2\nu_{hkl})} (\varepsilon_{11}^{hkl} + \varepsilon_{22}^{hkl} + \varepsilon_{33}^{hkl}) \right]$$

Phase I: Scientific Weld Specimens

Strain-Relief Techniques

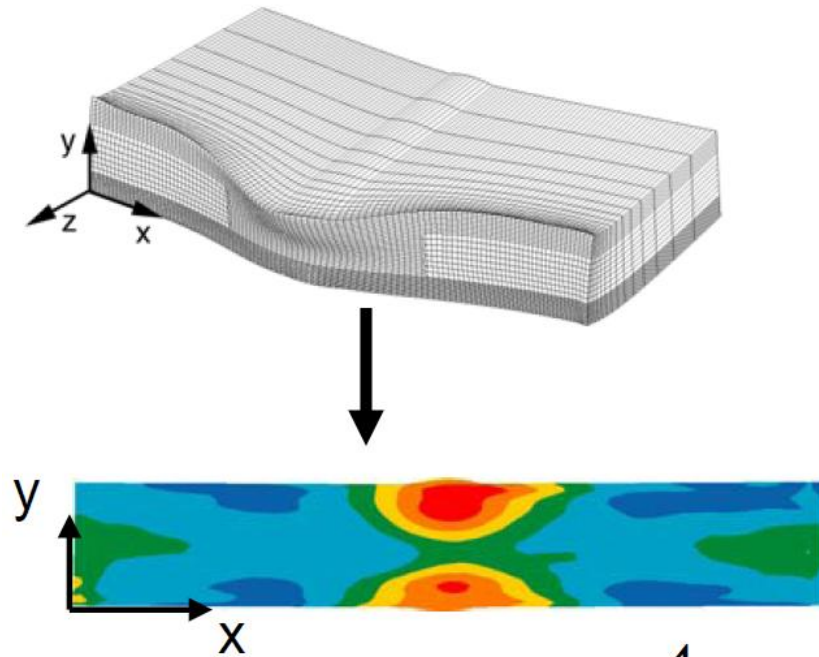
- Incremental slitting: near surface



Phase I: Scientific Weld Specimens

Strain-Relief Techniques

- Contour method: bulk

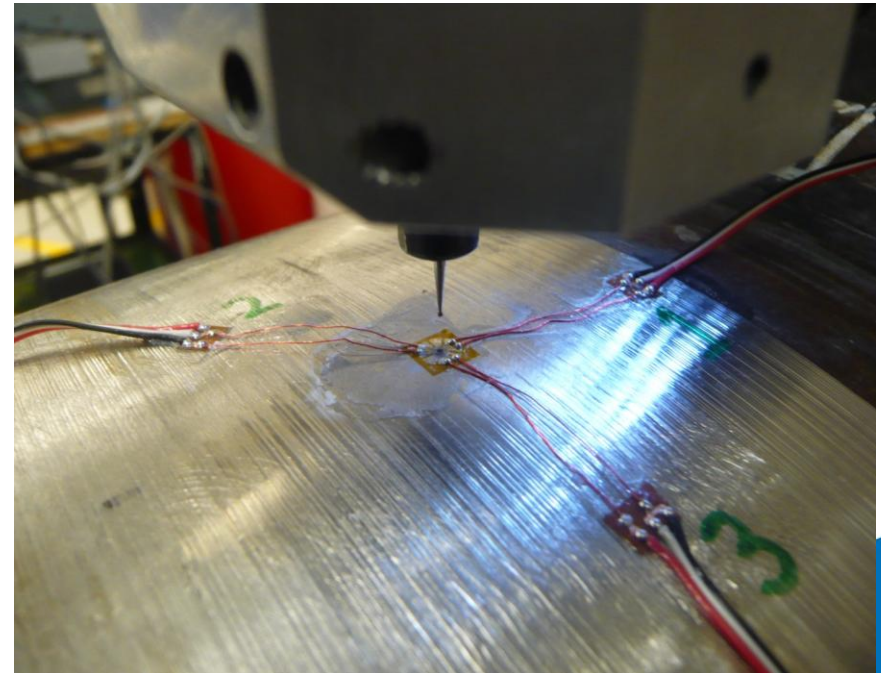
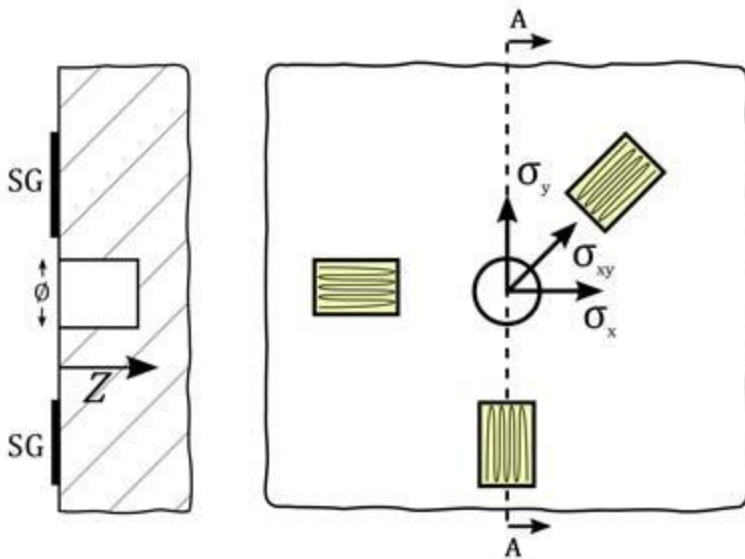


Source: Hill Engineering

Phase I: Scientific Weld Specimens

Strain-Relief Techniques

- Incremental center hole drilling: can be near-surface

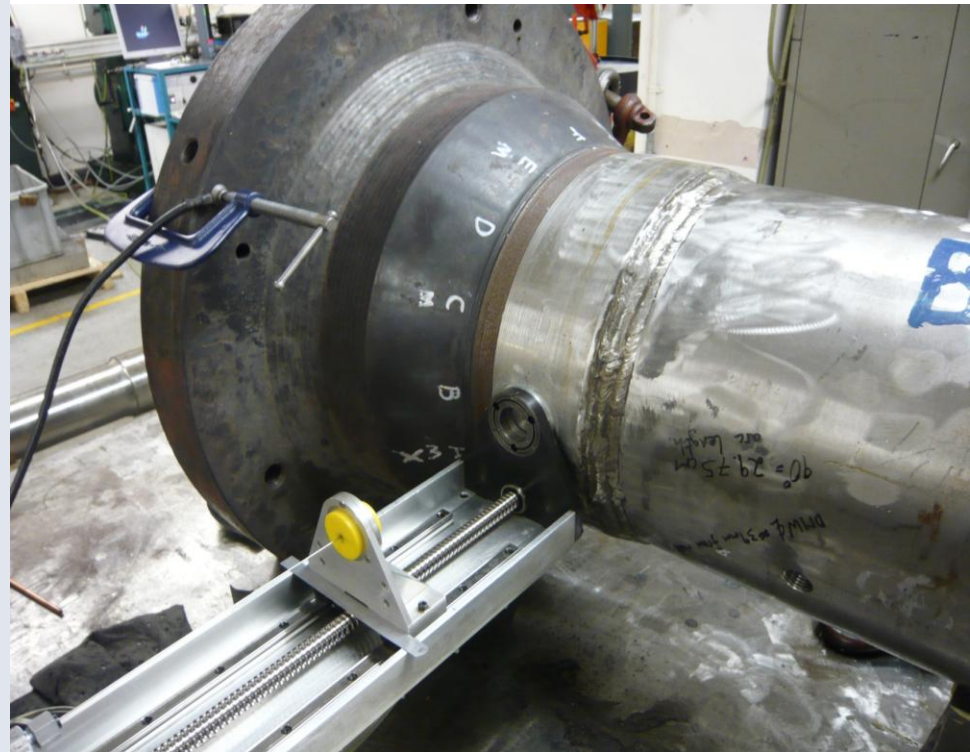
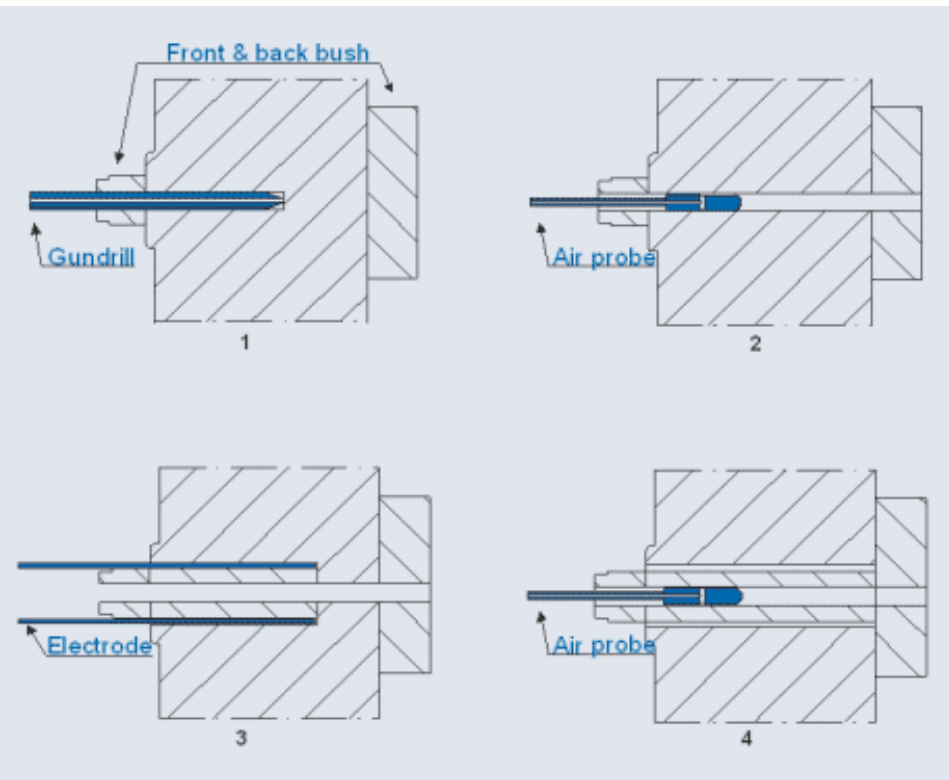


Source: VEQTER, Ltd.

Phase I: Scientific Weld Specimens

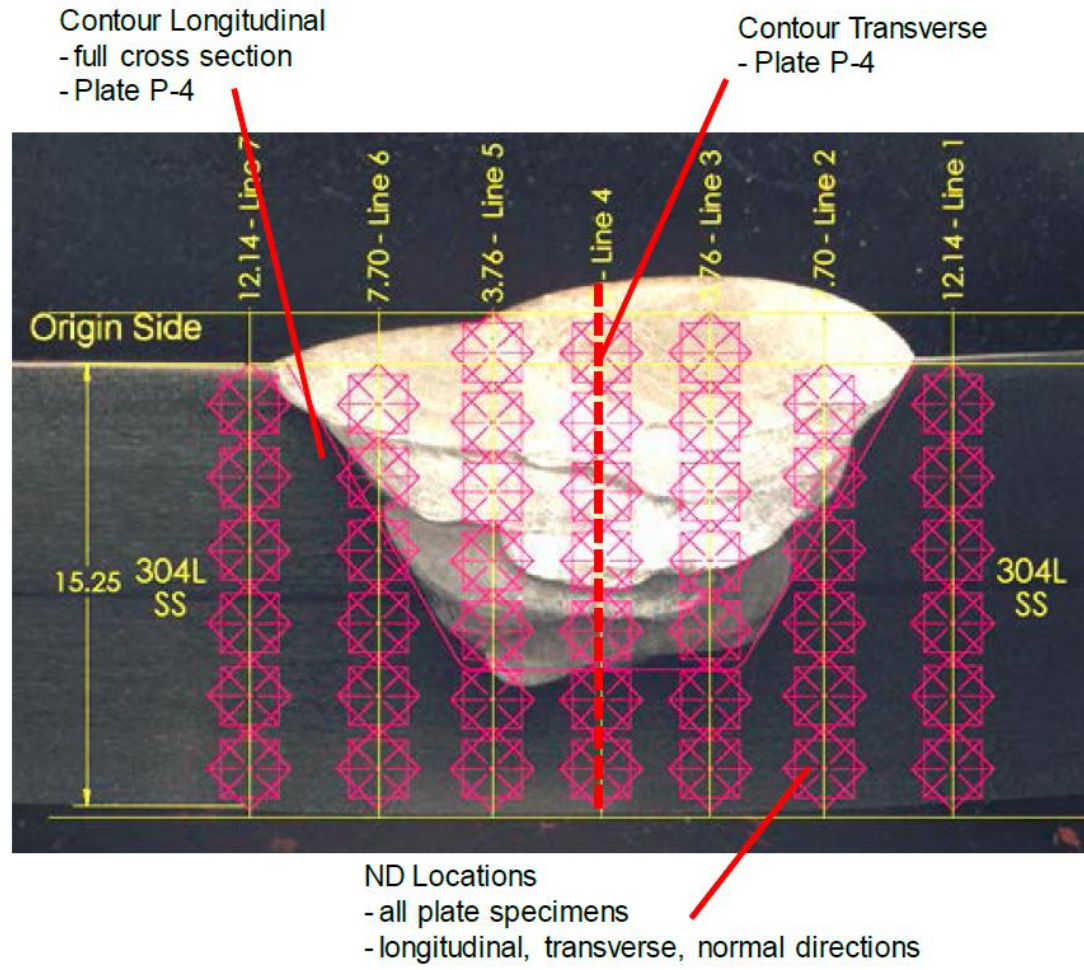
Strain-Relief Techniques

- Deep hole drilling: bulk



Phase I: Scientific Weld Specimens

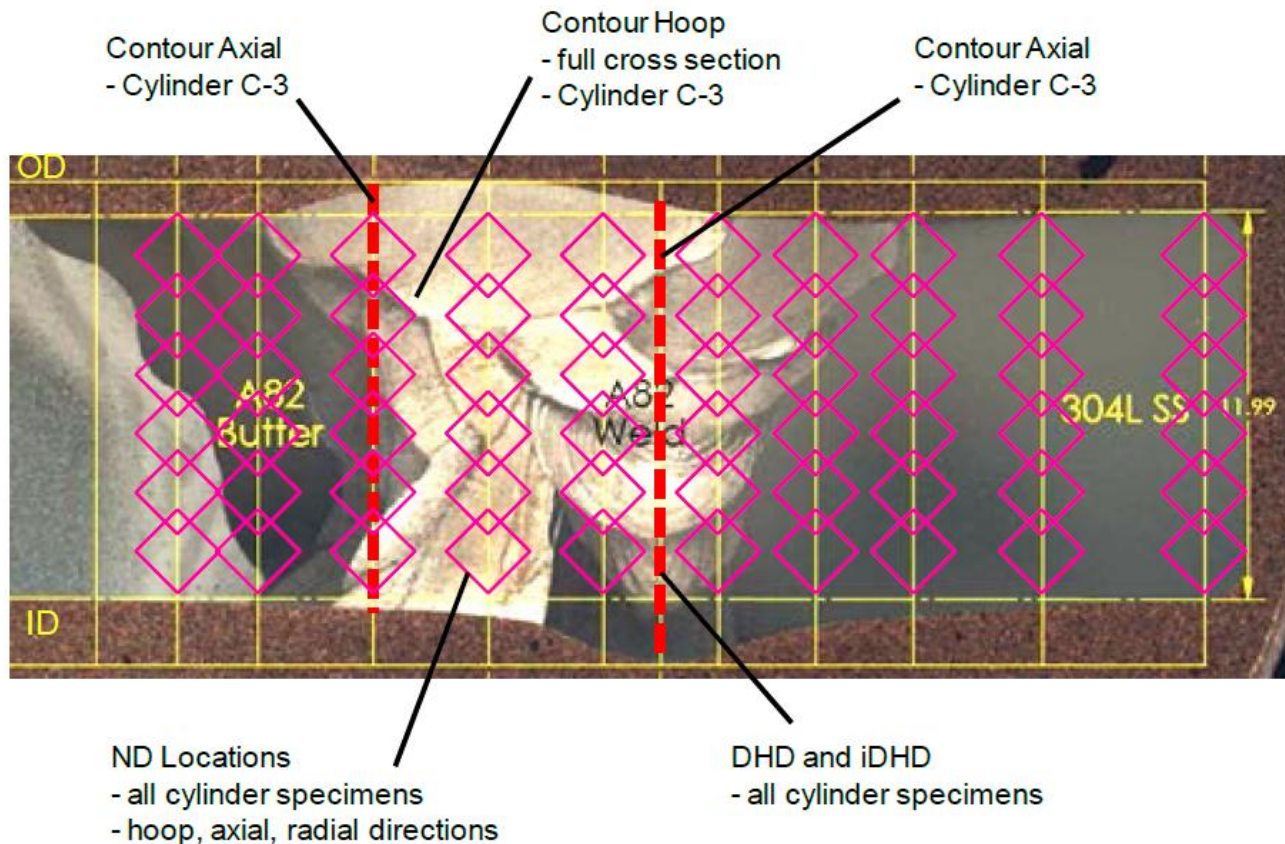
Measurement Summary: Plate Specimens



Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

Measurement Summary: Cylinder Specimens

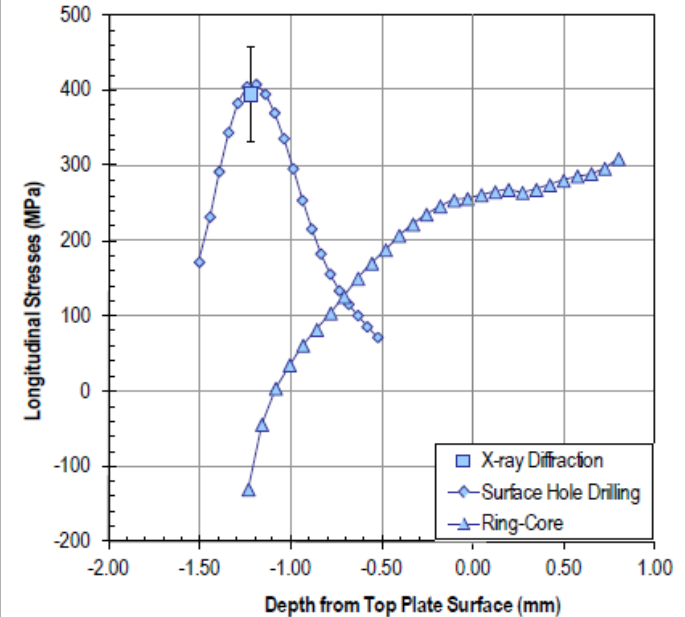
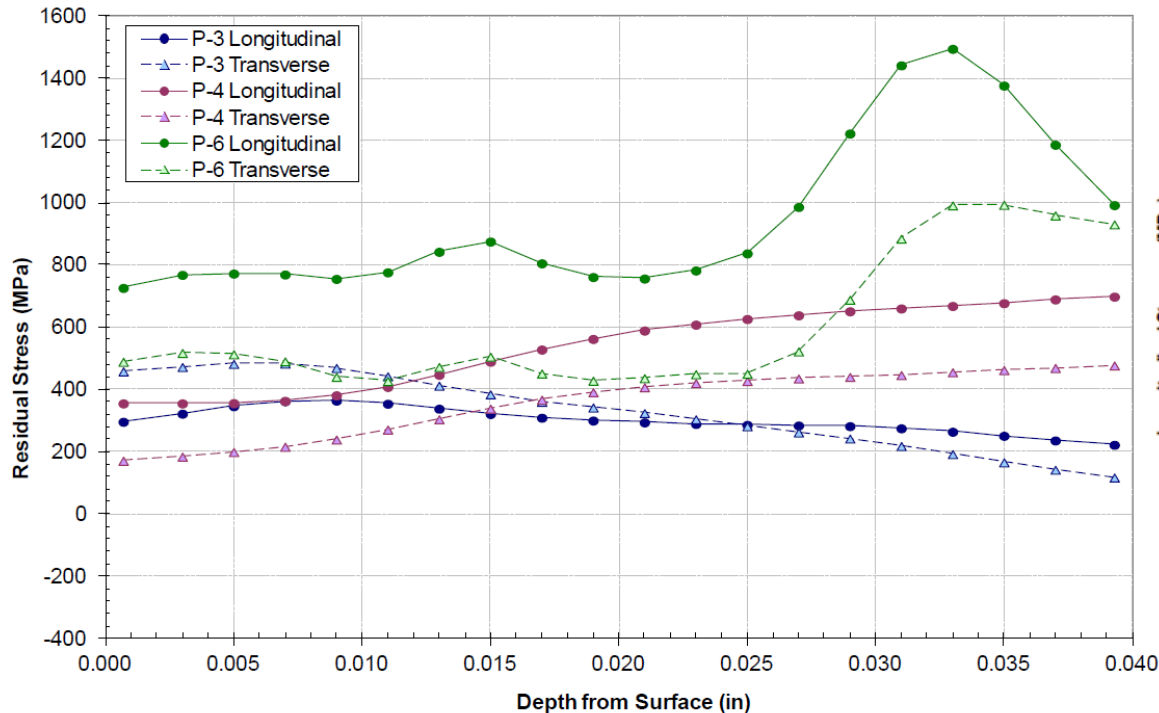


Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

Surface Stress Measurement Results

Hole-Drilling Residual Stress Results



- Unrealistically large values: e.g., 1500 MPa
- Independent techniques did not compare well with each other

Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

Surface Stress Measurement Results

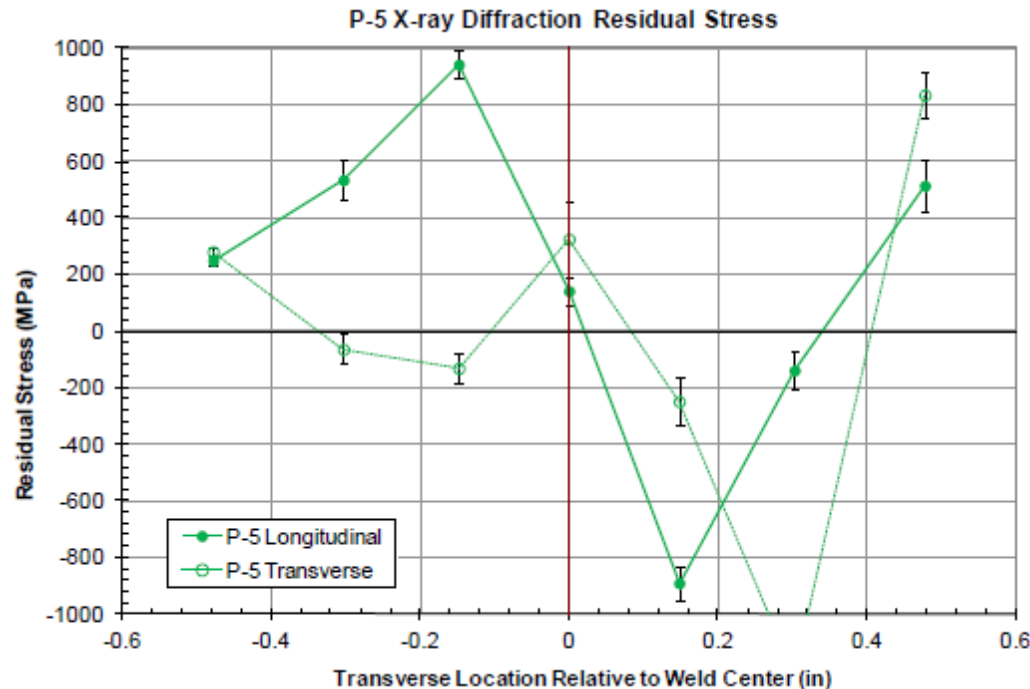


Plate Specimen

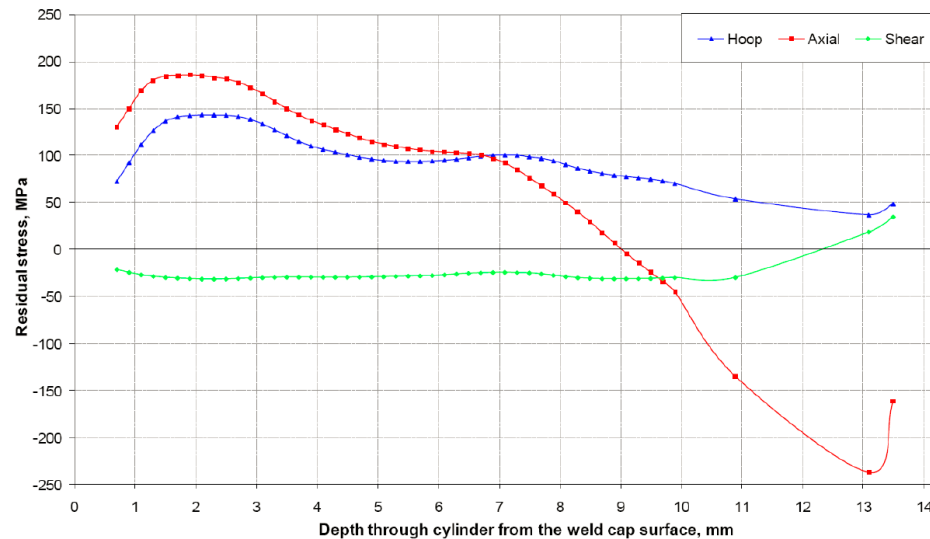
- X-ray diffraction showed large fluctuations in the data: e.g., from 950 to -950 MPa
- Data is asymmetric for a similar metal weld

Source: MRP-316, EPRI, 2011

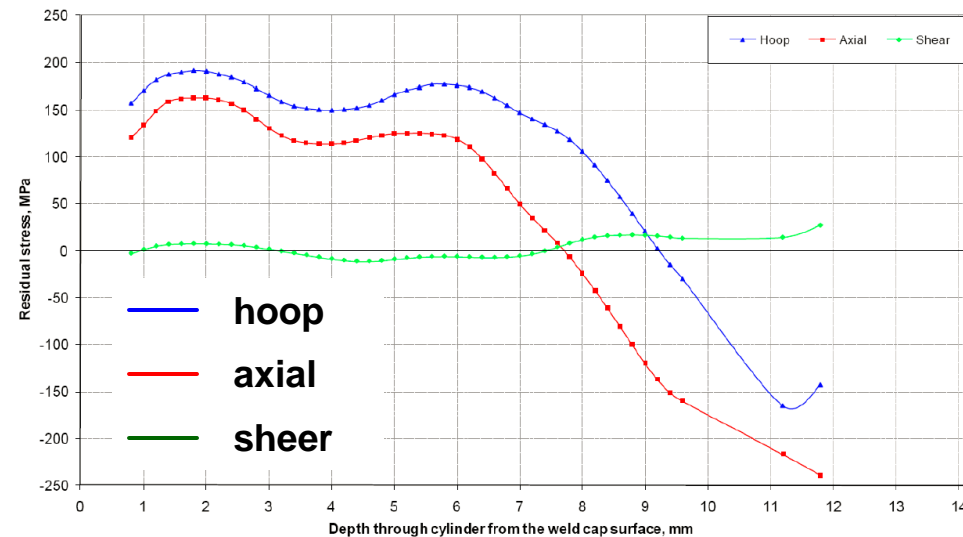
Phase I: Scientific Weld Specimens

Bulk Stress Measurement Results: Deep Hole Drilling

Weld Centerline



Repair Weld Centerline



Cylinder Specimen

- Smooth trends and reasonable magnitudes: e.g., -200 to 200 MPa
- Repair weld significantly affected the hoop stress

Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

Bulk Stress Measurement Results: Contour

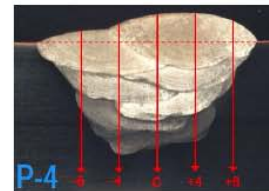
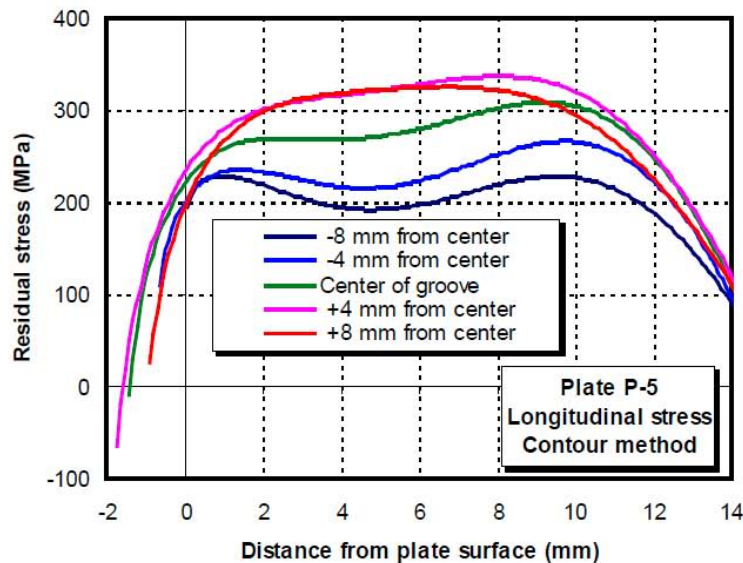
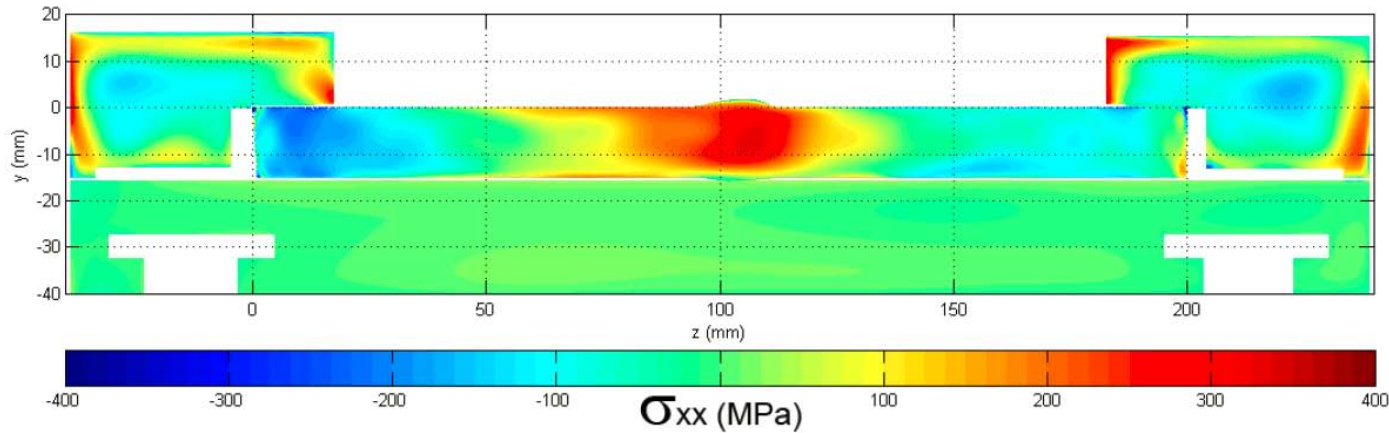
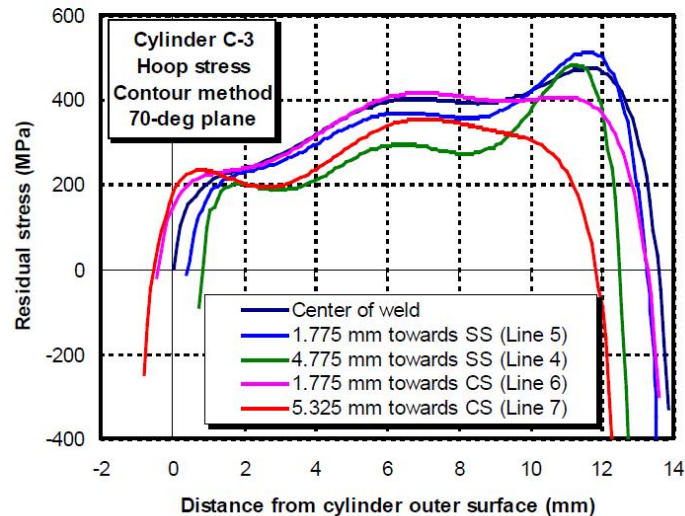
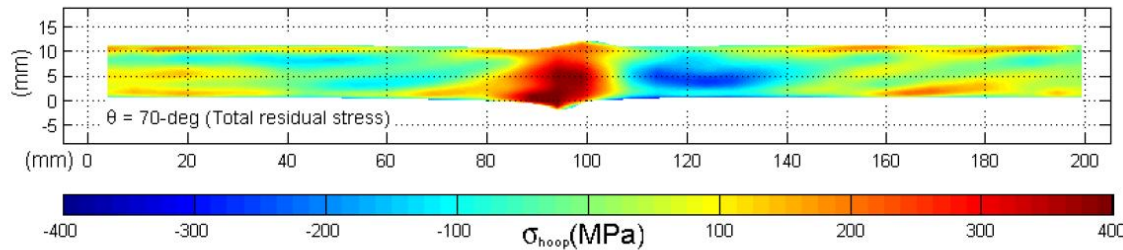


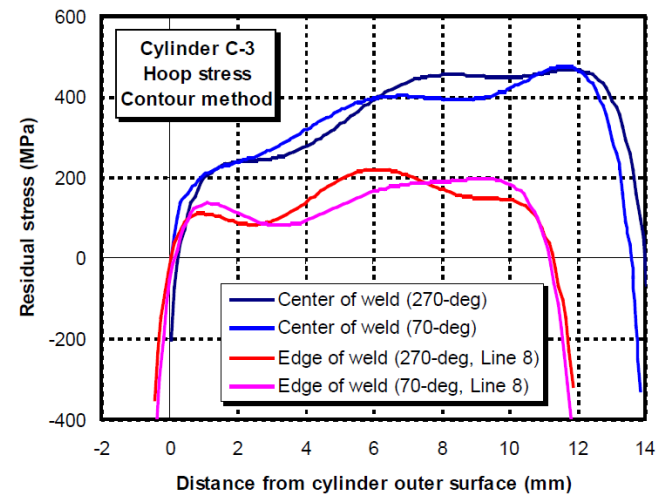
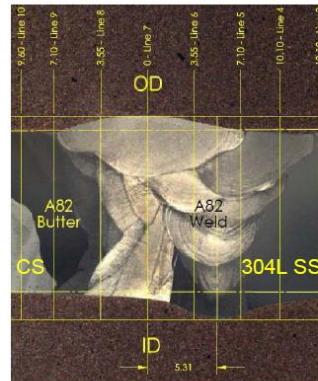
Plate Specimen

Phase I: Scientific Weld Specimens

Bulk Stress Measurement Results: Contour



Ring Specimen

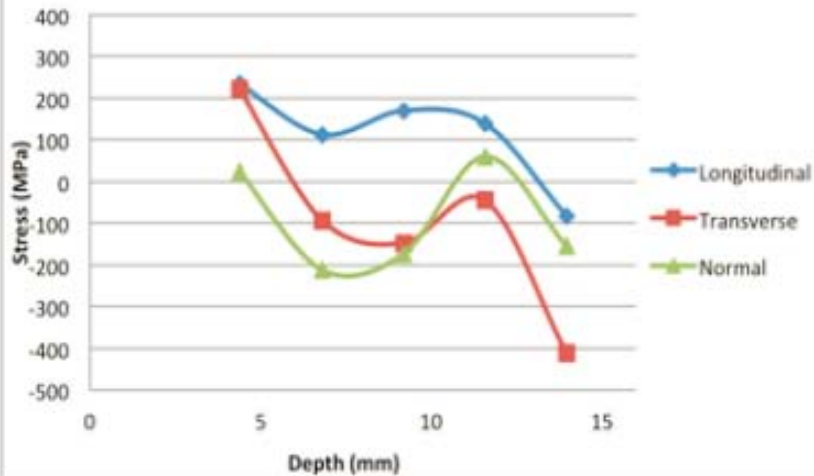


Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

Bulk Stress Measurement Results: Neutron Diffraction

P3 Stress Line 5 (MPa)



P3 Stress Line 3 (MPa)

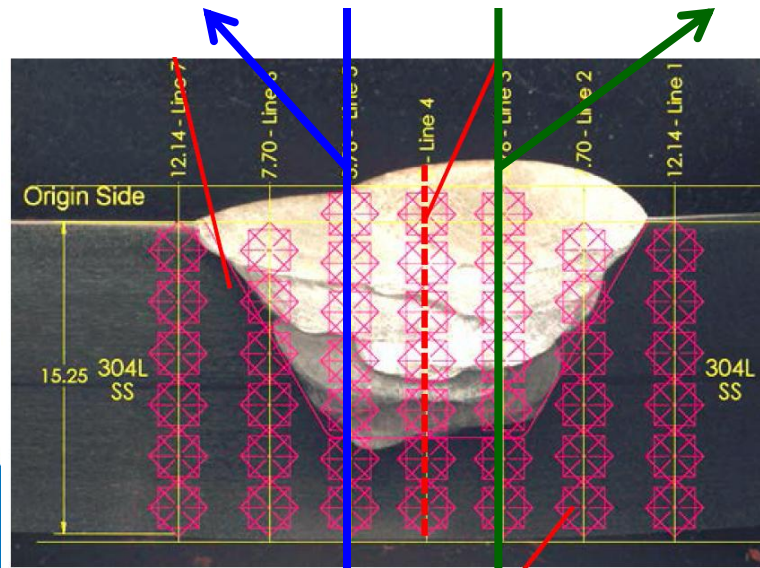
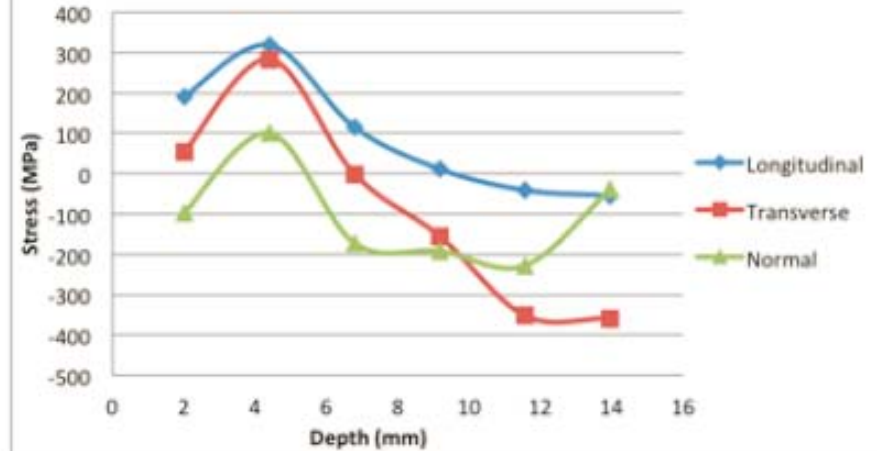


Plate Specimen

Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

Finite Element Modeling

- Sequentially-coupled thermal-mechanical model
 - Temperature distribution in space and time is calculated first
 - Stress distribution in space and time is calculated second
- 2-dimensional plane strain or axisymmetric
 - True nature of the moving heat source is not modeled
 - A given weld pass, with associated heat input, is applied along the entire surface of the part simultaneously
- Weld pass geometry approximated by laser profilometry results

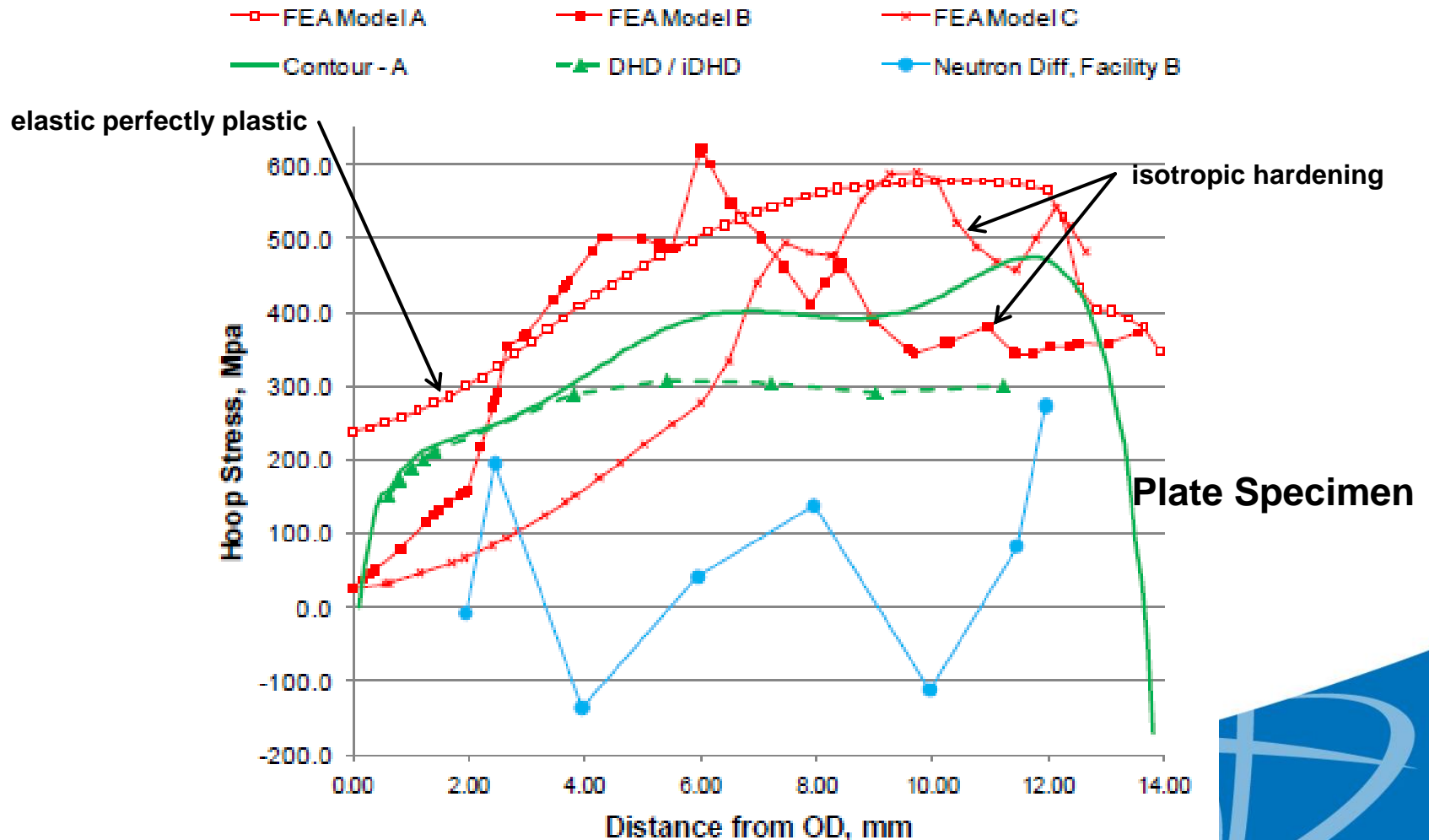
Phase I: Scientific Weld Specimens

Finite Element Modeling

- Thermal and mechanical properties as a function of temperature
 - e.g., specific heat, thermal conductivity, elastic modulus, thermal expansion
- Strain hardening law
 - Plastic deformation is expected
 - Elastic-perfectly plastic, isotropic hardening, kinematic hardening, mixed isotropic-kinematic hardening
- Heat input model
 - Goldak
 - “Tuned” to match the thermocouple measurements

Phase I: Scientific Weld Specimens

Model-Measurement Comparison: More Work to Do



Phase I: Scientific Weld Specimens

Data from a Pulsed Neutron Source

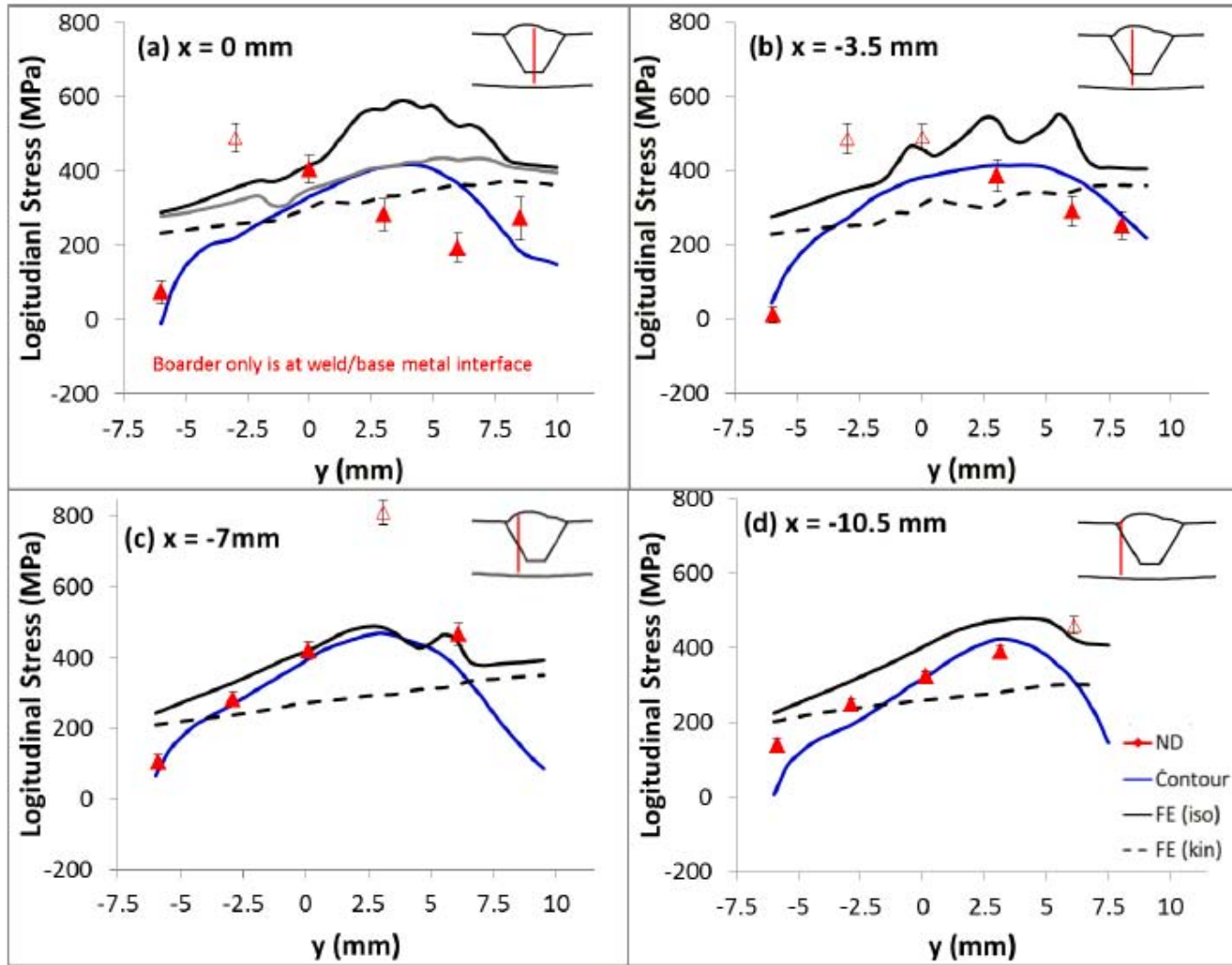


Plate Specimen

Phase I: Scientific Weld Specimens

Measurement Summary

- X-ray and neutron diffraction
 - d_o varies spatially because of chemical concentration gradients near the weld
 - Texture and grain size effects
 - Less confidence in diffraction-based results
 - Attenuation of the beam can be an issue for thick components
- Strain relief
 - Near-surface results did not appear reasonable
 - For bulk measurements, less experimental difficulties than diffraction

Phase I: Scientific Weld Specimens

Conclusions

- Phase 1 of the program focused on simple weld geometries in order to develop measurement and modeling techniques
- Near-surface stress is experimentally problematic
- In general, mechanical strain relief techniques seemed most reliable
- Agreement between models and experiment seems feasible
- Modeling uncertainty is possible: hardening law

Outline

- Overview
- Phase I Work
- **Phase II Work**
- Phase III Work
- Phase IV Work
- Conclusions

Phase II: Fabricated Prototype Nozzles

Overview

- Full-scale mockups
 - Two mockups: Only Phase IIa discussed here
 - Fabricated under controlled conditions
- Finite Element Round Robin
 - Double-blind: i.e., modelers did not have access to the measurement data
 - Obtain modeling results from a community of independent modelers
- Objectives
 - To validate WRS modeling with experiment
 - To assess WRS modeling uncertainty

ic Weld Specimens

A: Restrained Plates (QTY 4)

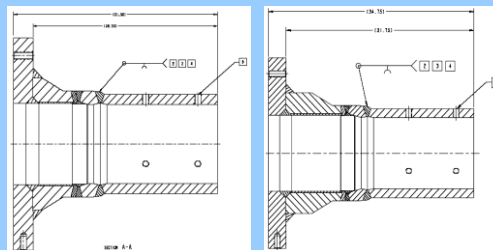
B: Small Cylinders (QTY 4)

Develop FE models.

Phase 2 - NRC

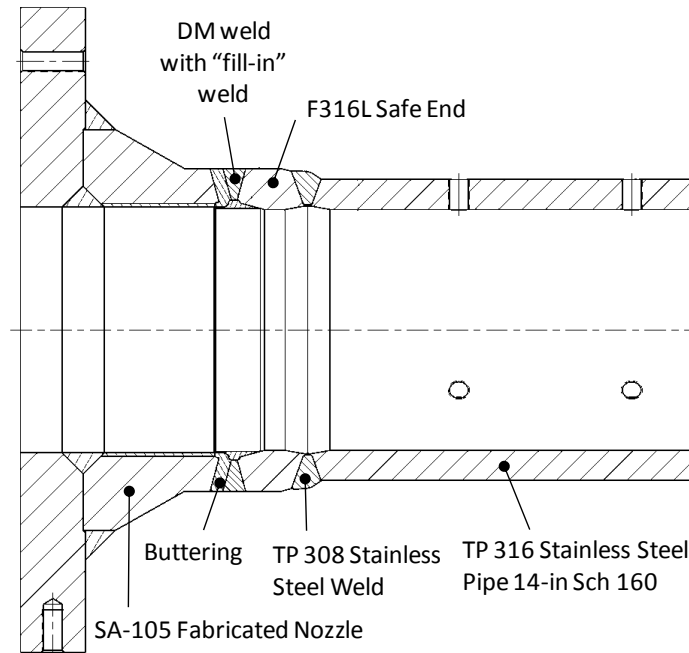
•Fabricated Prototypic Nozzles

- Type 8 Surge Nozzles (QTY 2)
- Purpose: Prototypic scale under controlled conditions. Validate FE models.



Phase II: Fabricated Prototype Nozzles

Mockup Fabrication

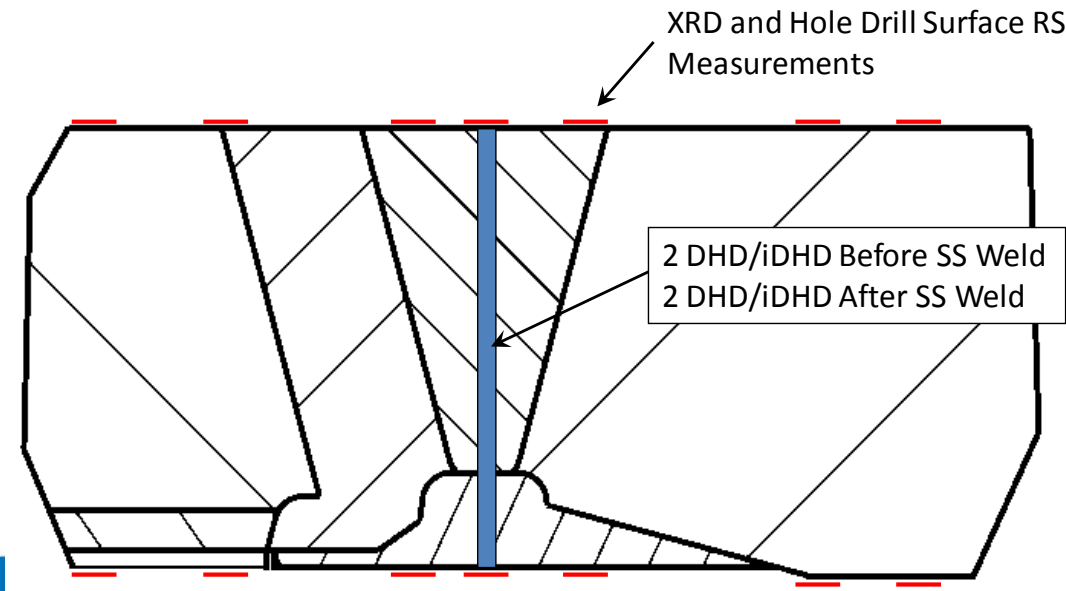


- Pressurizer surge nozzle
- Welding performed by automated gas tungsten arc welding
- Thermocouple and laser profilometry readings
- Rough dimensions: 31" overall length, 11" inner diameter

Phase II: Fabricated Prototype Nozzles

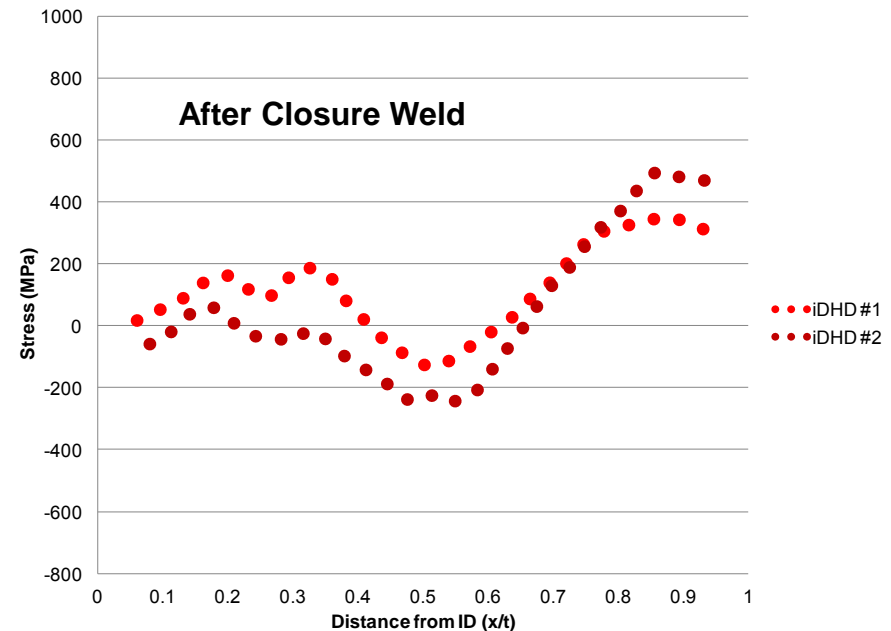
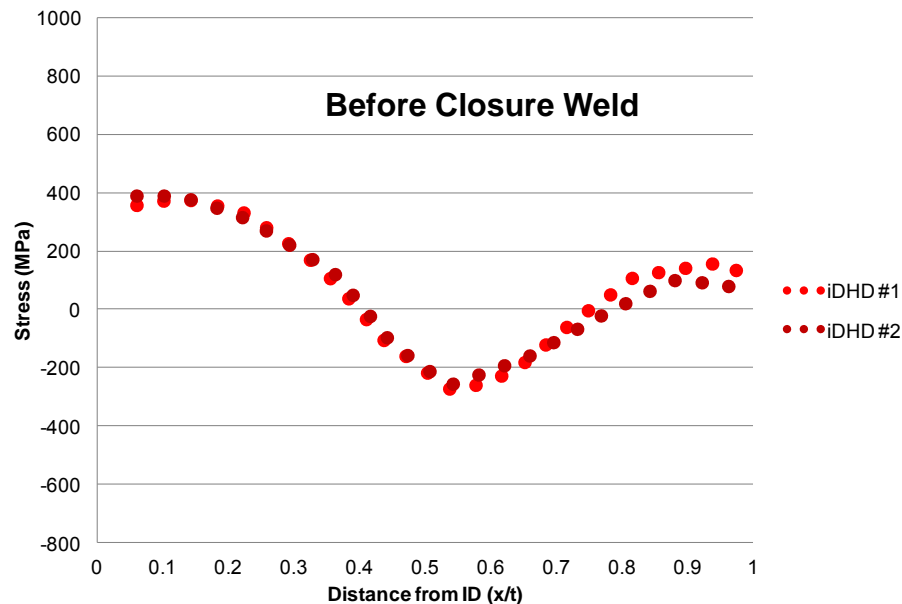
WRS Measurement

- Incremental deep hole and deep hole drilling - bulk
- Measurements taken before and after safe end to pipe weld was complete
 - Safe end to pipe weld can affect the stress field at the dissimilar metal weld



Phase II: Fabricated Prototype Nozzles

Stainless Steel Closure Weld Effect: Deep Hole Drilling



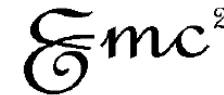
- Axial stresses shown here
- Safe end to pipe weld can potentially have a beneficial affect on inner diameter stress
- Safe end length can be an important parameter

Phase II: Fabricated Prototype Nozzles

Finite Element Round Robin

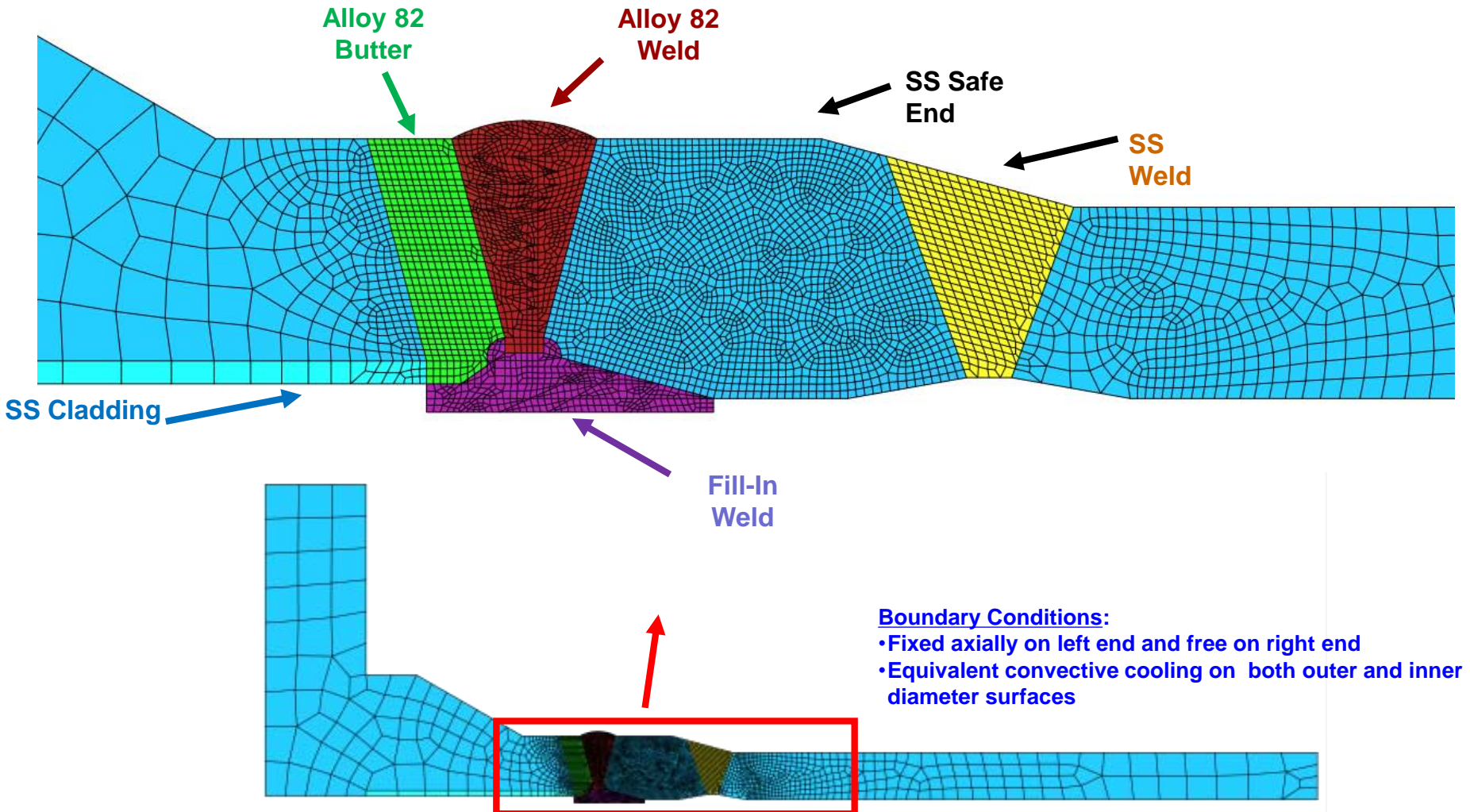


- ANSTO (Australia)
- AREVA (USA and EU)
- Battelle (USA)
- Dominion Engineering (USA)
- Goldak Technologies (Canada)
- ESI Group (USA)
- EMC² (USA)
- Inspecta Technology (EU)
- Institute of Nuclear Safety System (Japan)
- Osaka University (Japan)
- Rolls Royce (UK)
- Structural Integrity Associates (USA)
- Westinghouse Electric Company (USA)



Phase II: Fabricated Prototype Nozzles

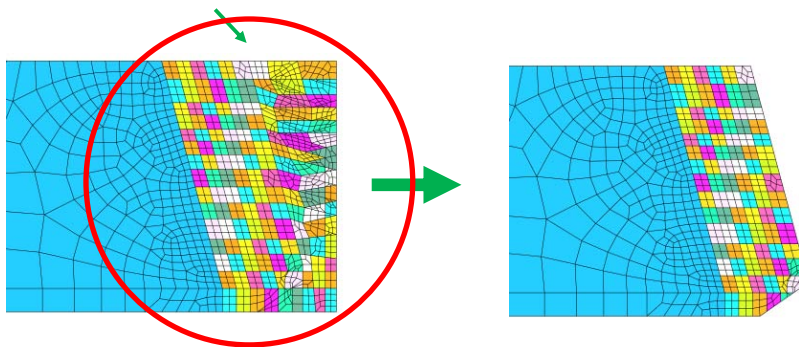
Example Model Geometry



Phase II: Fabricated Prototype Nozzles

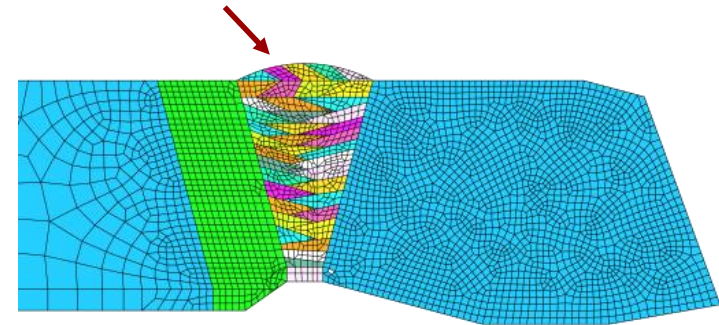
Example Model Geometry

Alloy 82
Butter
(137 Passes)

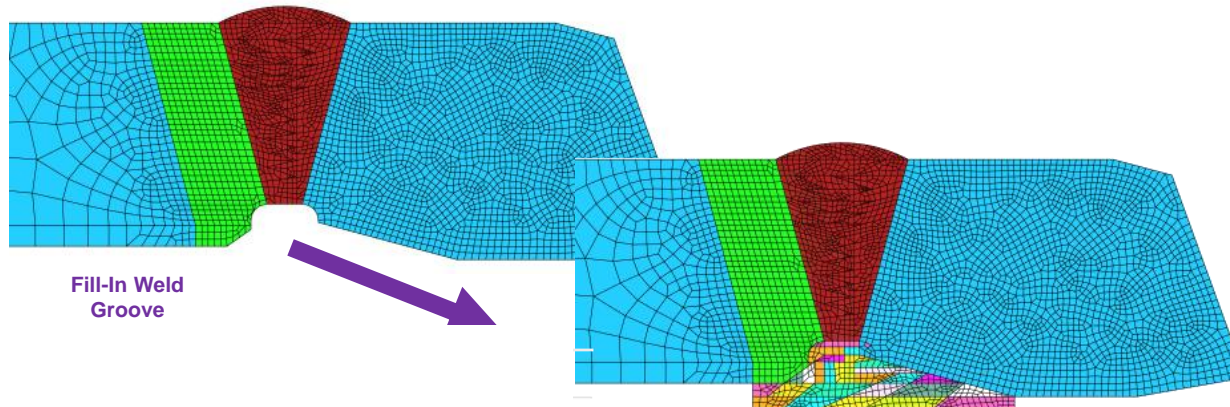


heat treatment

Alloy 82
Weld
(40 Passes)



Fill-In Weld
Groove



Alloy 82 Fill-In
Weld
(27 Passes)



Phase II: Fabricated Prototype Nozzles

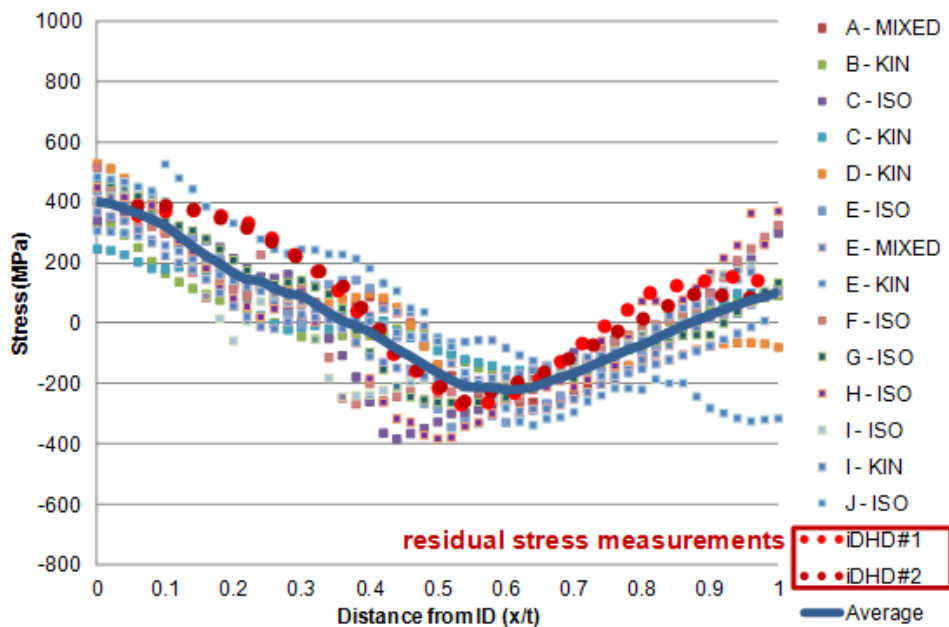
Analysis Stages: Can We Reduce Uncertainty?

- Postulated sources of uncertainty: welding heat input and material properties
- Three analysis stages
 - No thermocouple data or material property data supplied
 - Thermocouple data only supplied
 - Thermocouple and material property data supplied
- Models completed before and after the stainless steel closure weld

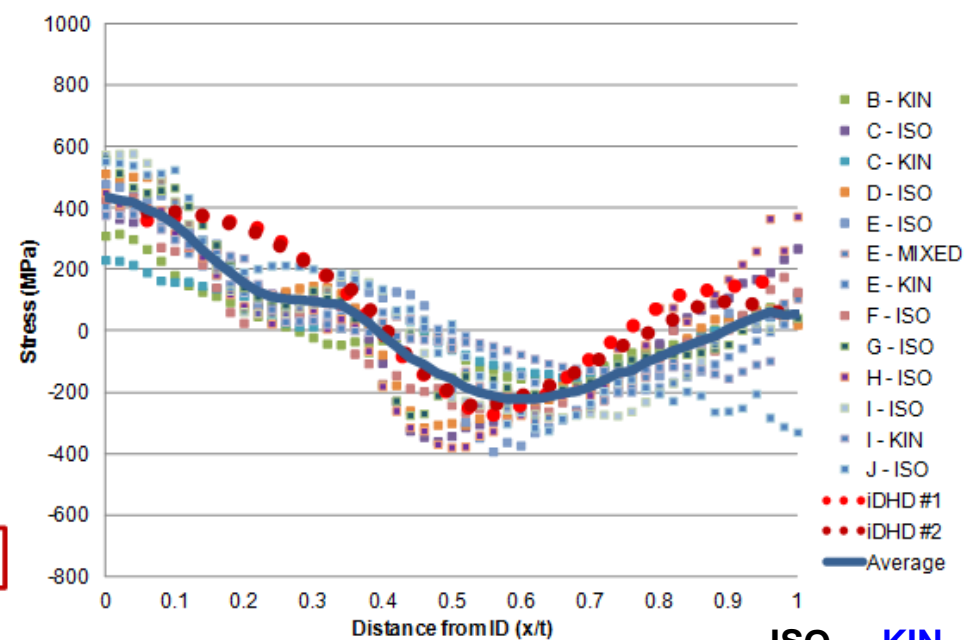
Phase II: Fabricated Prototype Nozzles

FEA Round Robin Results

Pre-stainless steel weld
No material properties
No thermal couple data

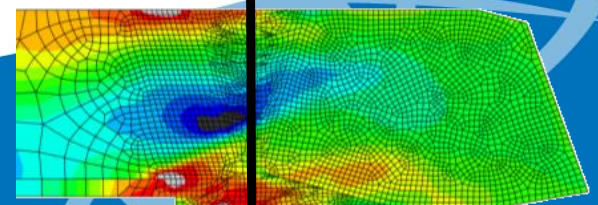


Pre-stainless steel weld
Supplied material properties
Supplied thermal couple data



- Axial stresses shown here
- Variety of hardening laws employed
- Modeling uncertainty is the same

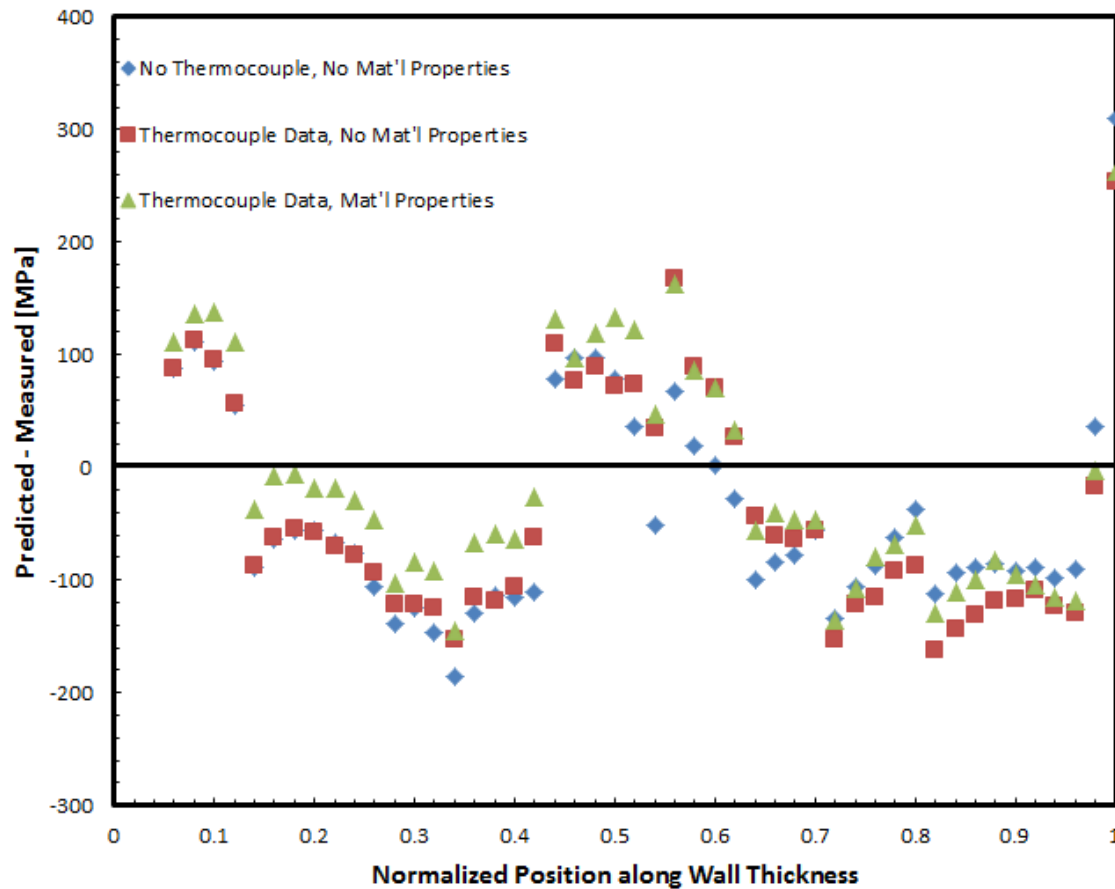
Axial Stress



Hoop Stress

Phase II: Fabricated Prototype Nozzles

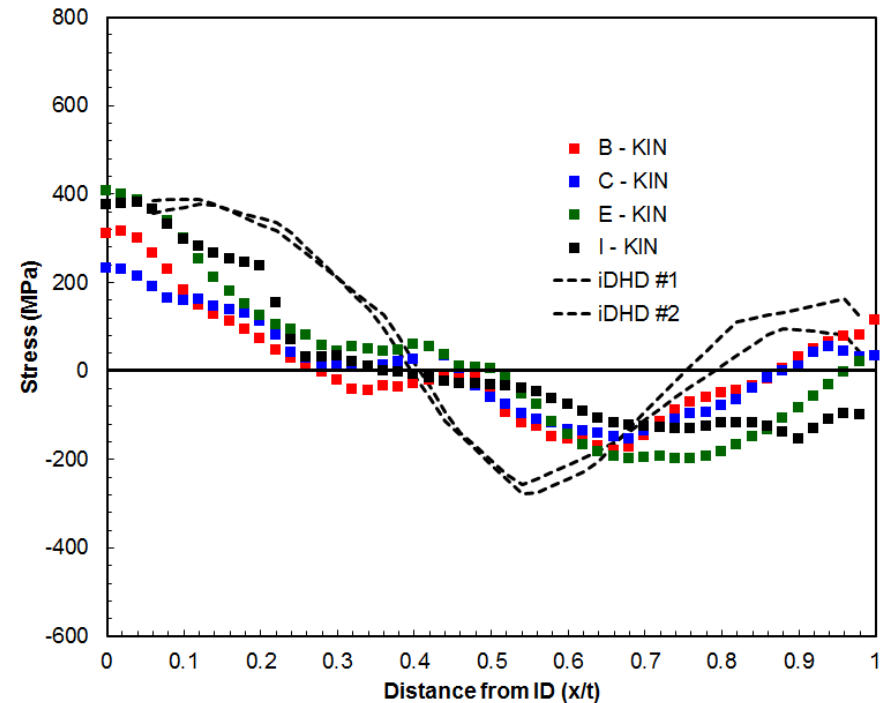
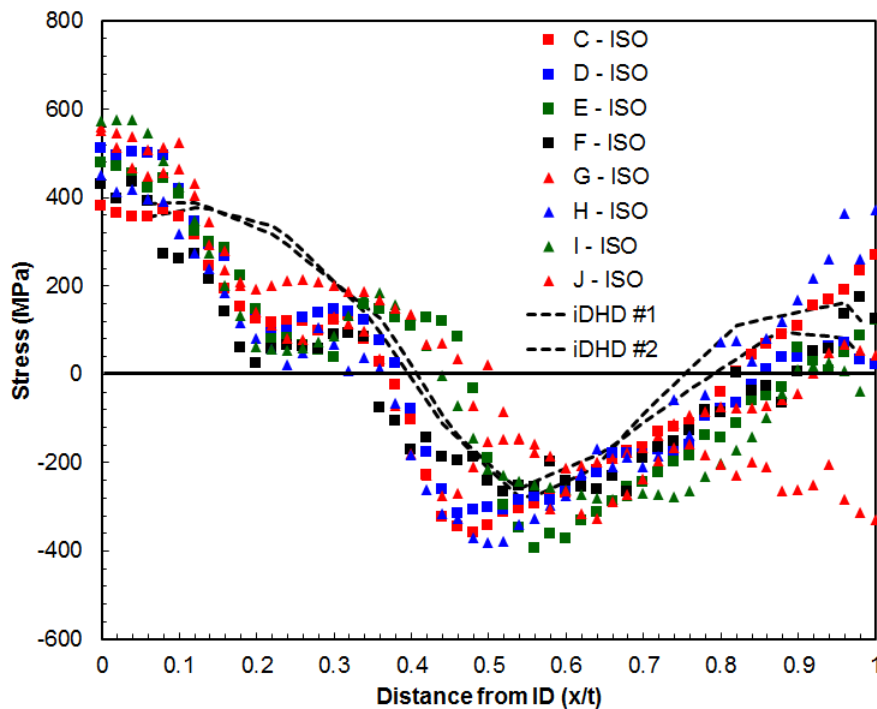
FEA Round Robin Results: Single Modeler



Hoop Stress
Pre-stainless steel weld
Supplied material properties
Supplied thermal couple data

Phase II: Fabricated Prototype Nozzles

FEA Round Robin Results: Separate Hardening Law

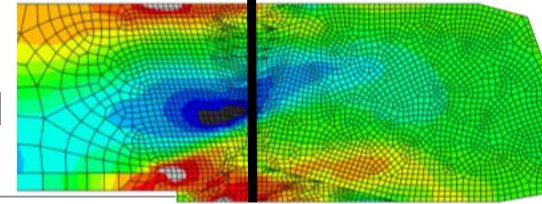


Axial Stress
Pre-stainless steel weld
Supplied material properties
Supplied thermal couple data 46

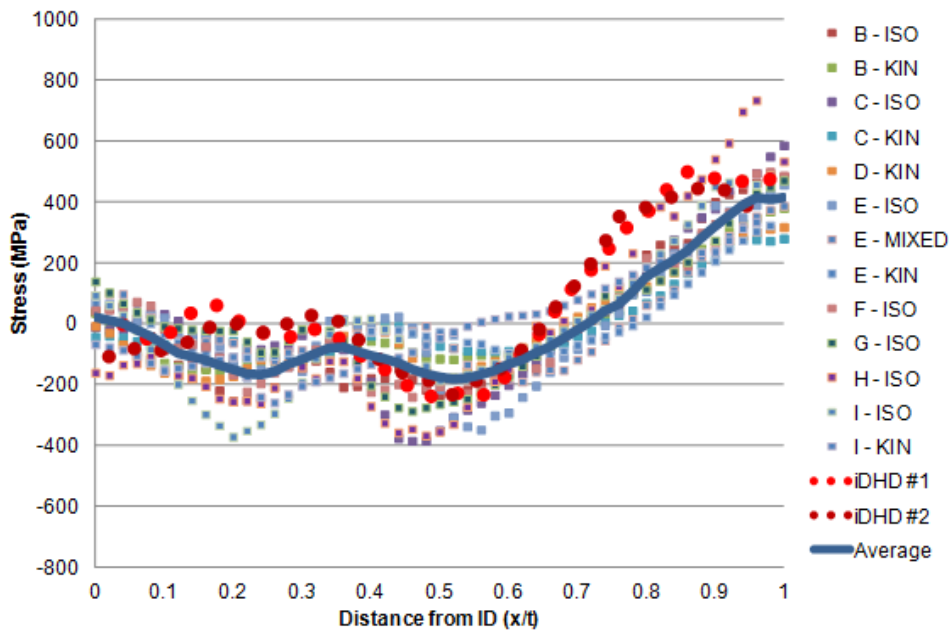
Phase II: Fabricated Prototype Nozzles

FEA Round Robin Results

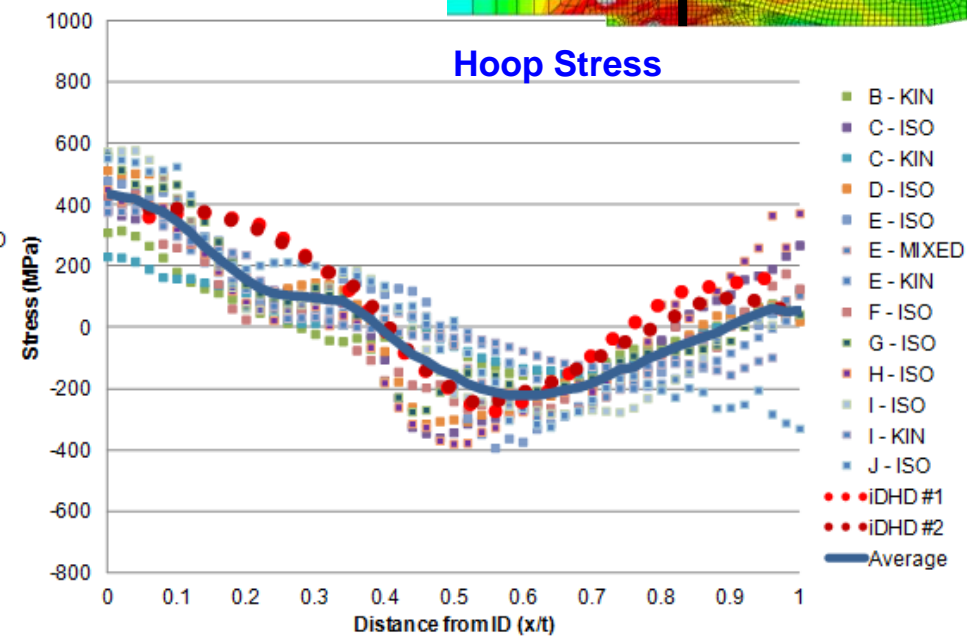
Axial Stress



Including stainless steel weld



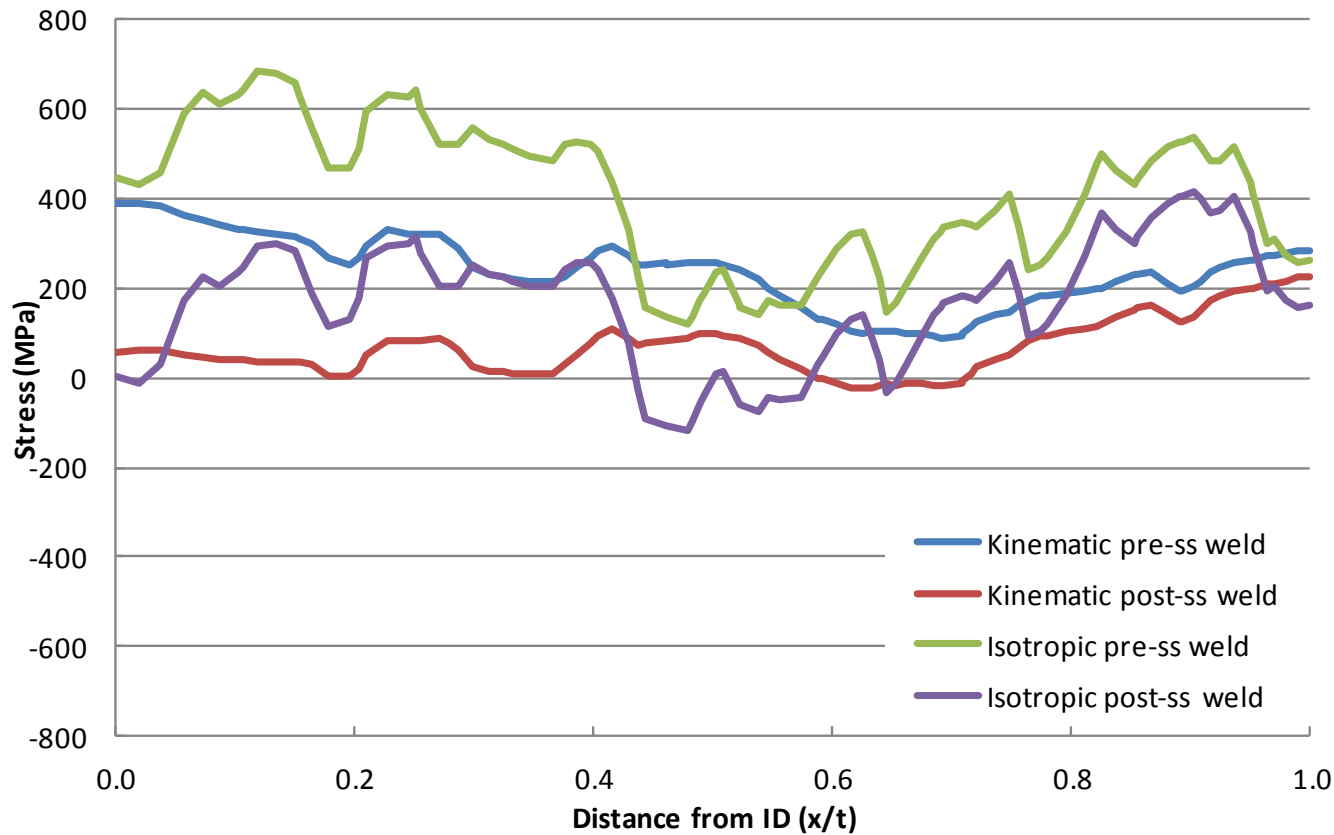
Pre-stainless steel weld



- Axial stresses shown here
- Models show beneficial affect of stainless steel weld for the welding geometry modeled here

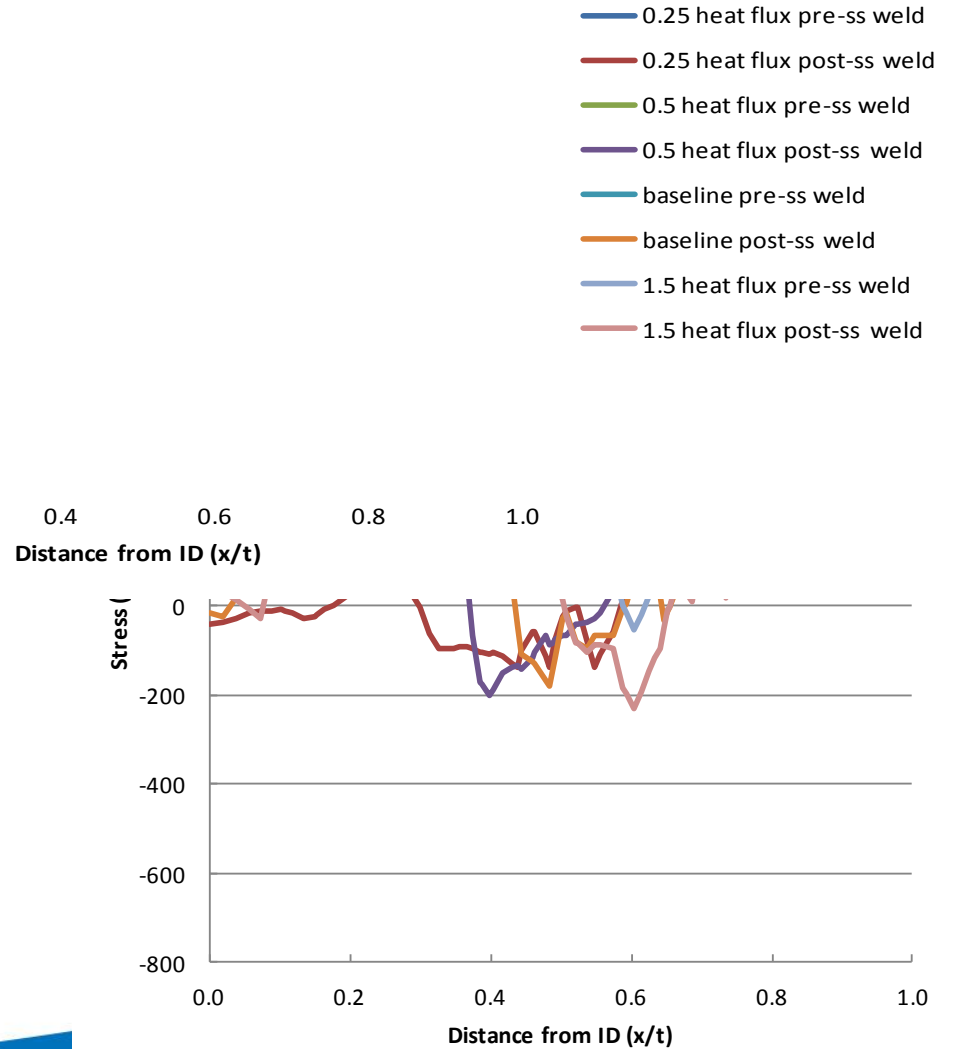
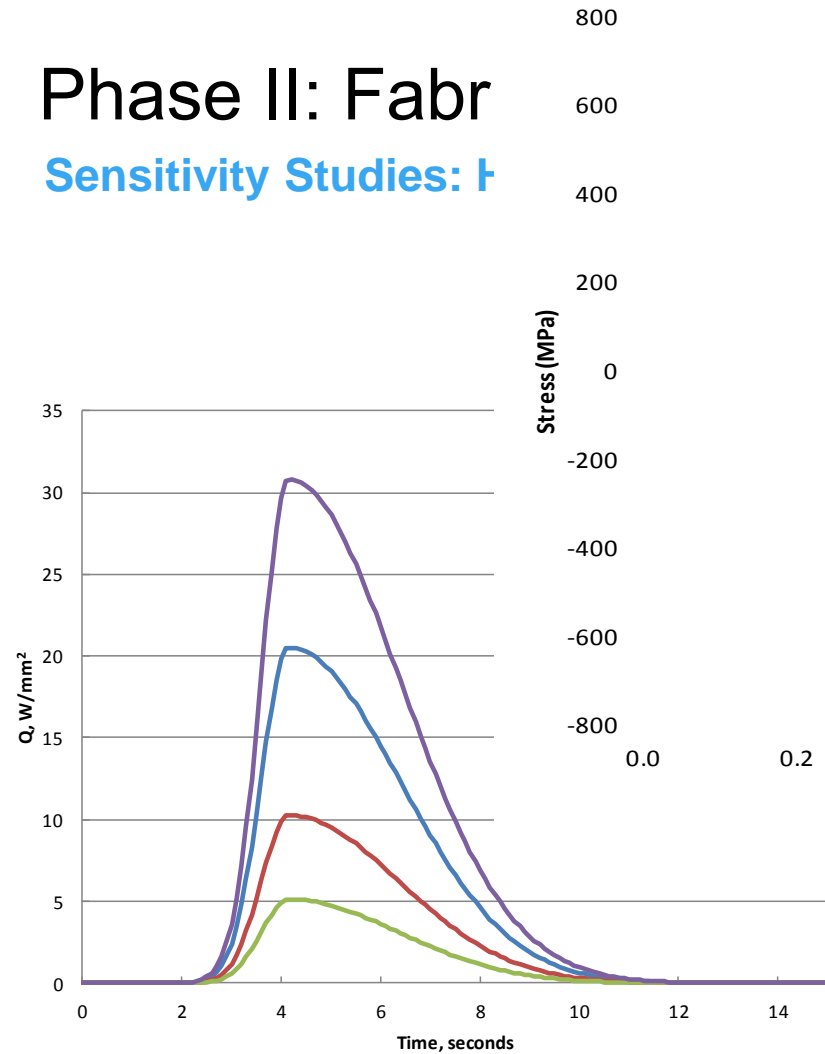
Phase II: Fabricated Prototype Nozzles

Sensitivity Studies: Hardening Law



Phase II: Fabr

Sensitivity Studies: I



Phase II: Fabricated Prototype Nozzles

Observations from Phase II Work

- While modeling and measurement results show reasonable agreement in magnitude and profile shape, there is significant model-to-model variability
- Providing thermocouple data and material property data did not decrease modeling uncertainty
- Weld uncertainty
 - Process sequence
 - Arc efficiency (may be reduced by thermal couple data)
 - Material properties
- Modeling uncertainty
 - Choice of hardening law (largest affect on Phase II models)
 - Mesh density, post processing

Outline

- Overview
- Phase I Work
- Phase II Work
- **Phase III Work**
- Phase IV Work
- Conclusions

Phase III: Cancelled Plant Nozzles

Overview

- Full-scale components
 - Actual pressurizer nozzles fabricated for intended service
- Finite Element Round Robin
 - Double-blind: i.e., modelers did not have access to measurement data
 - Obtain modeling results from a community of independent modelers
- Objectives
 - To validate WRS modeling with experiment
 - To assess WRS modeling uncertainty

•Scientific Weld Specimens

•Phase 1A: Restrained Plates (QTY 4)

•Phase 1B: Small Cylinders (QTY 4)

•Purpose: Develop FE models.

•Fabricated Prototypic Nozzles

•Type 8 Surge Nozzles (QTY 2)

•Purpose: Prototypic scale uniaxial conditions. Validate FE model

Phase 3 - EPRI

•Plant Components

•WNP-3 S&R PZR Nozzles (QTY 3)

•Purpose: Validate FE models.



•Plant Components

•WNP-3 CL Nozzle (QTY 1)

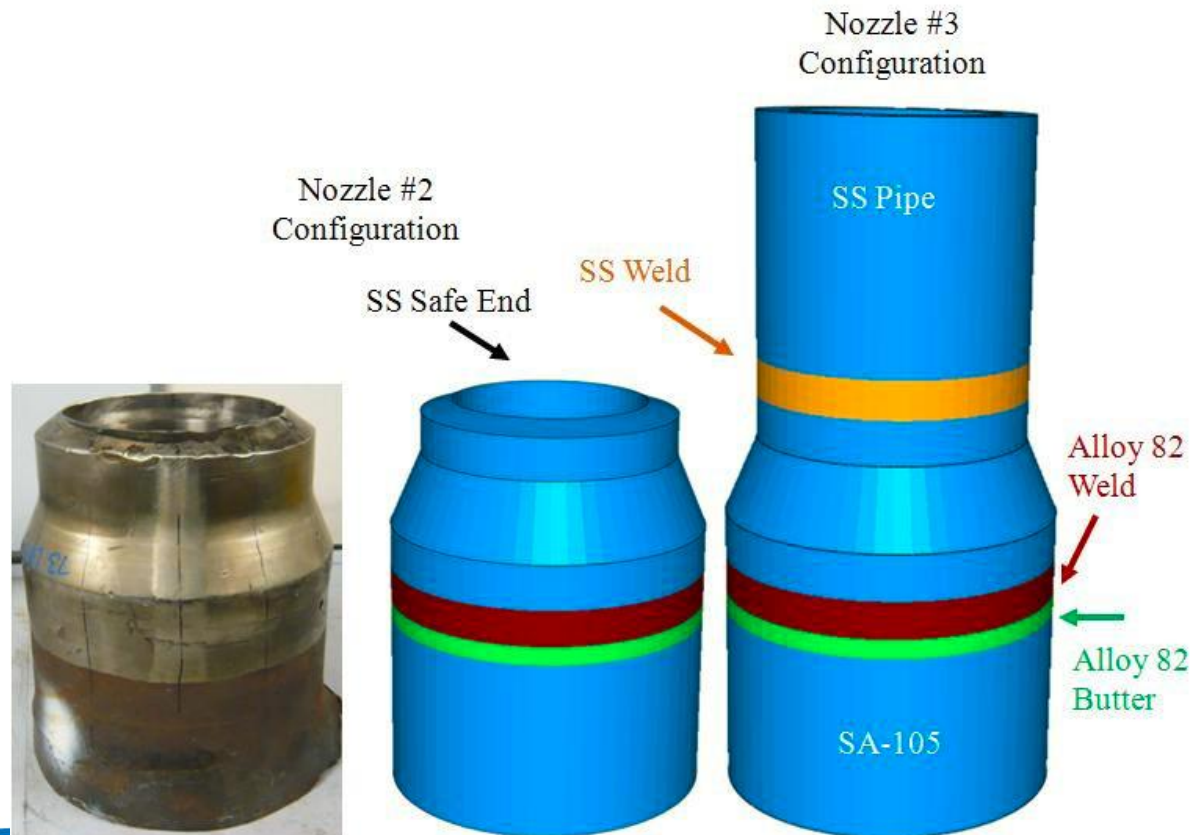
•RS Measurements funded by

•Purpose: Effect of overlay on

Phase III: Cancelled Plant Nozzles

Overview

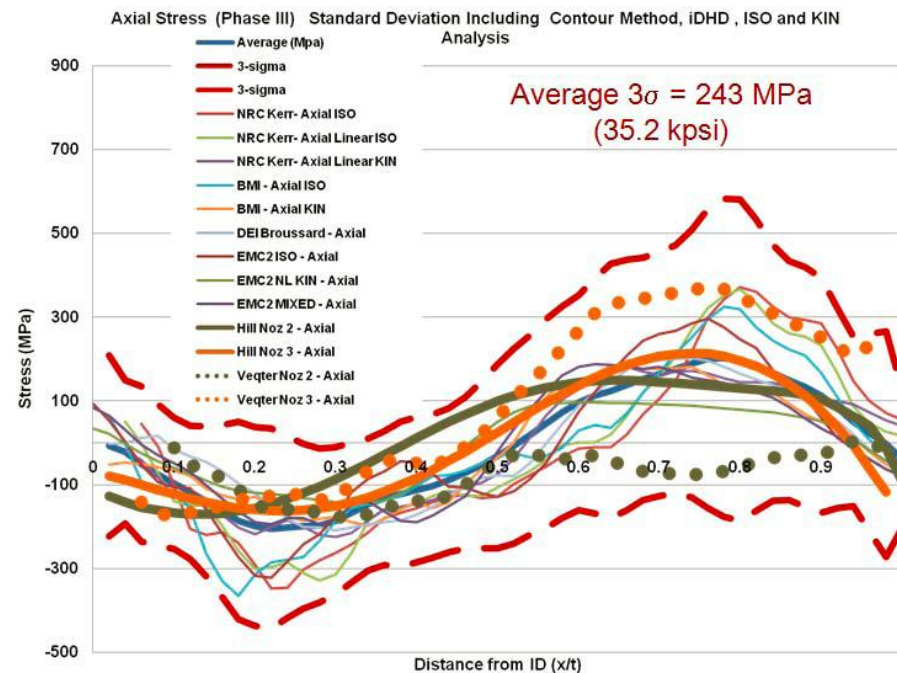
- Two nozzles required in order to apply the destructive contour method to both cases
- Outer diameter = 200 mm, Phase IIa was 350 mm



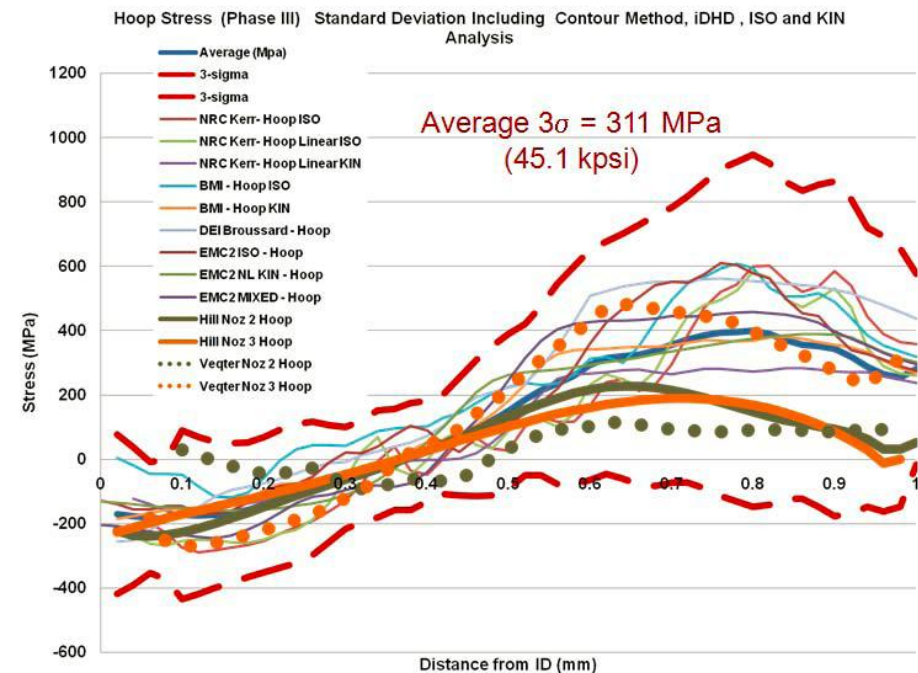
Phase III: Cancelled Plant Nozzles

Overview

Axial Stress Post safe end weld



Hoop Stress Post safe end weld



- Spread in modeling results evident in the Phase III results
- Phase 3 average $3\sigma = 243$ MPa, Phase 2a average $3\sigma = 278$ MPa

Phase III: Cancelled Plant Nozzles

Observations from Phase III Work

- Measurement and modeling results show similar trends
- Spread still evident in Phase III modeling results
- Uncertainty between Phase III and Phase II results is comparable, maybe slightly less

Outline

- Overview
- Phase I Work
- Phase II Work
- Phase III Work
- **Phase IV Work**
- Conclusions

Phase IV: Cancelled Plant Nozzles

Overview

- Full-scale components
 - Actual cold leg nozzle fabricated for intended service

ic Weld Specimens Finite Element Round Robin Fabricated Prototypic Nozzles

- Double-blind: i.e., modelers did not have access to measurement data
- Obtain modeling results from a community of independent modelers

- Objectives
 - To validate WRS modeling with experiment
 - To assess WRS modeling uncertainty
 - To assess weld overlay effectiveness

Components

- W&R PZR Nozzles (QTY 3)
- Validate FE models.

Phase 4 - EPRI

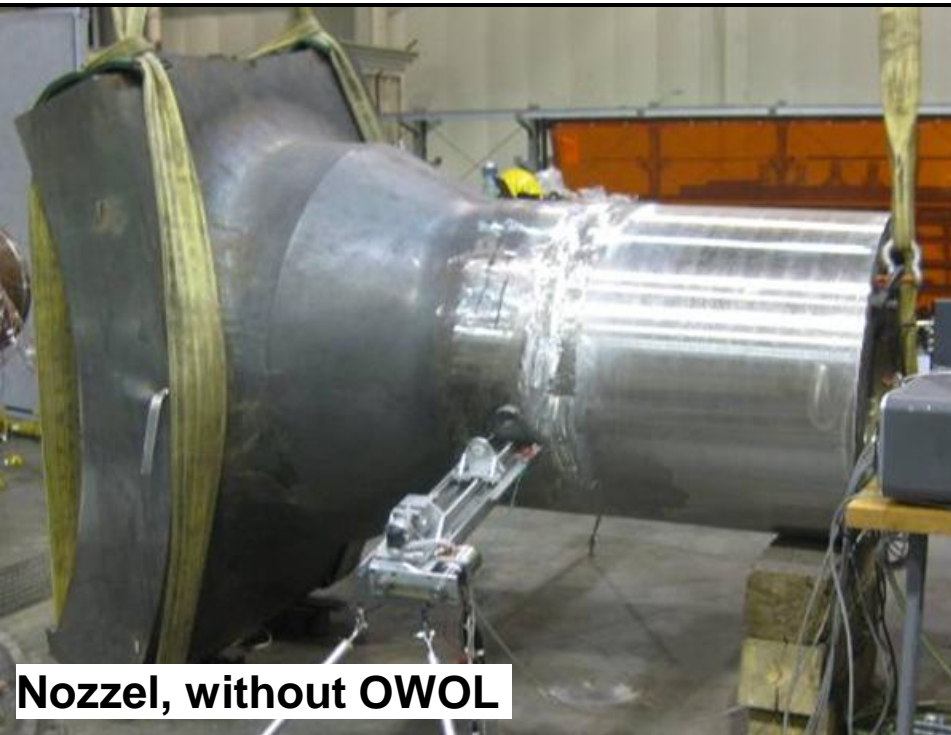
•Plant Components

- WNP-3 CL Nozzle (QTY 1)
- RS Measurements funded by NRC
- Purpose: Effect of overlay on ID.

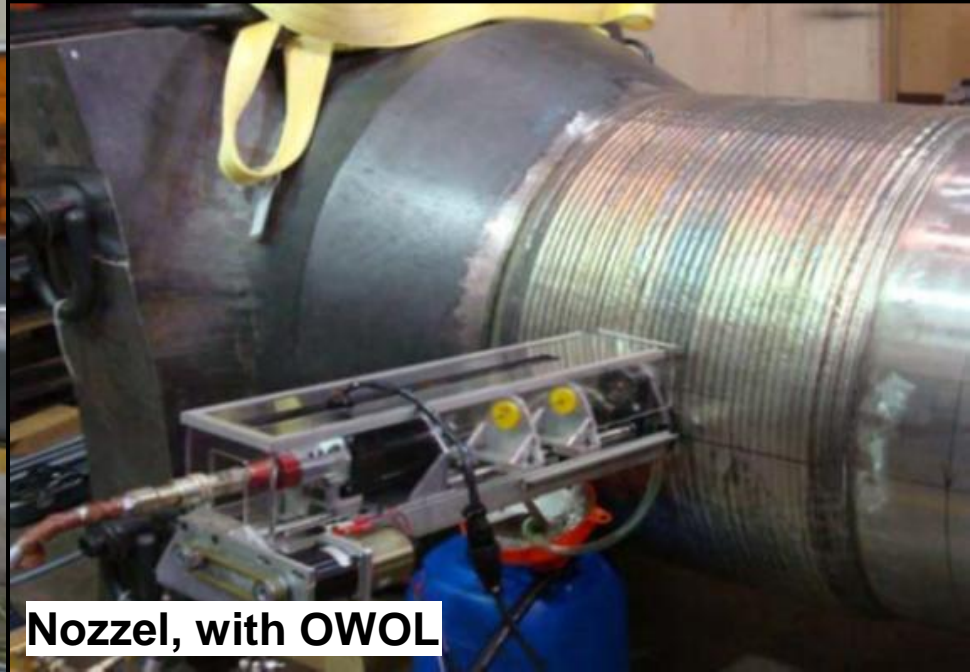


Phase IV: Cancelled Plant Nozzles

Mockups



Nozzel, without OWOL

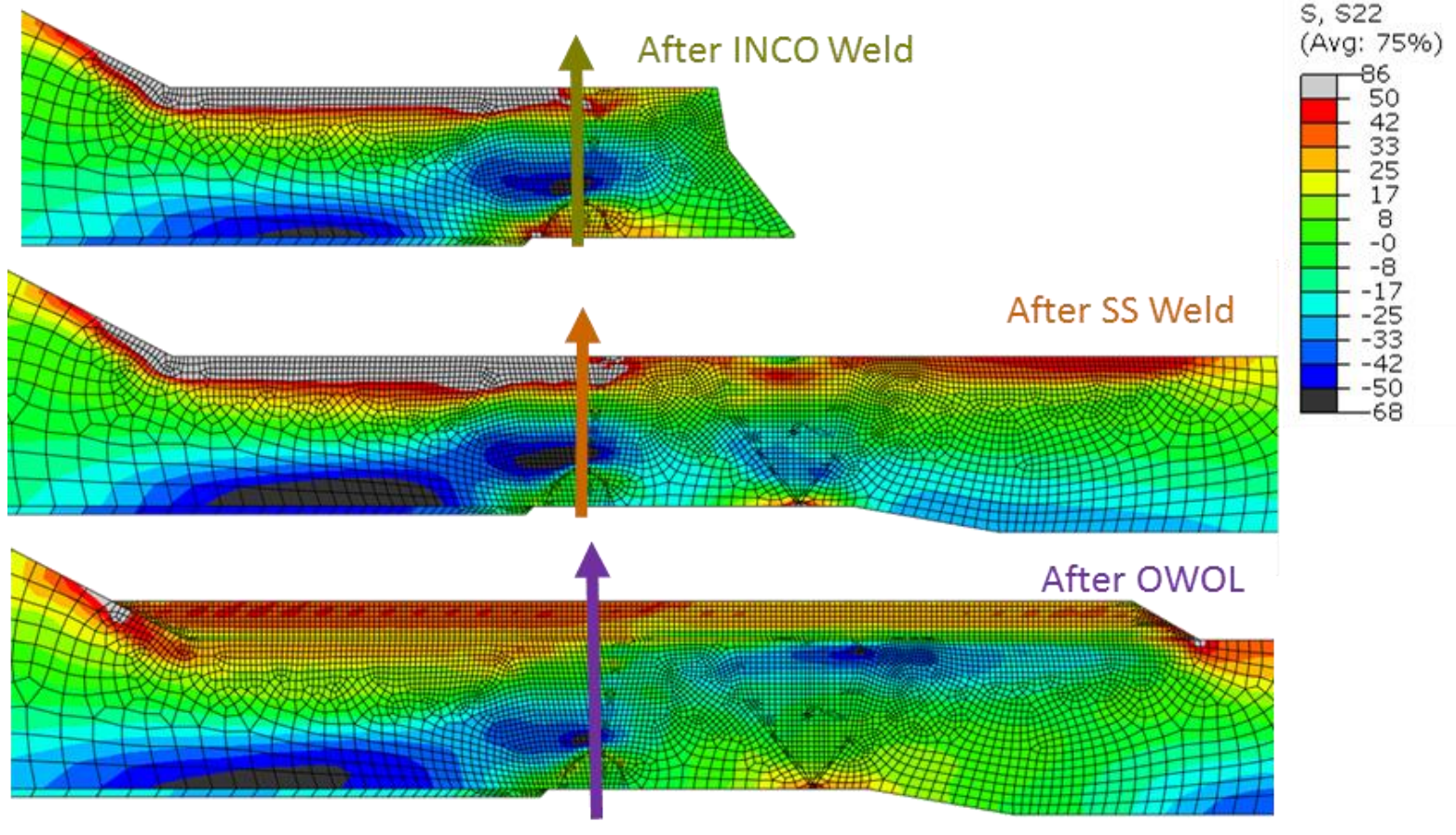


Nozzel, with OWOL

- Investigation of a mitigation technique: Optimized Weld Overlay (OWOL)

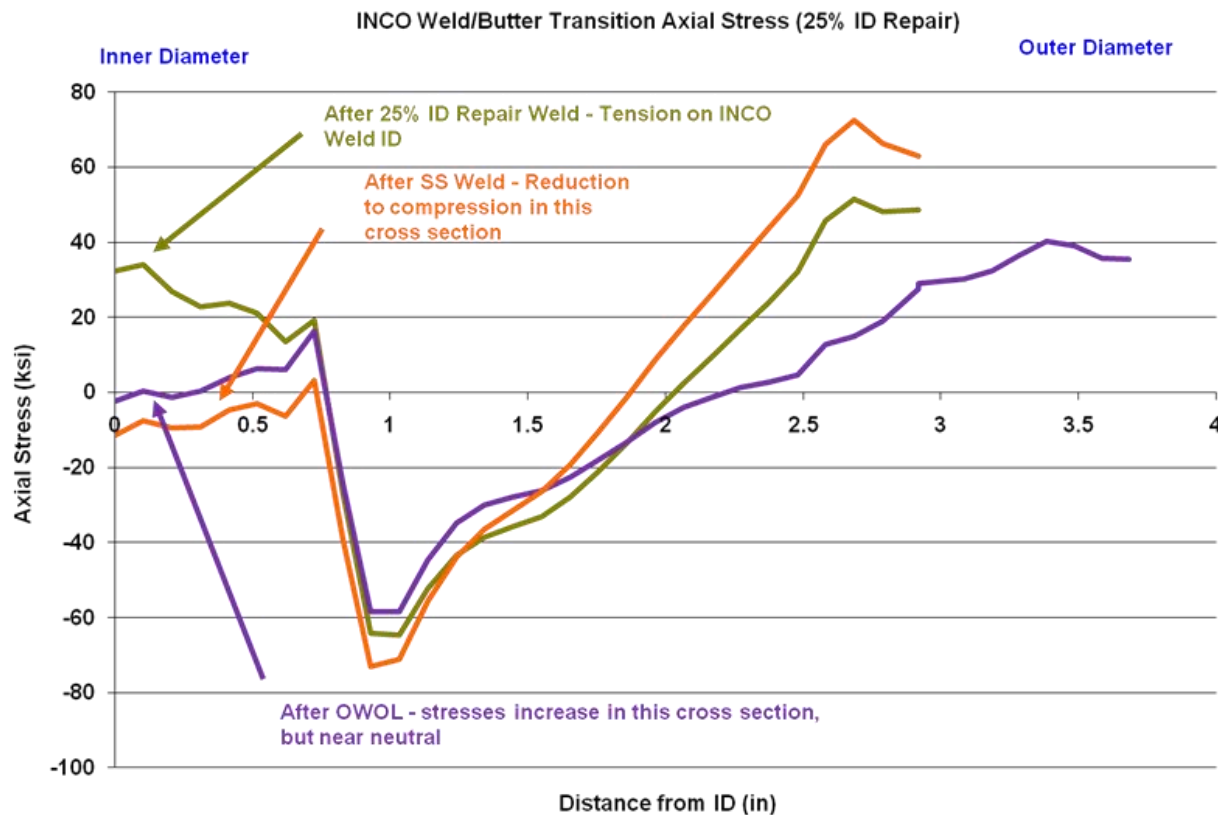
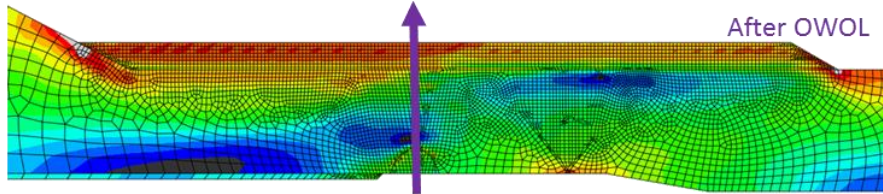
Phase IV: Cancelled Plant Nozzles

Results: Axial Stresses



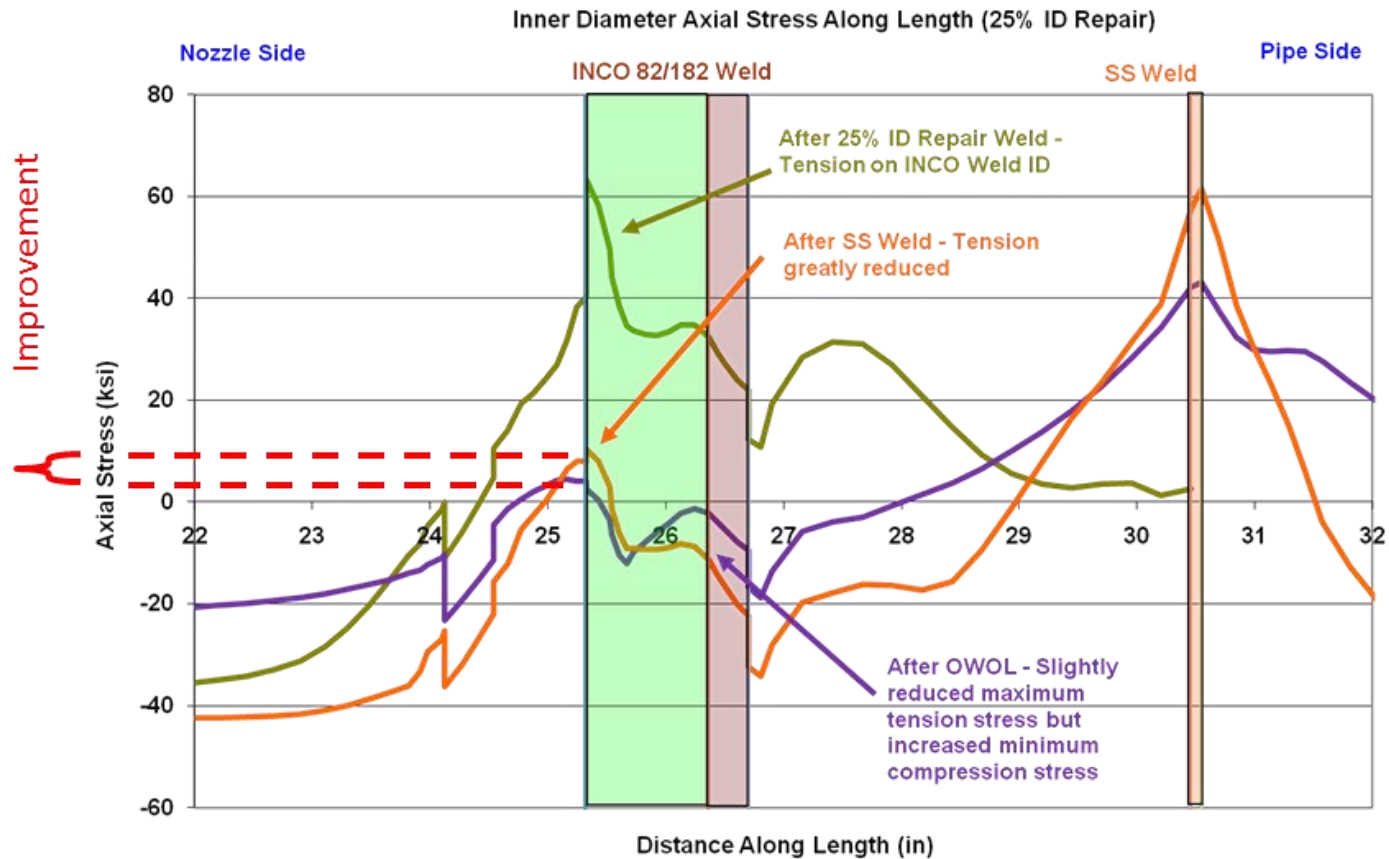
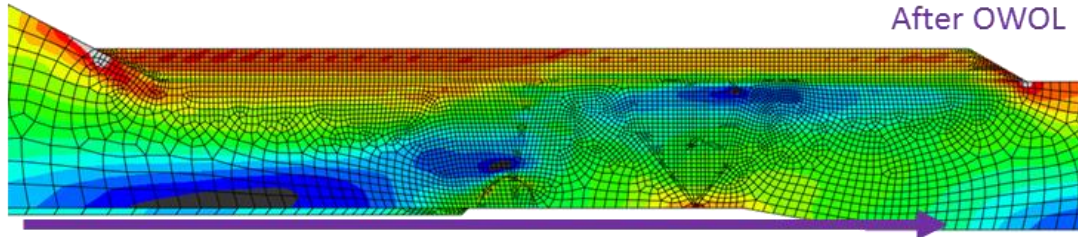
Phase IV: Cancelled Plant Nozzles

Results: Axial Stress, Midweld, Through Thickness



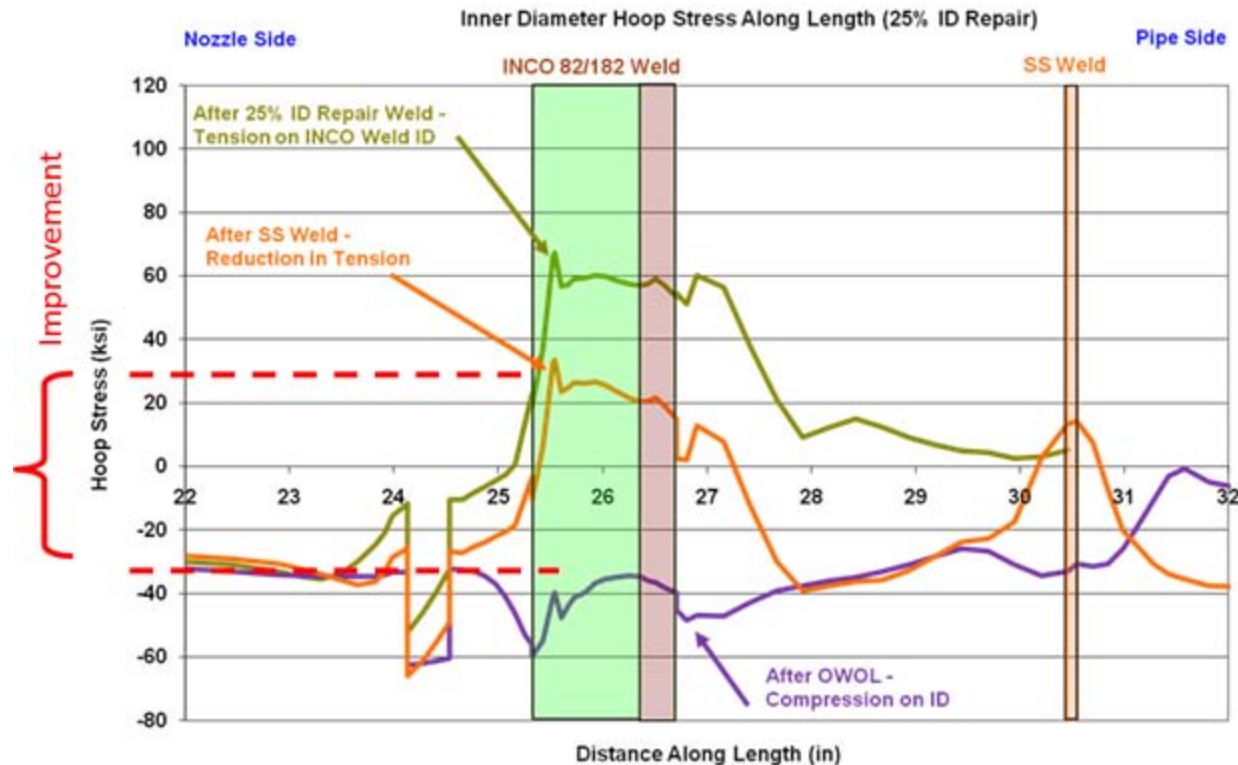
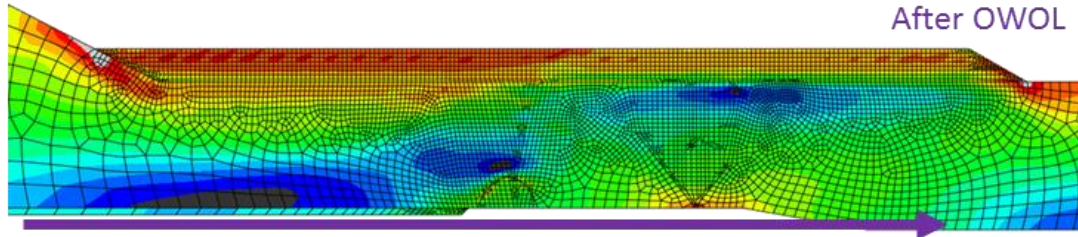
Phase IV: Cancelled Plant Nozzles

Results: Axial Stress, ID, Transverse to Weld



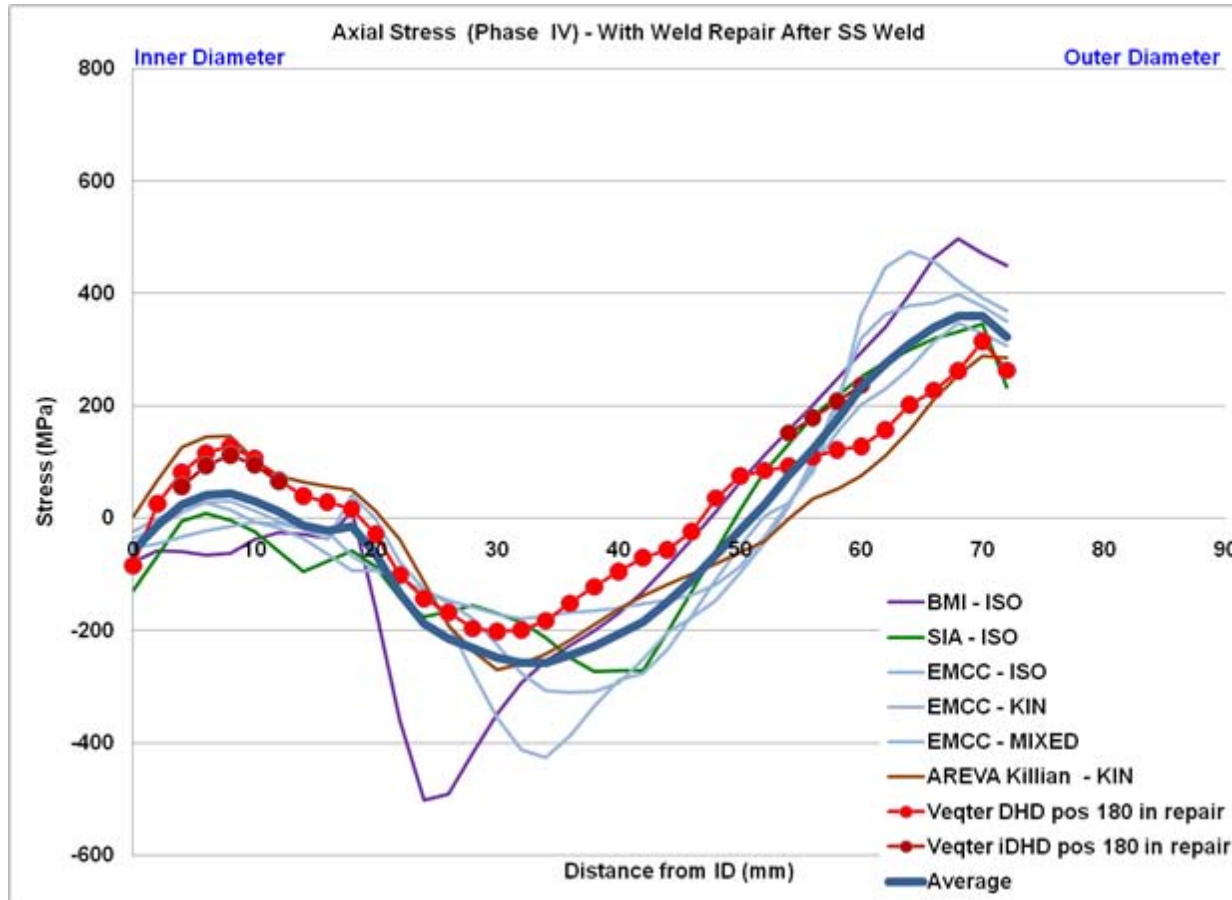
Phase IV: Cancelled Plant Nozzles

Results: Hoop Stress, ID, Transverse to Weld



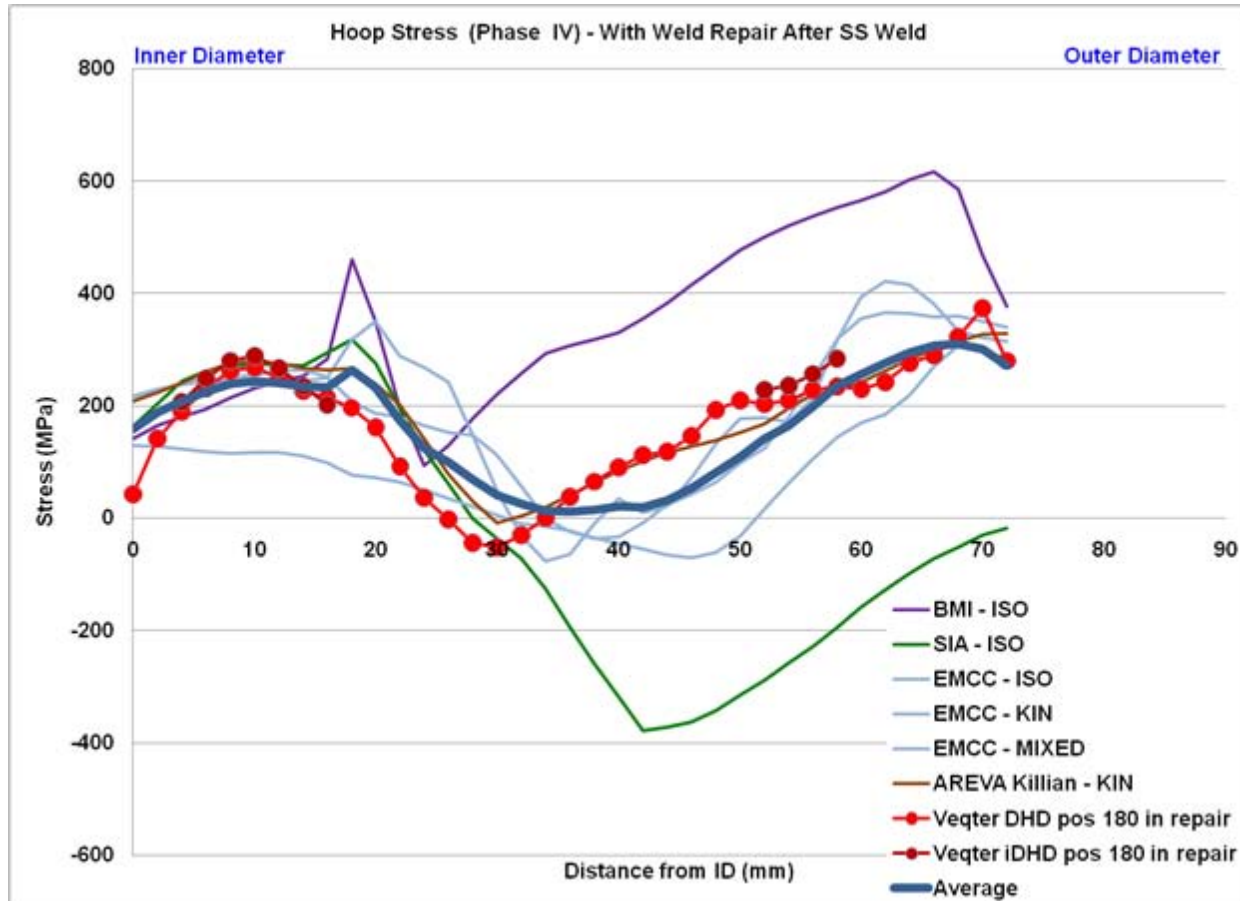
Phase IV: Cancelled Plant Nozzles

Results: Axial Stress



Phase IV: Cancelled Plant Nozzles

Results: Hoop Stress



Phase IV: Cancelled Plant Nozzles

Observations from Phase IV Work

- The modeling and measurement results showed improvement of the residual stresses at the ID location after OWOL was applied
- Modeling uncertainty still exists, but general agreement between models and measurements

Outline

- Overview
- Phase I Work
- Phase II Work
- Phase III Work
- Phase IV Work
- **Conclusions**

Conclusions

- Accomplishments
 - Double-blind WRS modeling validation by prototypic nuclear component mockups
 - Beneficial effect of OWOL confirmed by modeling and experiment: led to safety evaluation input
 - Sources of uncertainty have been identified
- Sources of uncertainty
 - Weld uncertainty
 - Process details (bead sequencing and heat input)
 - Material properties
 - Modeling uncertainty
 - Hardening law
 - Finite element details: e.g., mesh density, post processing
- Lessons learned from xLPR and the WRS Validation Program to reduce modeling uncertainty

Conclusions

- Opportunities to improve understanding of WRS:
 - No procedures in place to reduce the modeling uncertainty
 - Some sources of uncertainty not well quantified: sensitivity studies
 - No current acceptance criteria for WRS input in place

Weld Residual Stress **Validation Program**

Michael Benson

David Rudland

Aladar Csontos

U.S. NRC RES/DE/CIB

**ACRS Meeting of the Subcommittee on
Materials, Metallurgy, & Reactor Fuels**

February 6, 2013

Rockville, MD

Purpose and Objective

- Purpose of meeting
 - To brief the ACRS Materials, Metallurgy, and Reactor Fuels Subcommittee on the
 - Recently completed Phase I-IV weld residual stress validation effort
 - Upcoming continued weld residual stress validation effort

- Objective
 - Achieve a common understanding of WRS validation status, objectives, priorities and planned path forward
 - ACRS review and advice on project

Presentation Outline

- Three presentations
 - Background and Regulatory Impact
 - Accomplishments
 - Future

WRS Validation Program

Background and Regulatory Impact

David Rudland
U.S. NRC RES/DE/CIB

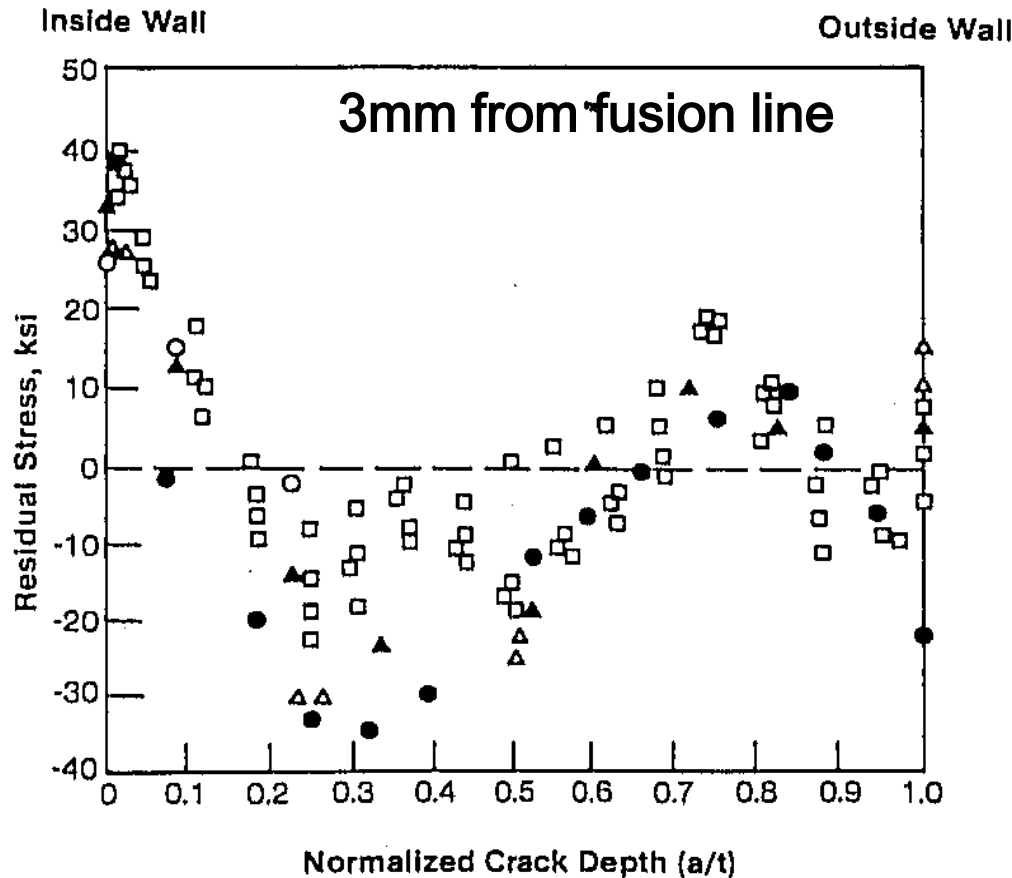
**ACRS Meeting of the Subcommittee on
Materials, Metallurgy, & Reactor Fuels**
February 6, 2013
Rockville, MD

Background

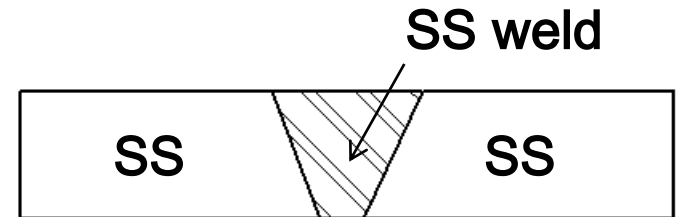
- Indications found in service in Class 1 piping must be analyzed per ASME Section XI
- If the material is susceptible to SCC, weld residual stress (WRS) must be included in the analyses per Appendix C
- Currently limited guidance on determination of weld residual stress is available in code
- Currently code does not account for uncertainty in WRS

WRS in Section XI

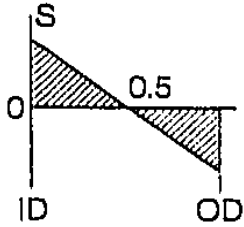
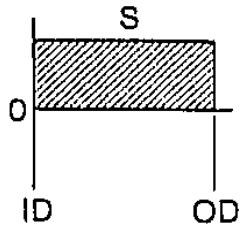
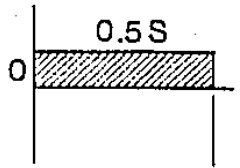
Appendix C technical basis document provides some data for austenitic stainless steels only



Results suggest that within the HAZ and into the base metal, the WRS are consistent from weld to weld



Pipe Flaw Evaluation Recommendation

Wall Thickness	Through-Wall Residual Stress ¹	
	Axial	Circumferential ²
<1 inch		
≥1 inch	See Note 3	

¹ S = 30 ksi

² Considerable variation with weld heat input.

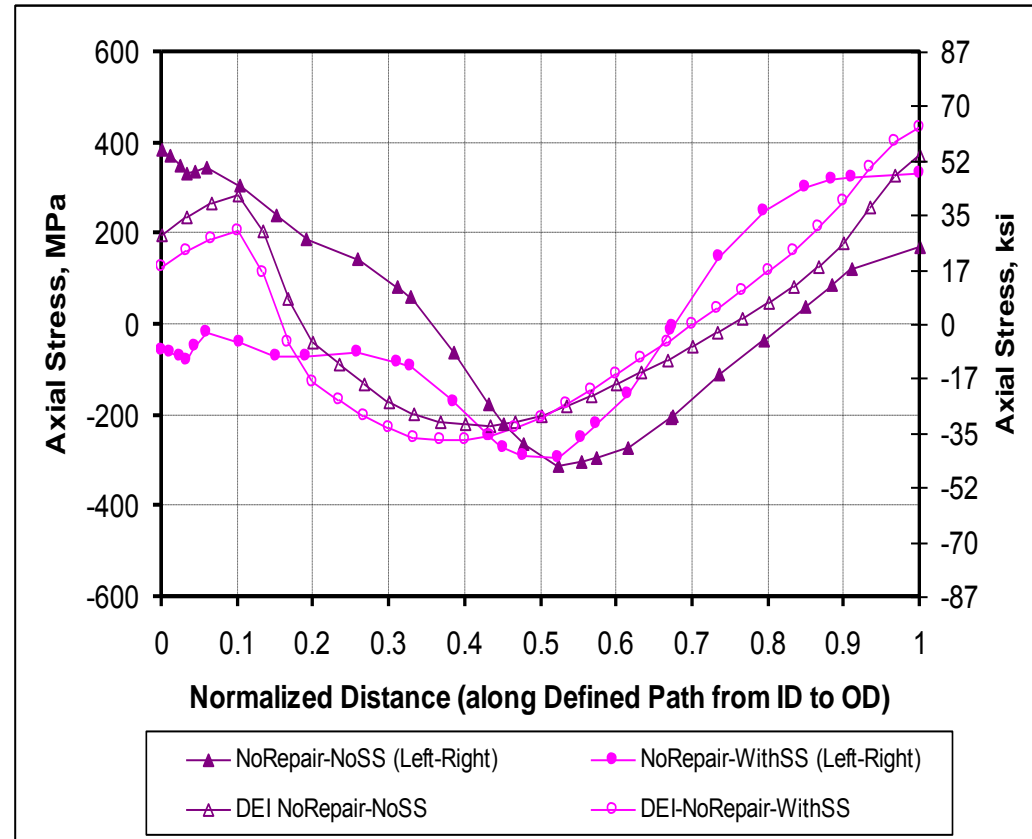
³ $\sigma = \sigma_i [1.0 - 6.91 (a/t) + 8.69 (a/t)^2 - 0.48 (a/t)^3 - 2.03 (a/t)^4]$
 σ_i = stress at inner surface ($a = 0$)

WRS in HAZ

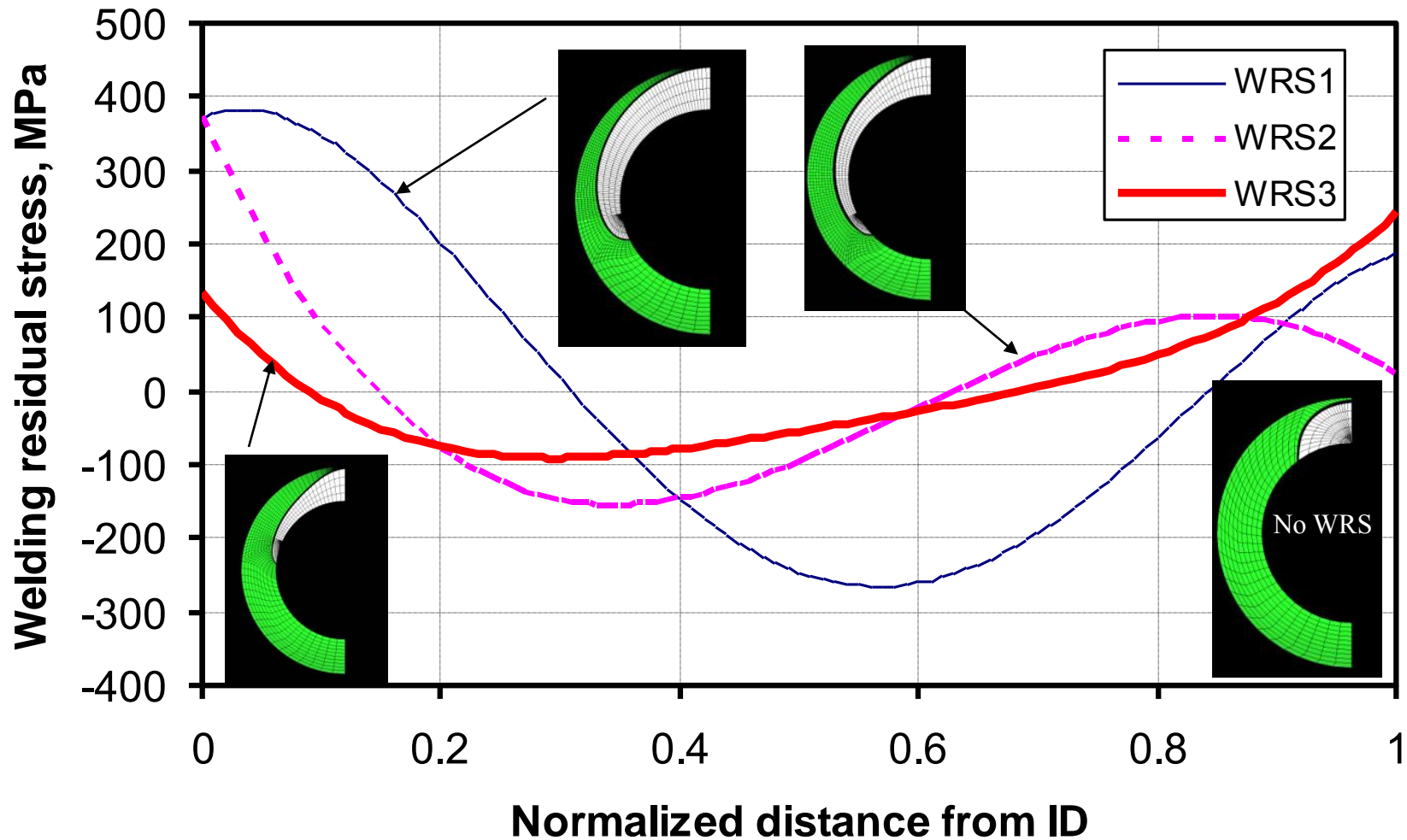
- Many BWR IGSCC evaluations used with WRS shown previously and approved by NRC
- The effects of weld sequence and procedure are not as pronounced for WRS in base metal or HAZ
- Within the weld, the dependence of the WRS on geometry, welding parameters, and weld sequence becomes much greater

Wolf Creek and Advanced FEA

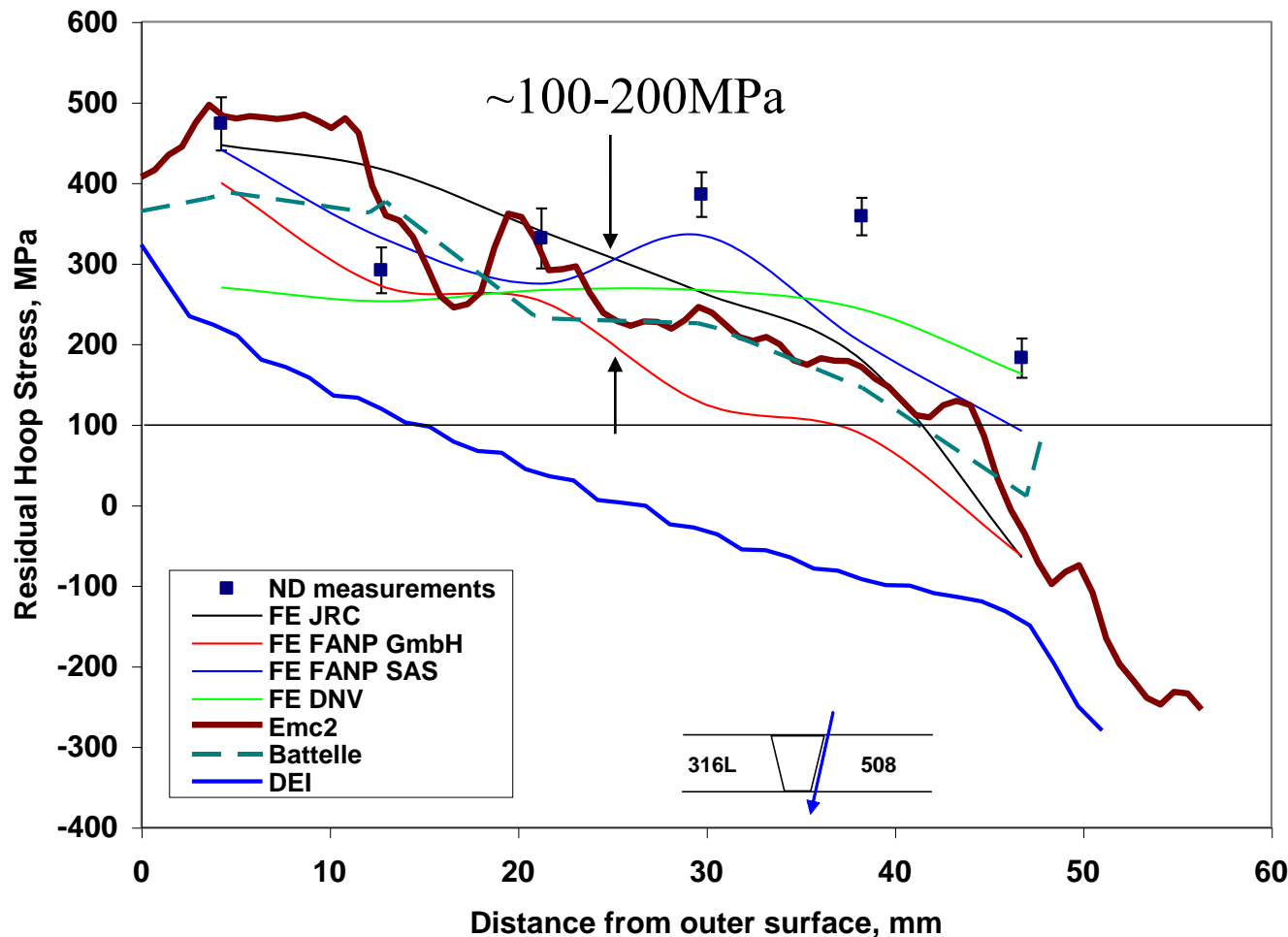
- Ultrasonic examinations at Wolf Creek in Fall 2006 found indications in pressurizer Alloy 600 dissimilar metal butt welds
- Staff and industry conducted analyses that demonstrated WRS has large impact on flaw evaluation



Effects of WRS on Crack Growth



Advanced FEA Project: WRS Validation



- Open WRS validation conducted
- Used results from NESC III PROJECT
- Results suggested 100-200MPa scatter between analysts

What about measurement error and uncertainty??

Wolf Creek and Advanced FEA

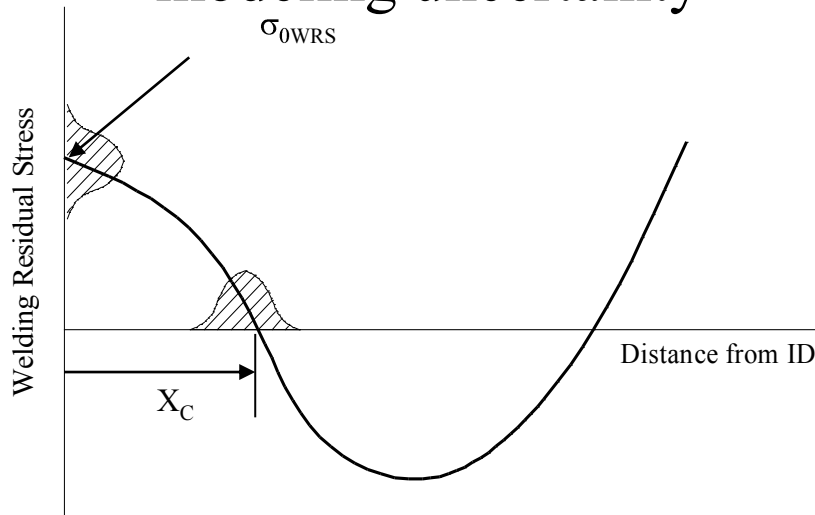
- NRC issued (2007) confirmatory action letters (CAL) to 40 plants
 - Enhanced leak monitoring
 - Inspection/mitigation of the pressurizer welds for all the PWRs with uninspected Alloy 82/182 pressurizer welds (including 9 plants scheduled for 2008 inspection/mitigation)
- Staff briefed ACRS on crack growth predictions for these indications and their implications to other plants on March 2007
- ACRS concluded:
 - Technical basis was sufficient
 - Additional work on residual stress including validation is required.

xLPR and WRS

- In April, 2012, Staff presented a summary of the ongoing Extremely Low Probability of Rupture (xLPR) program to ACRS
 - Modular-based probabilistic fracture mechanics code
 - Version 2 will be used to assess direct compliance with GDC-4 to ensure leak-before-break is still valid for those systems undergoing degradation due to PWSCC
 - Pilot Study demonstrated crack initiation and WRS are main drivers of rupture probabilities for piping with SCC
- ACRS concluded:
 - Realistic crack initiation model needed
 - Proper characterization of WRS and treatment of uncertainties is essential

WRS in xLPR

- Version 1
 - 3rd order curve fit with variability on WRS at ID and at X_c
 - Difficulty fitting WRS data and properly modeling uncertainty



Data developed from WRS Validation effort will be used as input to xLPR

- Version 2
 - Piece-wise linear representation
 - Uncertainty can be represented at each point
 - Fits WRS data better and flexible on modeling uncertainty

Table 1 Stress Variability Table - xLPR

Mean Stress (Mpa)	Plus 2σ Stress (Mpa)	Minus 2σ Stress (Mpa)	x/t
σ_1	σ_1^+	σ_1^-	0
σ_2	σ_2^+	σ_2^-	0.05
σ_3	σ_3^+	σ_3^-	0.1
σ_4	σ_4^+	σ_4^-	0.15
...
...
σ_{20}	σ_{20}^+	σ_{20}^-	0.95
σ_{21}	σ_{21}^+	σ_{21}^-	1

MRP-287

PWSCC Flaw Evaluation Guidance

- Recently, through the ongoing efforts in PWSCC flaw evaluation, EPRI published MRP-287 which gives non-mandatory guidance on PWSCC flaw evaluation.
- Document incorporated NRC informal comments, but the report has not been formally reviewed by staff
- Document lists attributes of acceptable weld residual stress analyses
 - Geometry and materials
 - Weld configuration and fabrication sequence
 - Repairs
 - Safe-end to pipe weld
- Document recommends numerical procedure be benchmarked and validated against experiments

Flaw Evaluation Relief Requests

- Typically when SCC is found and analyzed per ASME Section XI, the analysis is reviewed by NRR
- The licensee supplies data on WRS assumed
 - From literature on a weld with similar characteristics
 - Generic WRS analysis
 - Case specific WRS analysis
- No information is presented with respect to WRS uncertainty and only a single through-thickness representation is presented to NRR – contrary to MRP-287
- From a regulatory viewpoint, how can we be confident that the WRS provided by licensee is validated and conservative with respect to the uncertainties?

Thoughts

- To add confidence in WRS predictions
 - Minimize model uncertainty – Develop reliable and consistent numerical procedures
 - Robust WRS validation methods
 - Minimize measurement uncertainty
 - Develop appropriate criteria for validation
- For flaw evaluations
 - Use best estimate WRS from numerical procedures that are reliable, consistent and validated
 - If not possible, use conservative WRS
 - Yield level
 - Geometry specific and bounding WRS

Ongoing
WRS
validation
work
**Today's
topic**

Ongoing
ASME code
work

Using WRS in Regulatory Space

- Reduce uncertainty in industry submitted deterministic flaw evaluation
 - Incorporate tiered WRS structure in ASME Section XI code (ongoing) and 10CFR50.55a
- Incorporate WRS uncertainty in analyses
 - xLPR for leak-before-break
- Best Practices on new and repair fabrication
 - Learn from operating plant experiences
 - Don't repeat deleterious fabrication methods of the past
 - Learn from the lead in other industries.....

WRS Validation Program

Future

Michael Benson
U.S. NRC RES/DE/CIB

**ACRS Meeting of the Subcommittee on
Materials, Metallurgy, & Reactor Fuels
February 6, 2013
Rockville, MD**

Introduction

- This talk :
 - Recaps the current accomplishments of the WRS Validation Program
 - Describes the knowledge gaps
 - Introduces potential future research activities of the WRS Validation Program

Accomplishments

State of Knowledge

- Modeling uncertainty is uncomfortably large
- Sources of uncertainty have been identified
 - Choice of hardening law
- Despite the large analyst-to-analyst scatter, axisymmetric finite element models agree with measurements

Accomplishments

Knowledge Gaps

- Commonly-accepted procedures for WRS input development are lacking
 - Can we reduce the modeling uncertainty?
- Criteria are needed for WRS acceptance and validation
 - How do we determine where a WRS input falls in the uncertainty band?
- No measurement data exists for j-groove weld configurations
- Affect of partial-arc repairs cannot be captured with axisymmetric models

Future Activities

List of EPRI/NRC Joint Research Activities

- Development of new Memorandum of Understanding Addendum for cooperative NRC/EPRI WRS Research
- Phase IIa mockup (NRC)
 - Original mockup already discussed in the previous talk
 - Contour and slitting measurements
- Phase IIb mockup (NRC)
 - Similar to Phase IIa, fabricated by manual SMAW welding
 - Deep hole drilling, contour, and slitting measurements
 - FE Round Robin: Use lessons learned to reduce modeling uncertainty
 - FE Round Robin: Apply developed guidelines, MRP-317

Future Activities

List of EPRI/NRC Joint Research Activities

- Draft of ASME Code best practices for weld residual stress inputs to flaw evaluations (NRC/EPRI)
- Development of 3-D moving arc analysis (EPRI/NRC)
- Development of Improved Hardening Laws (EPRI)

Future Activities

List of EPRI/NRC Joint Research Activities

- Validation of Upper-Head J-Weld WRS Model (EPRI)
- Validation of Lower-Head J-Weld WRS Model (EPRI)
- WRS Inputs for xLPR (NRC/EPRI)
 - Modeling uncertainty assessed by having multiple analysts independently modeling the same problem
 - Welding uncertainty assessed by performing sensitivity studies on material properties, weld sequencing, and heat input
- International WRS Research Programs (NRC/EPRI)

Summary

- Weld residual stresses have regulatory significance
 - Important input to engineering evaluations involving nuclear safety
 - Large uncertainties exist
- Future activities
 - Validate finite element modeling for other weld geometries
 - Develop codified guidelines for formulating WRS inputs
 - Reduce modeling uncertainty by considering hardening law and finite element modeling details
 - Quantify the uncertainty through sensitivity studies
 - Recommend acceptance criteria for regulators

Weld Residual Stress Validation Program

Michael Benson

David Rudland

Aladar Csontos

U.S. NRC RES/DE/CIB

**ACRS Meeting of the Subcommittee on
Materials, Metallurgy, & Reactor Fuels**

February 6, 2013

Rockville, MD

Purpose and Objective

- Purpose of meeting
 - To brief the ACRS Materials, Metallurgy, and Reactor Fuels Subcommittee on the
 - Recently completed Phase I-IV weld residual stress validation effort
 - Upcoming continued weld residual stress validation effort
- Objective
 - Achieve a common understanding of WRS validation status, objectives, priorities and planned path forward
 - ACRS review and advice on project

Presentation Outline

- Three presentations
 - Background and Regulatory Impact
 - Accomplishments
 - Future

WRS Validation Program Background and Regulatory Impact

David Rudland
U.S. NRC RES/DE/CIB

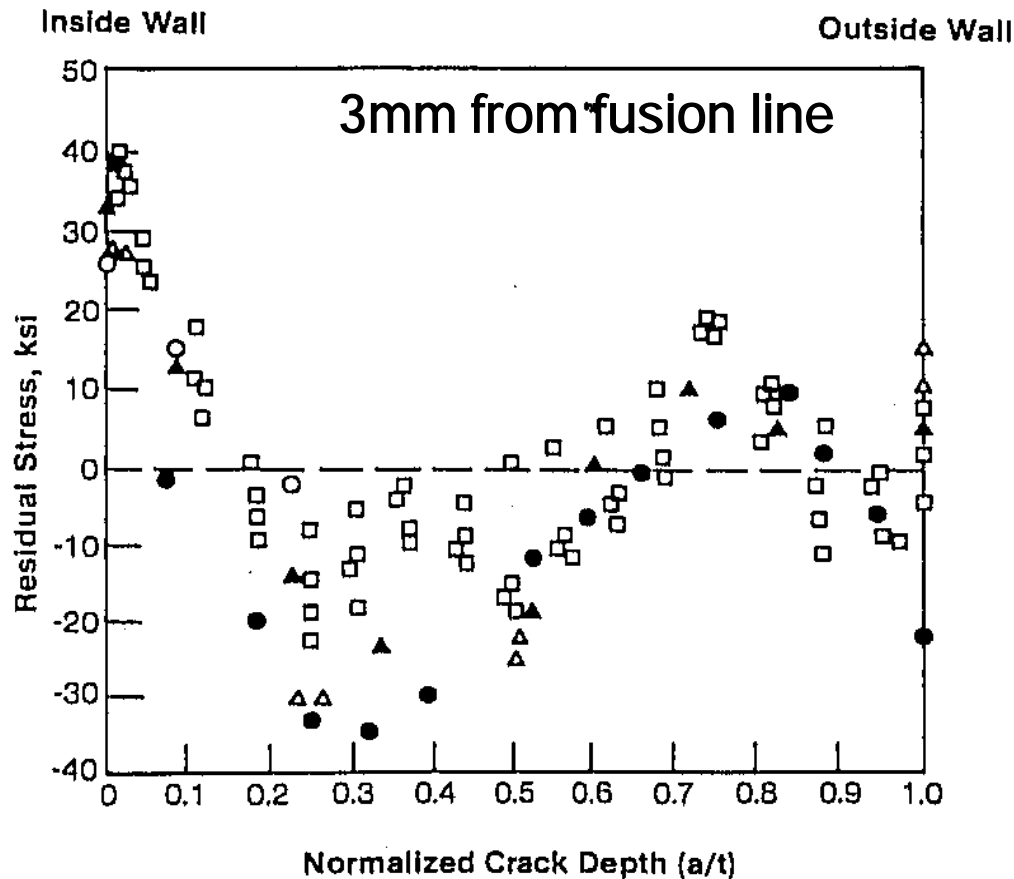
**ACRS Meeting of the Subcommittee on
Materials, Metallurgy, & Reactor Fuels**
February 6, 2013
Rockville, MD

Background

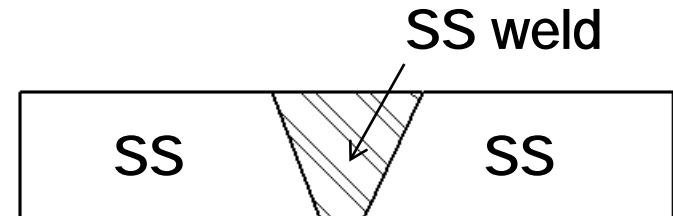
- Indications found in service in Class 1 piping must be analyzed per ASME Section XI
- If the material is susceptible to SCC, weld residual stress (WRS) must be included in the analyses per Appendix C
- Currently limited guidance on determination of weld residual stress is available in code
- Currently code does not account for uncertainty in WRS

WRS in Section XI

Appendix C technical basis document provides some data for austenitic stainless steels only

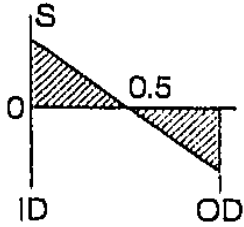
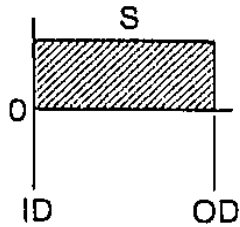
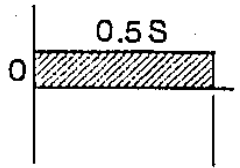


Results suggest that within the HAZ and into the base metal, the WRS are consistent from weld to weld



Open symbols – EPRI
Closed symbols – ANL

Pipe Flaw Evaluation Recommendation

Wall Thickness	Through-Wall Residual Stress ¹	
	Axial	Circumferential ²
<1 inch		
≥1 inch	See Note 3	

¹ S = 30 ksi

² Considerable variation with weld heat input.

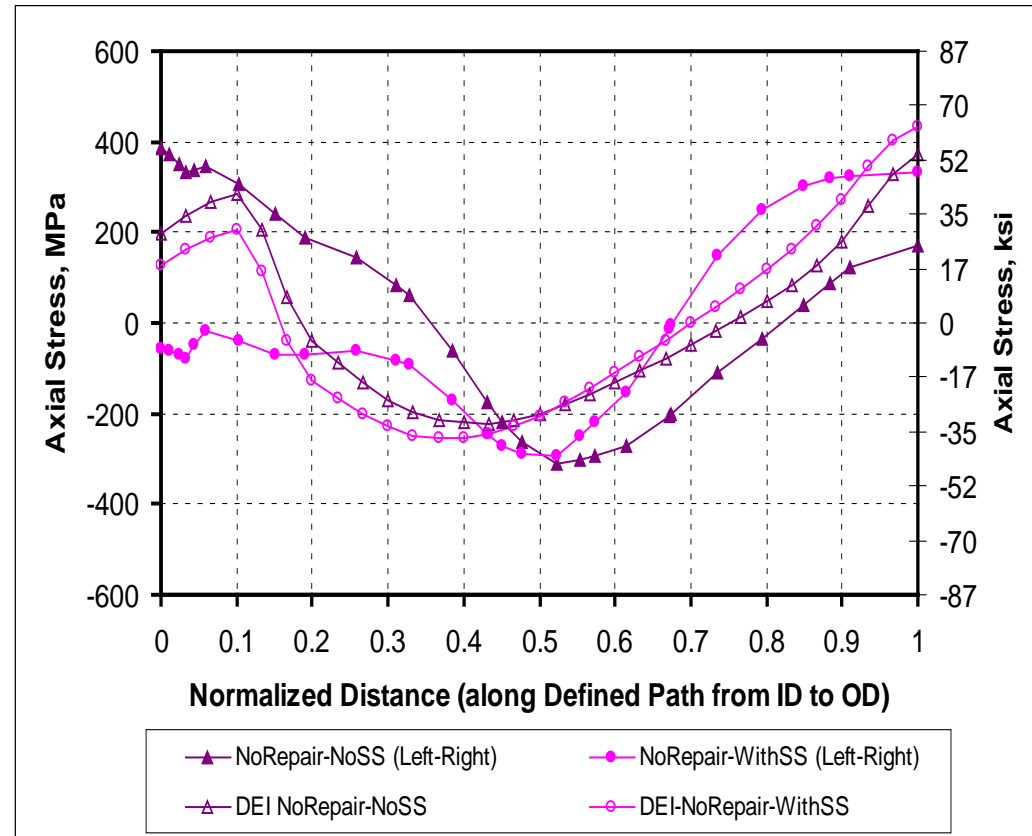
³ $\sigma = \sigma_i [1.0 - 6.91 (a/t) + 8.69 (a/t)^2 - 0.48 (a/t)^3 - 2.03 (a/t)^4]$
 σ_i = stress at inner surface ($a = 0$)

WRS in HAZ

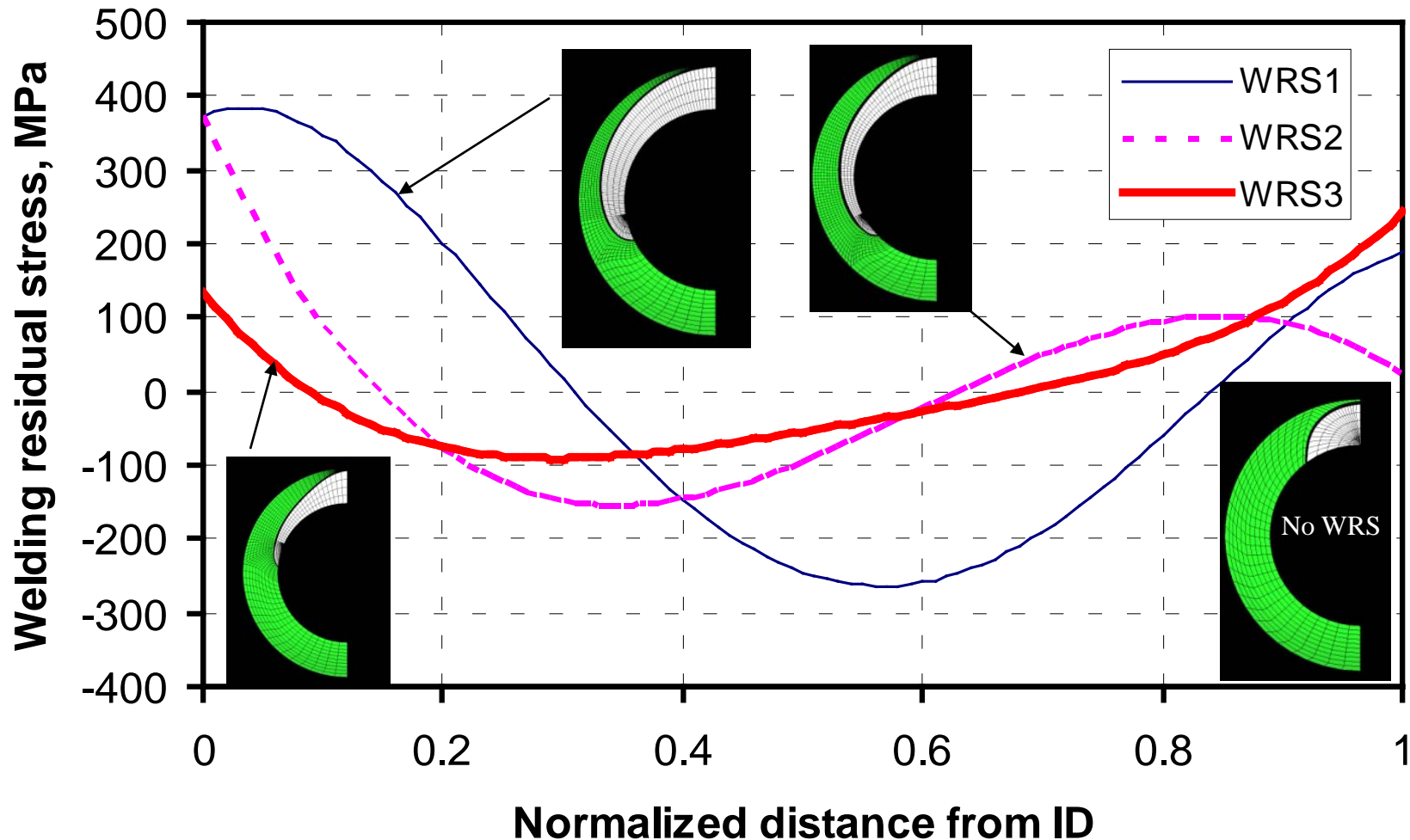
- Many BWR IGSCC evaluations used with WRS shown previously and approved by NRC
- The effects of weld sequence and procedure are not as pronounced for WRS in base metal or HAZ
- Within the weld, the dependence of the WRS on geometry, welding parameters, and weld sequence becomes much greater

Wolf Creek and Advanced FEA

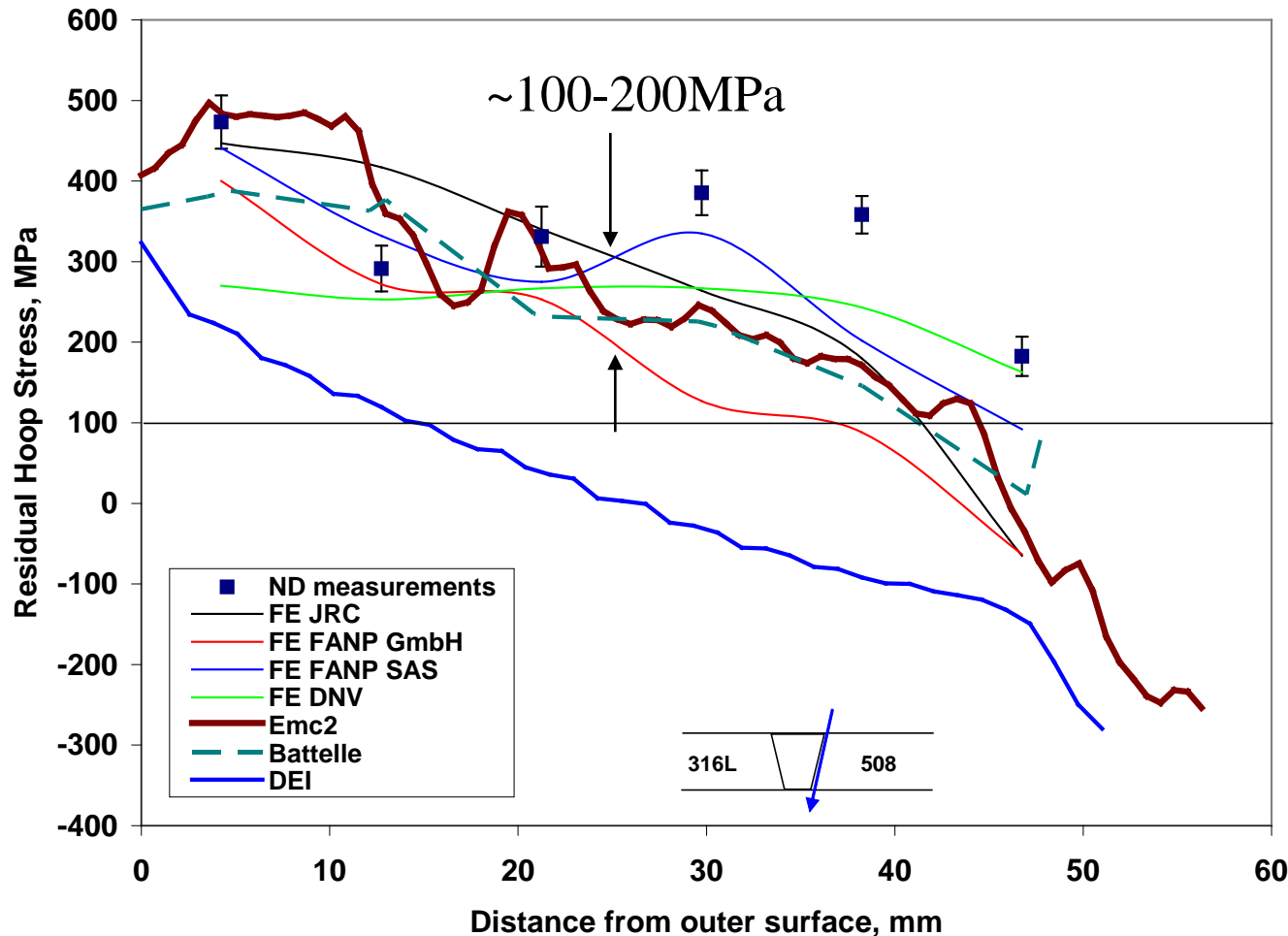
- Ultrasonic examinations at Wolf Creek in Fall 2006 found indications in pressurizer Alloy 600 dissimilar metal butt welds
- Staff and industry conducted analyses that demonstrated WRS has large impact on flaw evaluation



Effects of WRS on Crack Growth



Advanced FEA Project: WRS Validation



- Open WRS validation conducted
- Used results from NESC III PROJECT
- Results suggested 100-200MPa scatter between analysts

What about measurement error and uncertainty??

Wolf Creek and Advanced FEA

- NRC issued (2007) confirmatory action letters (CAL) to 40 plants
 - Enhanced leak monitoring
 - Inspection/mitigation of the pressurizer welds for all the PWRs with uninspected Alloy 82/182 pressurizer welds (including 9 plants scheduled for 2008 inspection/mitigation)
- Staff briefed ACRS on crack growth predictions for these indications and their implications to other plants on March 2007
- ACRS concluded:
 - Technical basis was sufficient
 - Additional work on residual stress including validation is required.

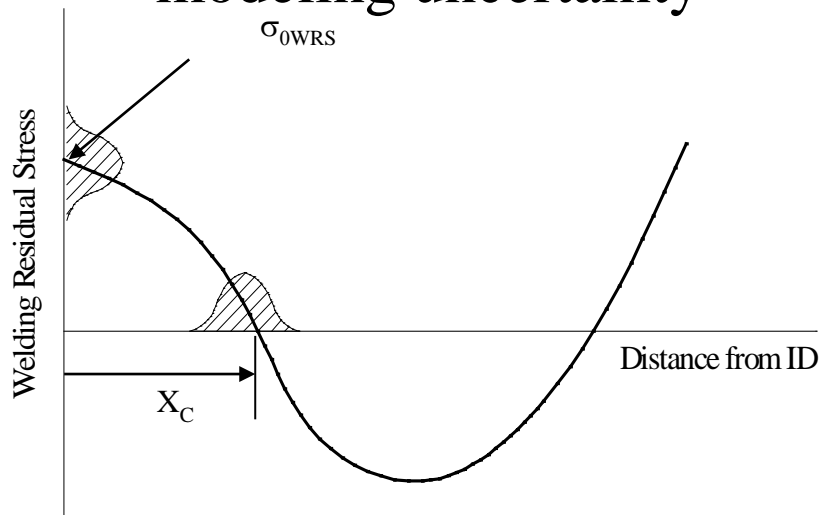
xLPR and WRS

- In April, 2012, Staff presented a summary of the ongoing Extremely Low Probability of Rupture (xLPR) program to ACRS
 - Modular-based probabilistic fracture mechanics code
 - Version 2 will be used to assess direct compliance with GDC-4 to ensure leak-before-break is still valid for those systems undergoing degradation due to PWSCC
 - Pilot Study demonstrated crack initiation and WRS are main drivers of rupture probabilities for piping with SCC
- ACRS concluded:
 - Realistic crack initiation model needed
 - Proper characterization of WRS and treatment of uncertainties is essential

WRS in xLPR

- Version 1

- 3rd order curve fit with variability on WRS at ID and at X_c
- Difficulty fitting WRS data and properly modeling uncertainty



Data developed from WRS Validation effort will be used as input to xLPR

02/06/2013

- Version 2

- Piece-wise linear representation
- Uncertainty can be represented at each point
- Fits WRS data better and flexible on modeling uncertainty

Table 1 Stress Variability Table - xLPR

Mean Stress (Mpa)	Plus 2 σ Stress (Mpa)	Minus 2 σ Stress (Mpa)	x/t
σ_1	σ_1^+	σ_1^-	0
σ_2	σ_2^+	σ_2^-	0.05
σ_3	σ_3^+	σ_3^-	0.1
σ_4	σ_4^+	σ_4^-	0.15
...
...
σ_{20}	σ_{20}^+	σ_{20}^-	0.95
σ_{21}	σ_{21}^+	σ_{21}^-	1

MRP-287

PWSCC Flaw Evaluation Guidance

- Recently, through the ongoing efforts in PWSCC flaw evaluation, EPRI published MRP-287 which gives non-mandatory guidance on PWSCC flaw evaluation.
- Document incorporated NRC informal comments, but the report has not been formally reviewed by staff
- Document lists attributes of acceptable weld residual stress analyses
 - Geometry and materials
 - Weld configuration and fabrication sequence
 - Repairs
 - Safe-end to pipe weld
- Document recommends numerical procedure be benchmarked and validated against experiments

Flaw Evaluation Relief Requests

- Typically when SCC is found and analyzed per ASME Section XI, the analysis is reviewed by NRR
- The licensee supplies data on WRS assumed
 - From literature on a weld with similar characteristics
 - Generic WRS analysis
 - Case specific WRS analysis
- No information is presented with respect to WRS uncertainty and only a single through-thickness representation is presented to NRR – contrary to MRP-287
- From a regulatory viewpoint, how can we be confident that the WRS provided by licensee is validated and conservative with respect to the uncertainties?

Thoughts

- To add confidence in WRS predictions

- Minimize model uncertainty – Develop reliable and consistent numerical procedures
- Robust WRS validation methods
- Minimize measurement uncertainty
- Develop appropriate criteria for validation

Ongoing
WRS
validation
work
**Today's
topic**

- For flaw evaluations

- Use best estimate WRS from numerical procedures that are reliable, consistent and validated
- If not possible, use conservative WRS
 - Yield level
 - Geometry specific and bounding WRS

Ongoing
ASME code
work

Using WRS in Regulatory Space

- Reduce uncertainty in industry submitted deterministic flaw evaluation
 - Incorporate tiered WRS structure in ASME Section XI code (ongoing) and 10CFR50.55a
- Incorporate WRS uncertainty in analyses
 - xLPR for leak-before-break
- Best Practices on new and repair fabrication
 - Learn from operating plant experiences
 - Don't repeat deleterious fabrication methods of the past
 - Learn from the lead in other industries.....

WRS Validation Program

Accomplishments

Michael Benson
U.S. NRC RES/DE/CIB

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Outline

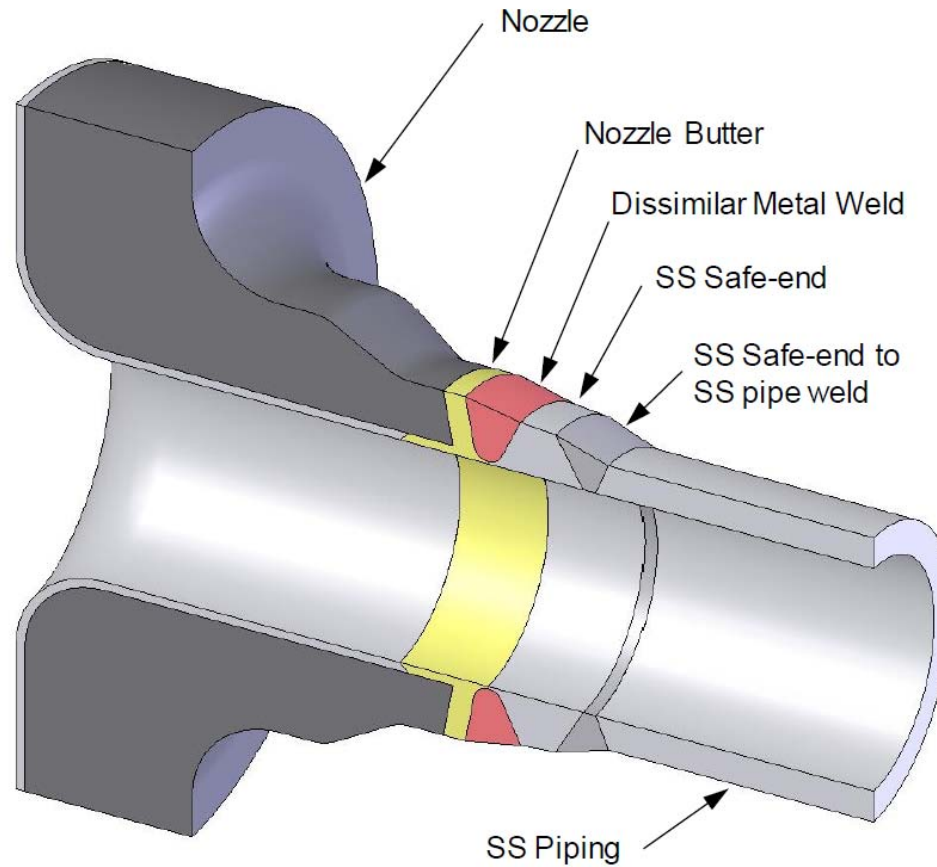
- Overview
- Phase I Work
- Phase II Work
- Phase III Work
- Phase IV Work
- Conclusions

Outline

- Overview
- Phase I Work
- Phase II Work
- Phase III Work
- Phase IV Work
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WRS Validation Program Overview

Dissimilar Metal Weld Geometry



WRS Validation Program Overview

Goals



- Identify, quantify, and minimize sources of model uncertainty
 - Develop reliable and consistent modeling procedures
- Validate WRS models with robust measurement techniques
- Develop acceptance criteria for WRS inputs to flaw evaluations

WRS Validation Program Overview

Memorandum of Understanding (MOU)



- Cooperative research performed under the Nuclear Regulatory Commission (NRC)/Electric Power Research Institute (EPRI) MOU
- Sets forth terms for cooperative research
- Addenda
 - Address specific research topics
 - Extremely Low Probability of Rupture
 - WRS Validation Program
 - Nondestructive Evaluation
 - High Density Polyethylene Piping
 - Environmental Fatigue

WRS Validation Program Overview

Memorandum of Understanding (MOU)

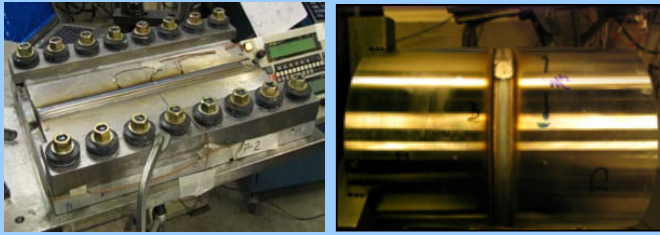
- EPRI
 - Designed/fabricated small-scale specimens and full-scale mockups for WRS measurement
 - Created finite element models
- NRC
 - Created finite element models
 - Organized finite element round robin studies
 - Designed/fabricated a full-scale mockup for WRS measurement

WRS Validation Program Overview

Research Phases

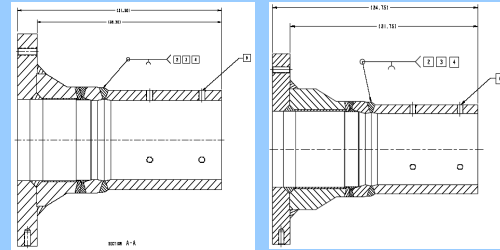
Phase 1 - EPRI

- Scientific Weld Specimens
- Phase 1A: Restrained Plates (QTY 4)
- Phase 1B: Small Cylinders (QTY 4)
- Purpose: Develop FE models.



Phase 2 - NRC

- Fabricated Prototypic Nozzles
- Type 8 Surge Nozzles (QTY 2)
- Purpose: Prototypic scale under controlled conditions. Validate FE models.



Phase 3 - EPRI

- Plant Components
- WNP-3 S&R PZR Nozzles (QTY 3)
- Purpose: Validate FE models.



Phase 4 - EPRI

- Plant Components
- WNP-3 CL Nozzle (QTY 1)
- RS Measurements funded by NRC
- Purpose: Effect of overlay on ID.



Outline

- Overview
- **Phase I Work**
- Phase II Work
- Phase III Work
- Phase IV Work
- Conclusions

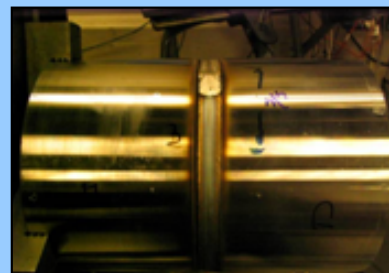
Phase I: Scientific Weld Specimens

Overview

- Simple, light-weight specimen geometries
 - Grooved plate
 - Butt-welded cylinders
- Objective
 - To demonstrate/develop WRS measurement and modeling capabilities

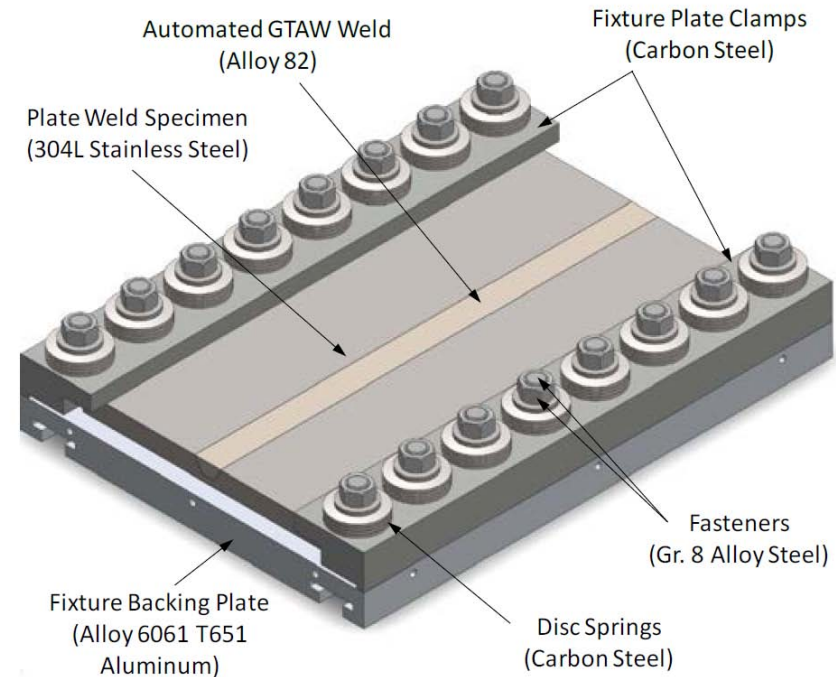
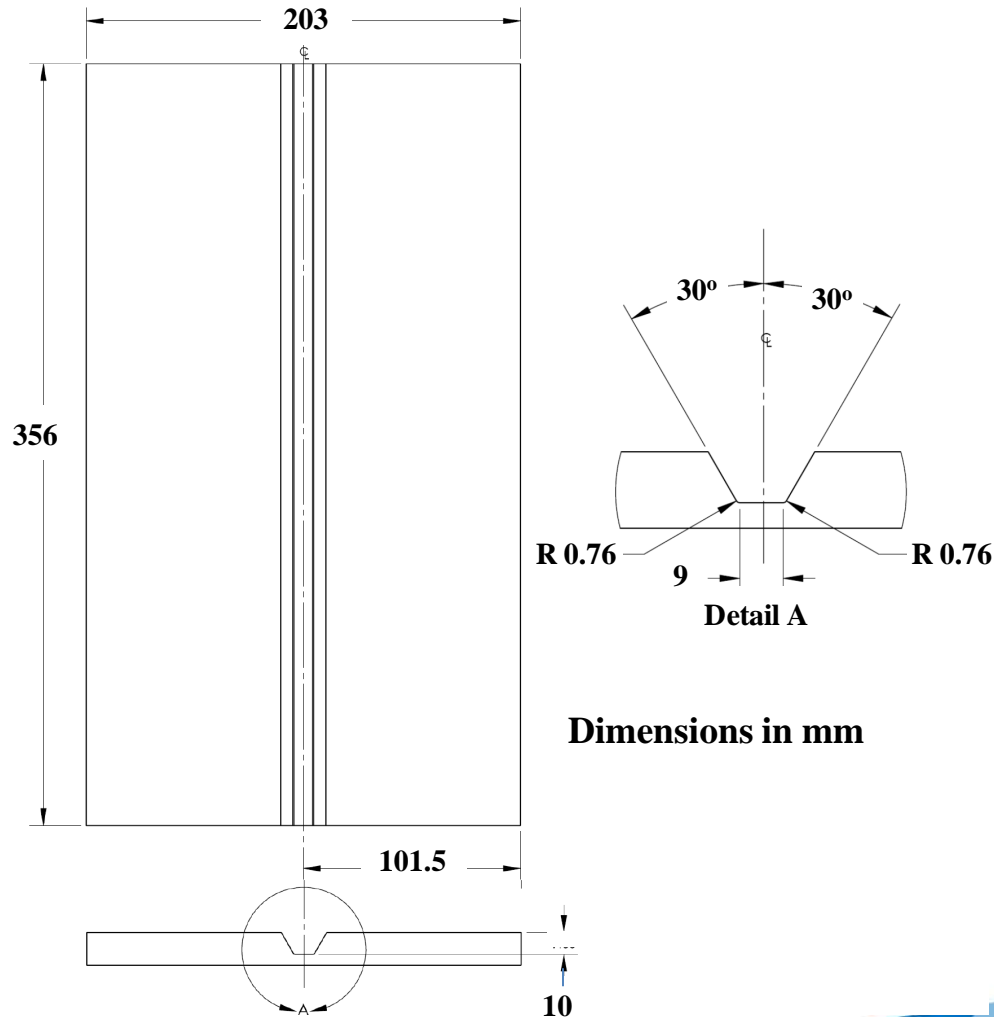
Phase 1 - EPRI

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Phase I: Scientific Weld Specimens

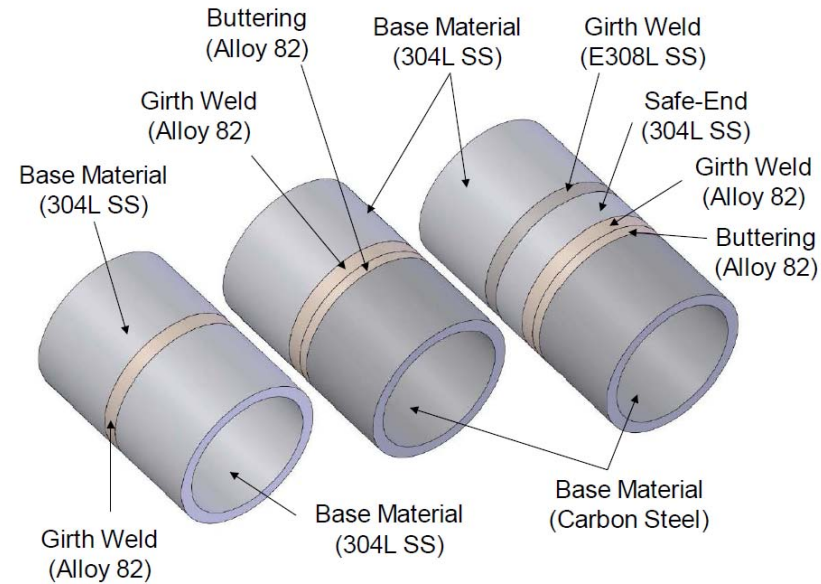
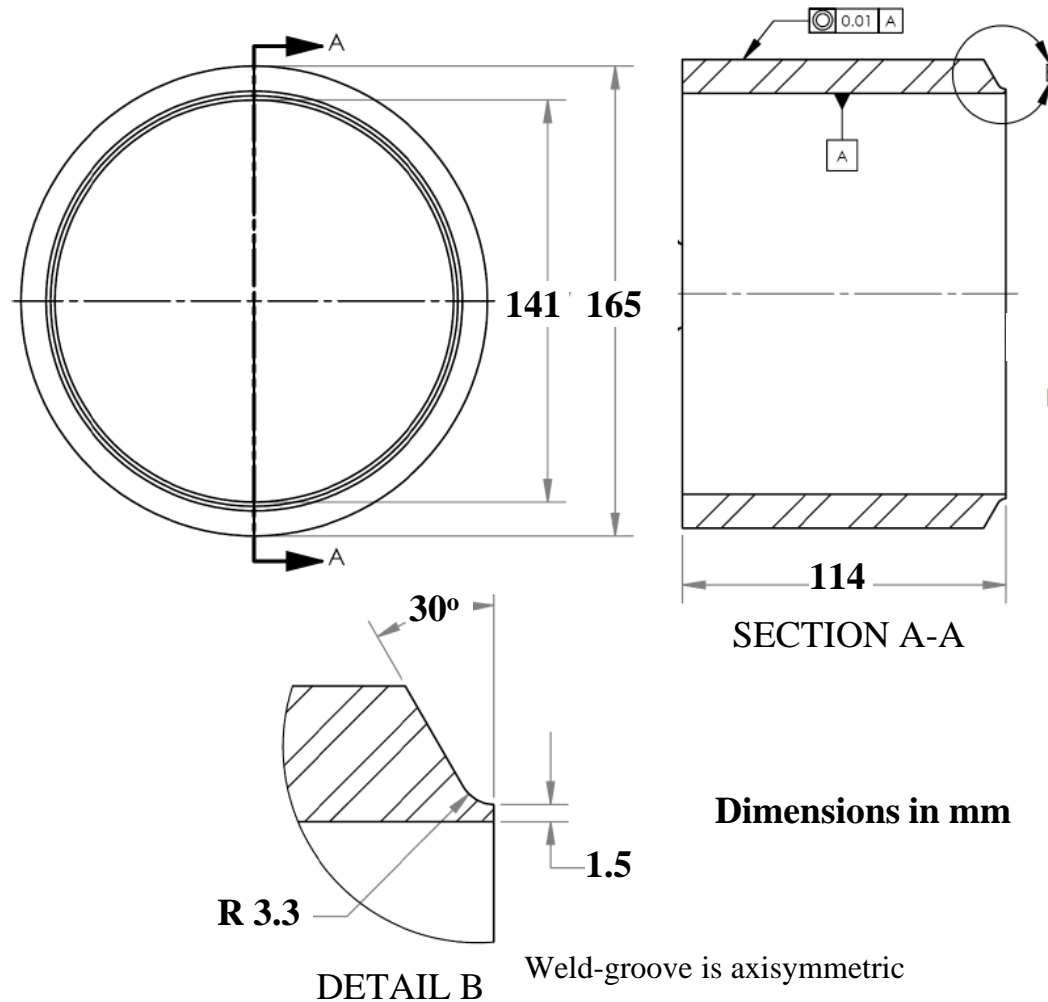
Plate Specimens



Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

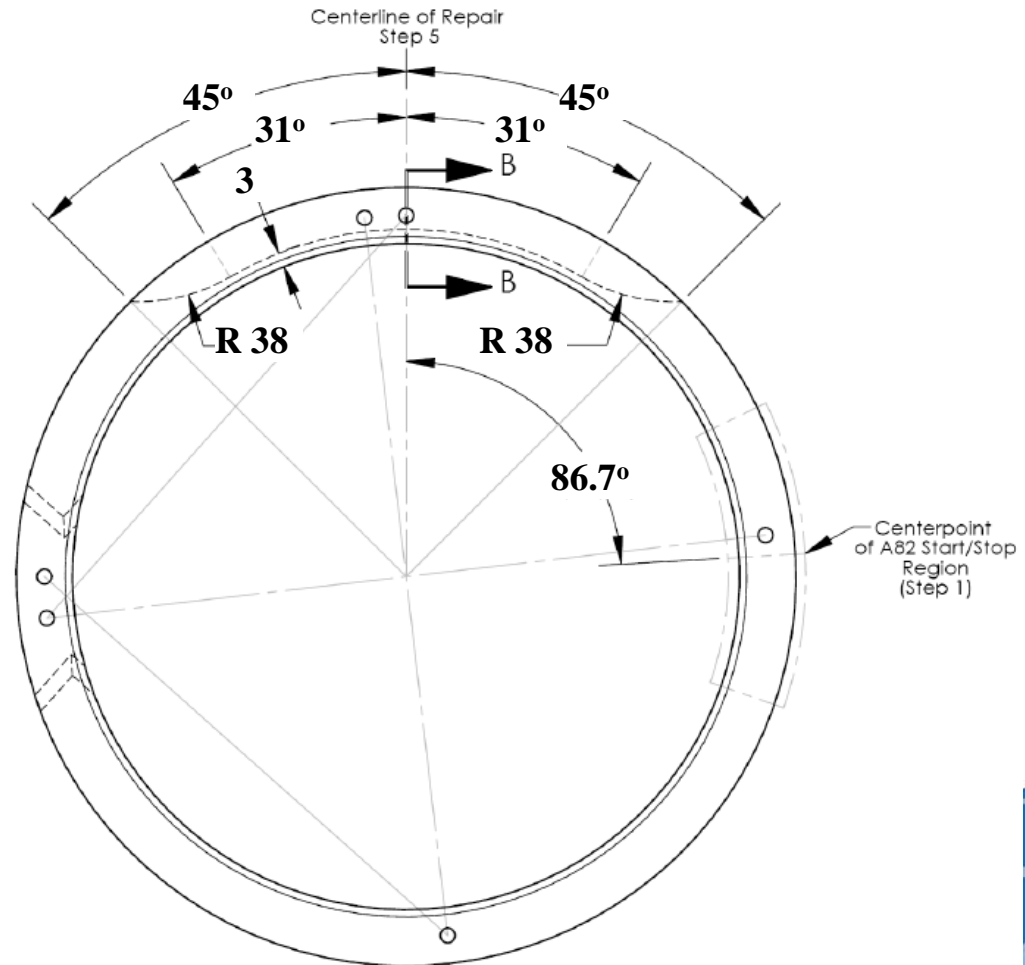
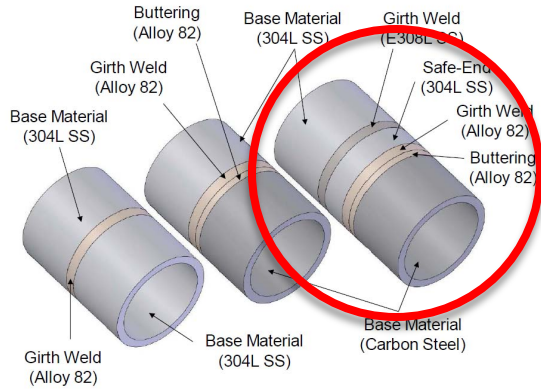
Cylindrical Specimens



Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

Weld Repair

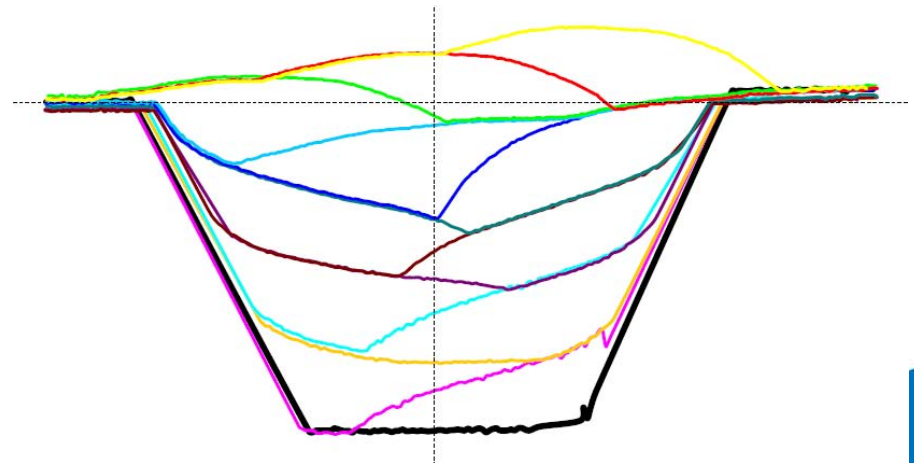
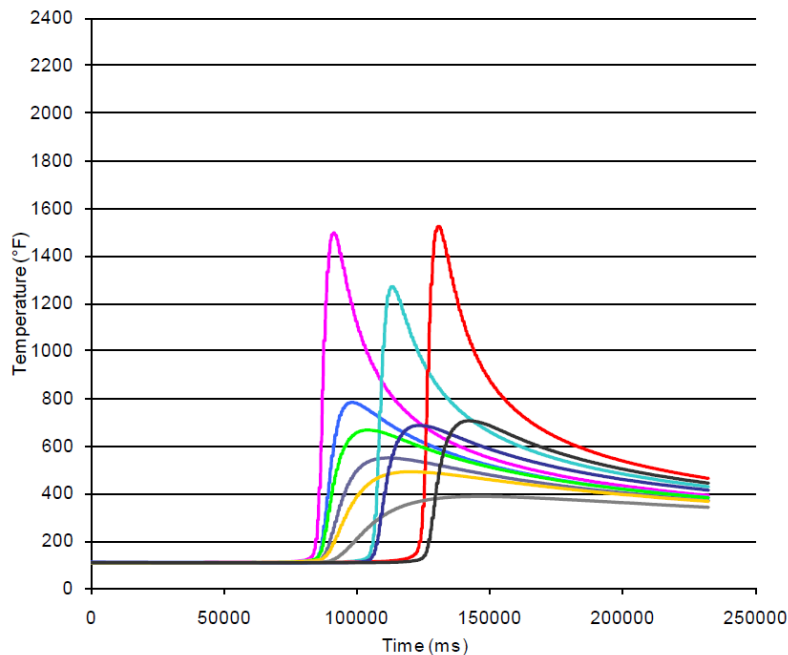


Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

In-Process Characterization

- Thermocouples were spot welded on the specimens to characterize temperature history at different locations
- Laser profilometer was used to measure individual weld beads

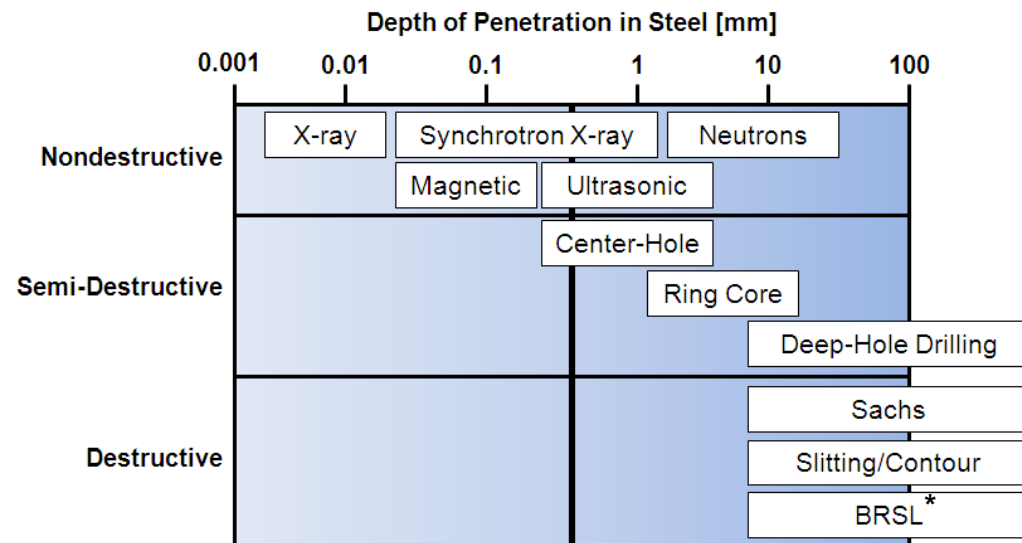


Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

WRS Measurement Techniques

- Neutron diffraction - Oak Ridge National Laboratory
- Contour - Hill Engineering
- X-ray diffraction - TEC
- Surface Hole Drilling - LTI
- Deep Hole Drilling - VEQTER
- Ring-Core - LTI
- Slitting - Hill Engineering



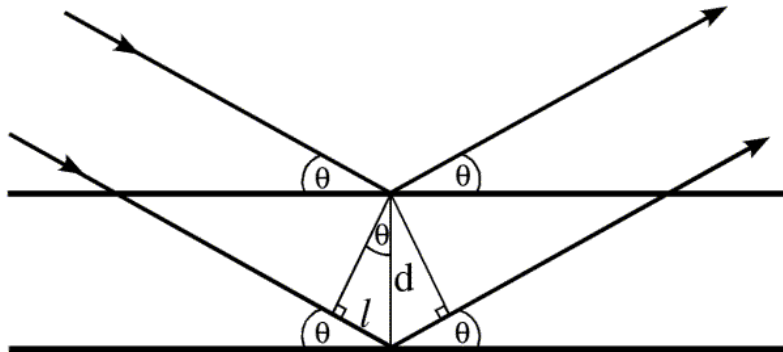
Source: Veqter, Ltd.

* Block Removal and Surface Layering

Phase I: Scientific Weld Specimens

Diffraction Techniques

- Measurement of lattice spacing, based upon the position of diffraction peaks
- Relies upon proper measurement of reference lattice spacing
- X-ray: surface, neutron: bulk



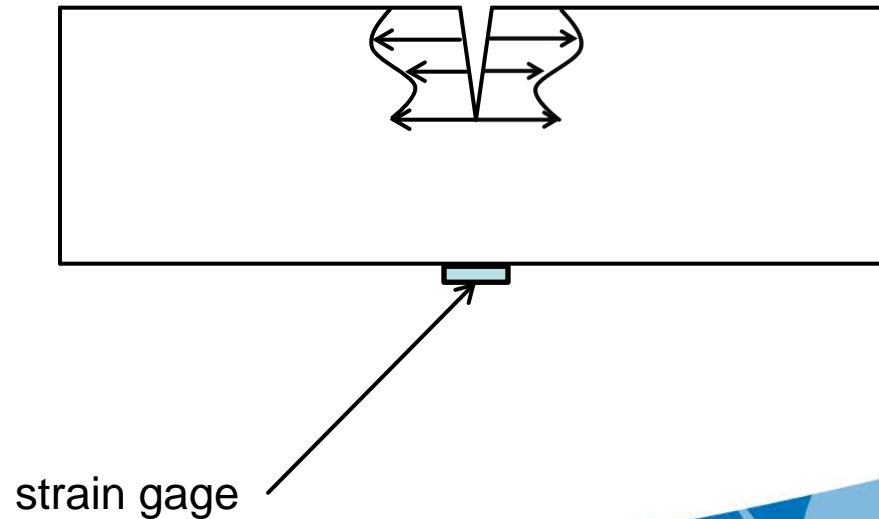
$$\varepsilon_{ii}^{hkl} = \frac{d_{hkl} - d_{hkl,0}}{d_{hkl,0}}$$

$$\sigma_{ii} = \frac{E_{hkl}}{(1 + \nu_{hkl})} \left[\varepsilon_{ii}^{hkl} + \frac{\nu_{hkl}}{(1 - 2\nu_{hkl})} (\varepsilon_{11}^{hkl} + \varepsilon_{22}^{hkl} + \varepsilon_{33}^{hkl}) \right]$$

Phase I: Scientific Weld Specimens

Strain-Relief Techniques

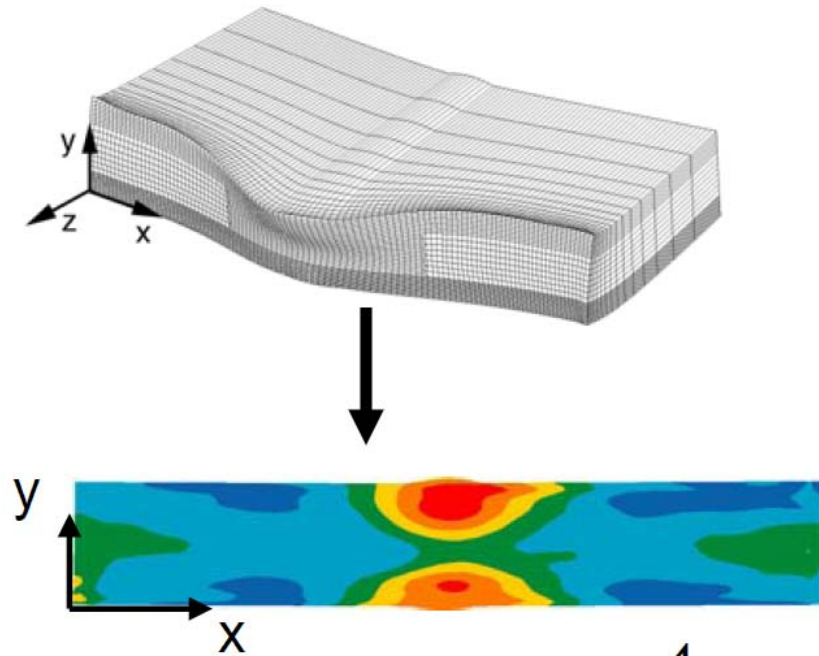
- Incremental slitting: near surface



Phase I: Scientific Weld Specimens

Strain-Relief Techniques

- Contour method: bulk

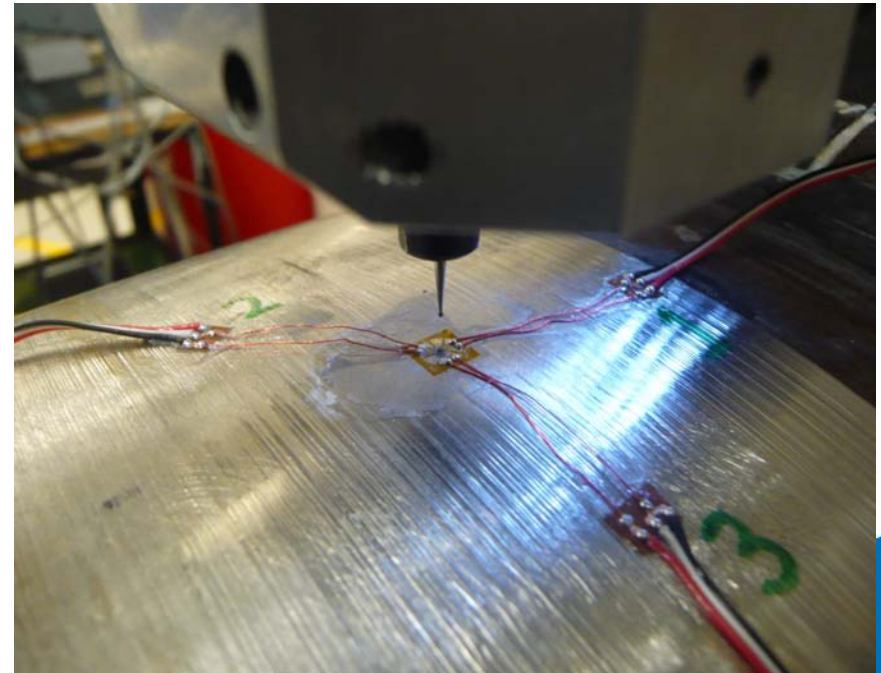
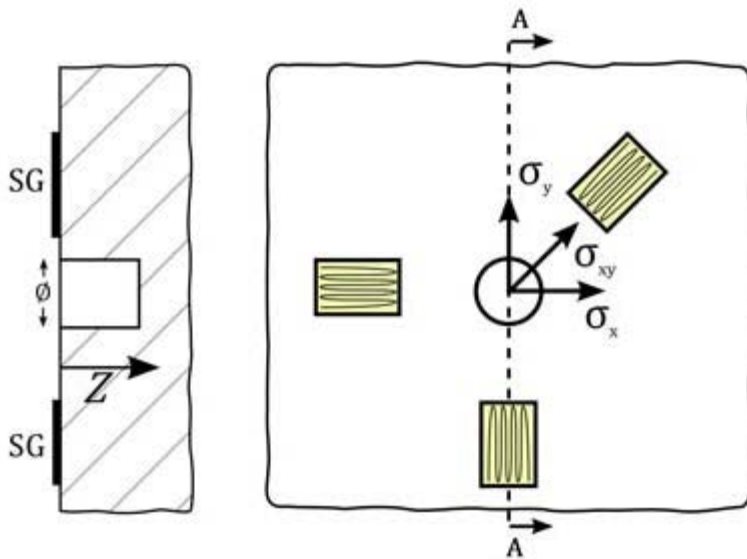


Source: Hill Engineering

Phase I: Scientific Weld Specimens

Strain-Relief Techniques

- Incremental center hole drilling: can be near-surface

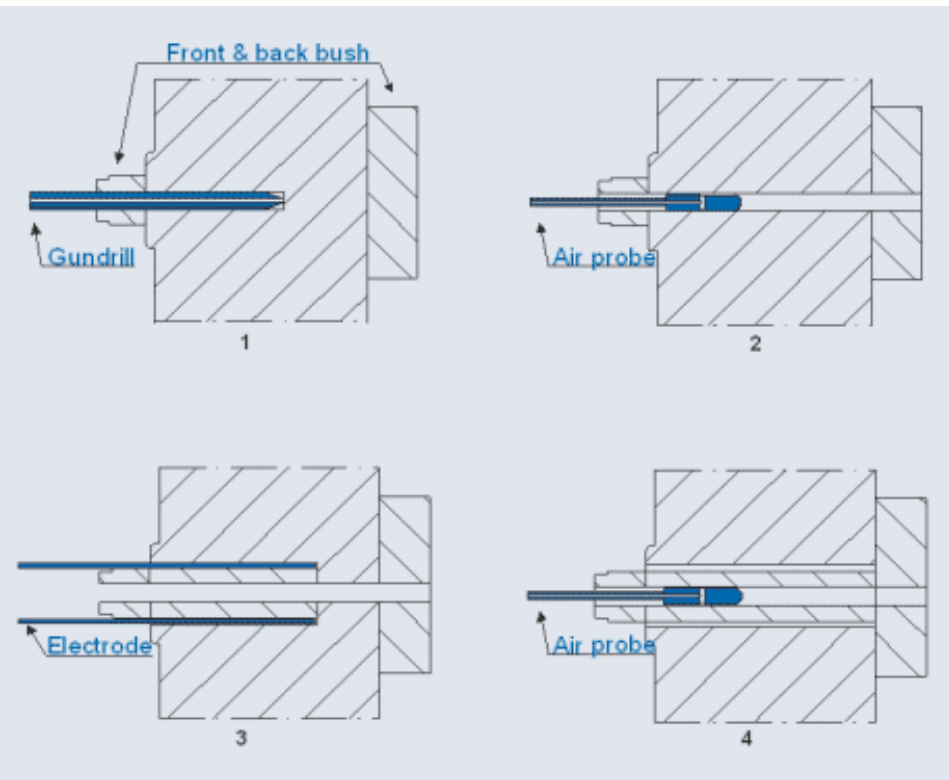


Source: VEQTER, Ltd.

Phase I: Scientific Weld Specimens

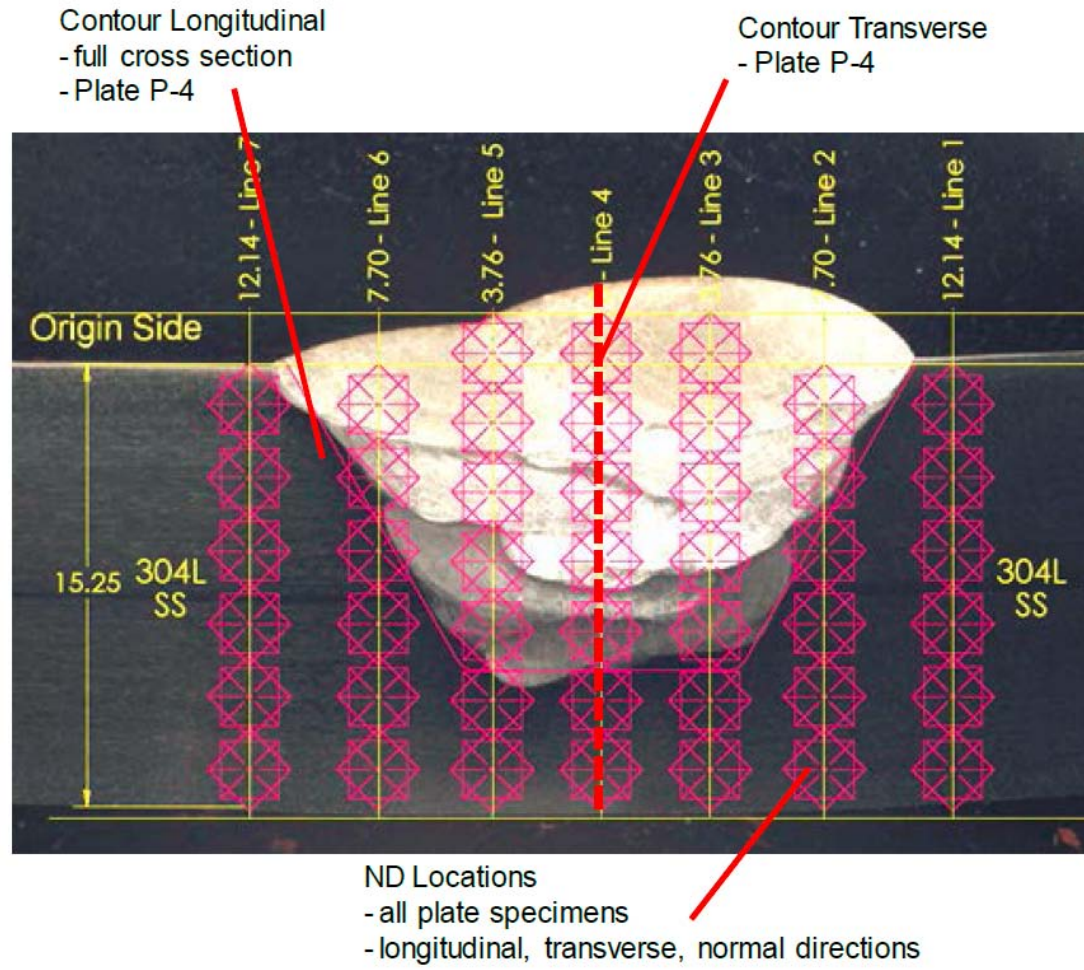
Strain-Relief Techniques

- Deep hole drilling: bulk



Phase I: Scientific Weld Specimens

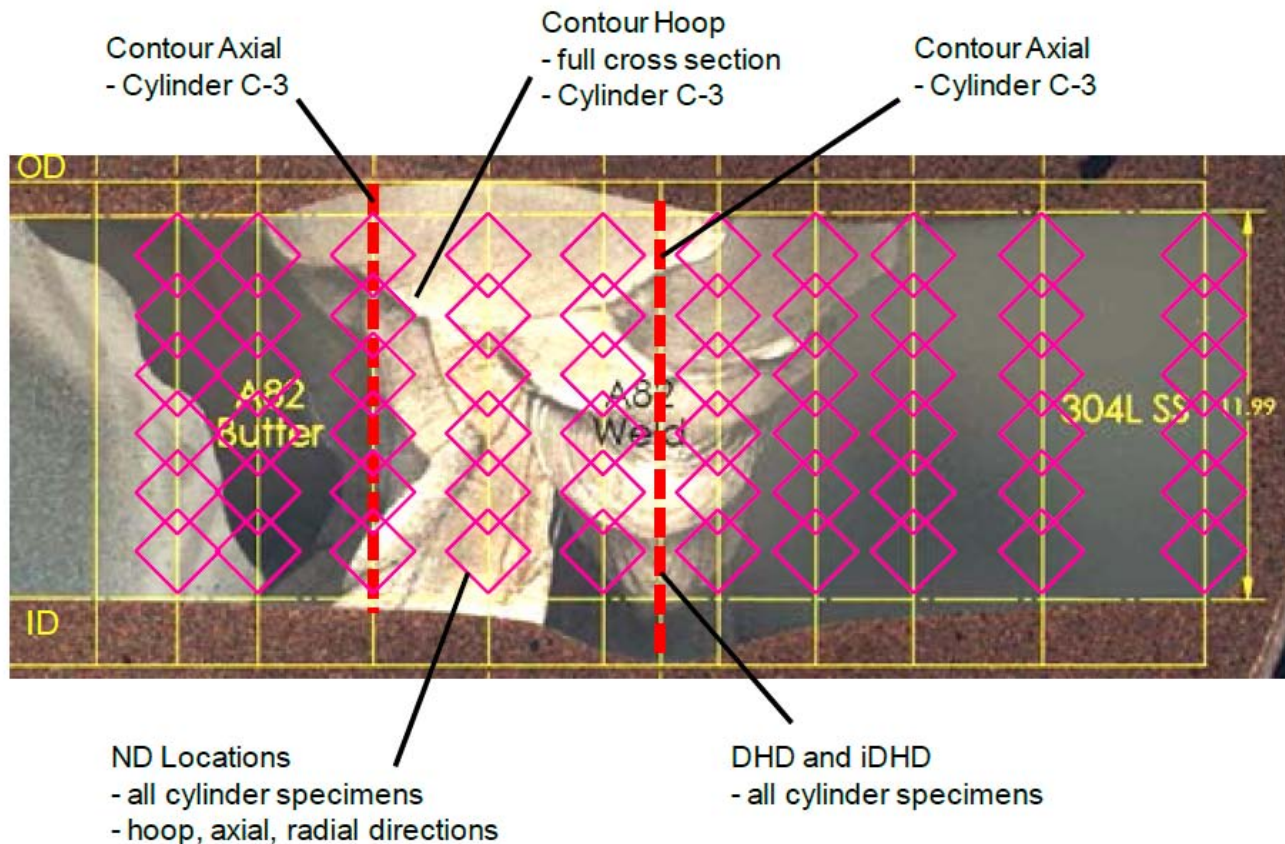
Measurement Summary: Plate Specimens



Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

Measurement Summary: Cylinder Specimens

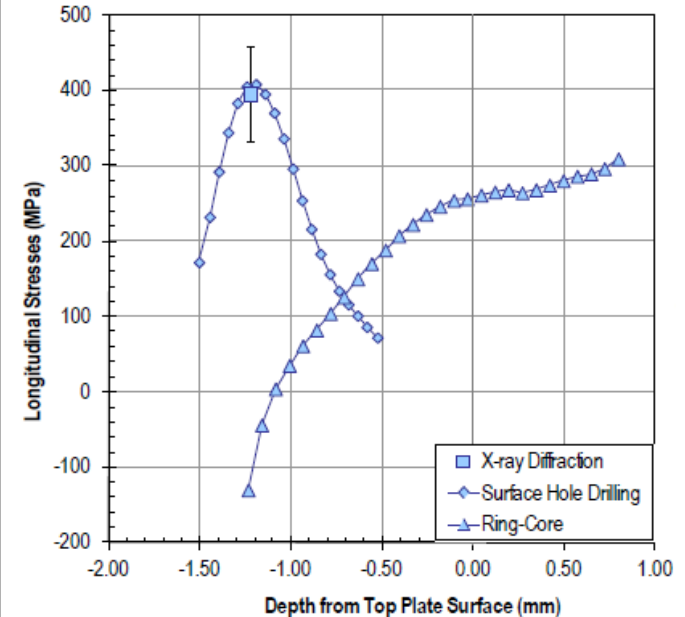
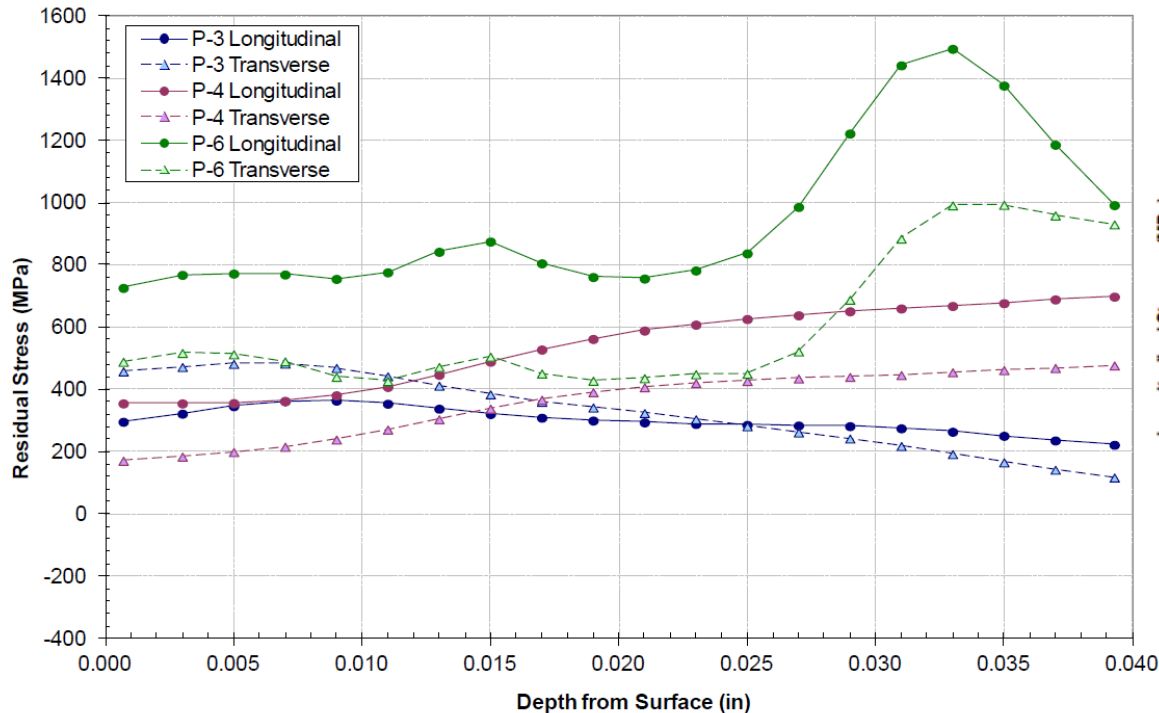


Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

Surface Stress Measurement Results

Hole-Drilling Residual Stress Results



- Unrealistically large values: e.g., 1500 MPa
- Independent techniques did not compare well with each other

Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

Surface Stress Measurement Results

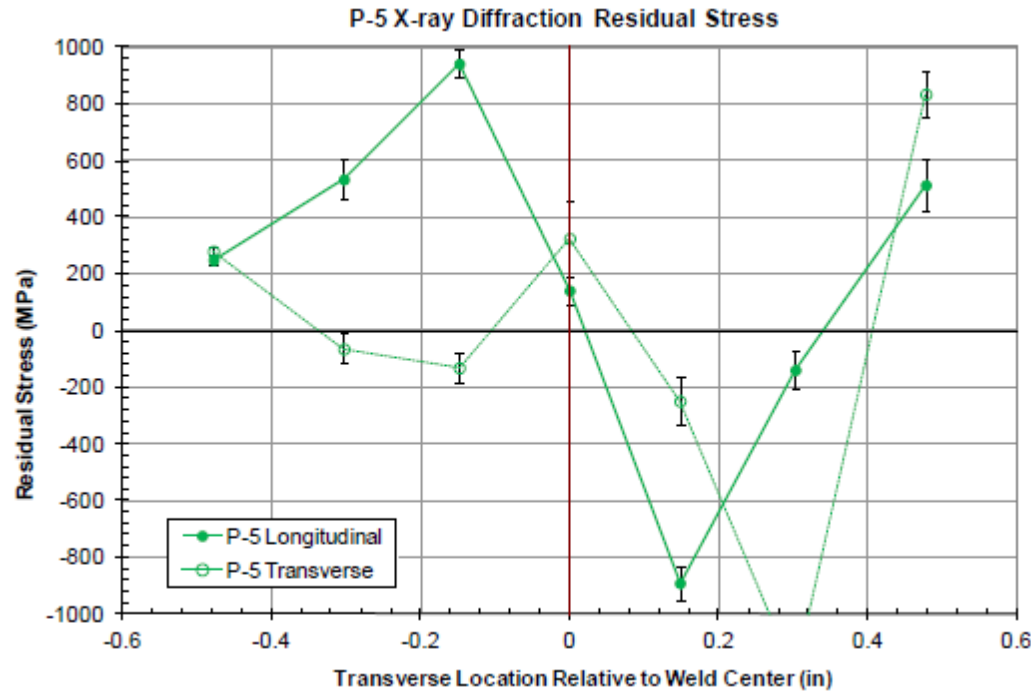


Plate Specimen

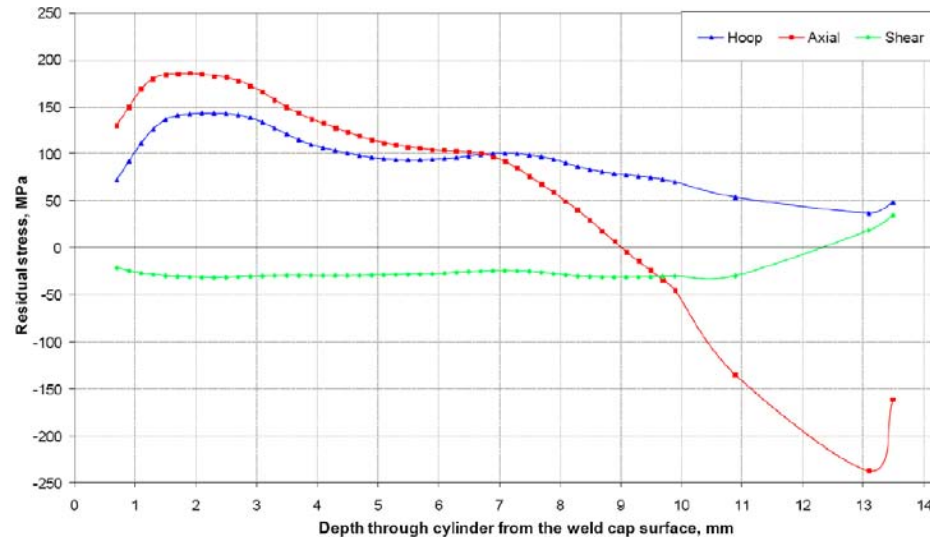
- X-ray diffraction showed large fluctuations in the data: e.g., from 950 to -950 MPa
- Data is asymmetric for a similar metal weld

Source: MRP-316, EPRI, 2011

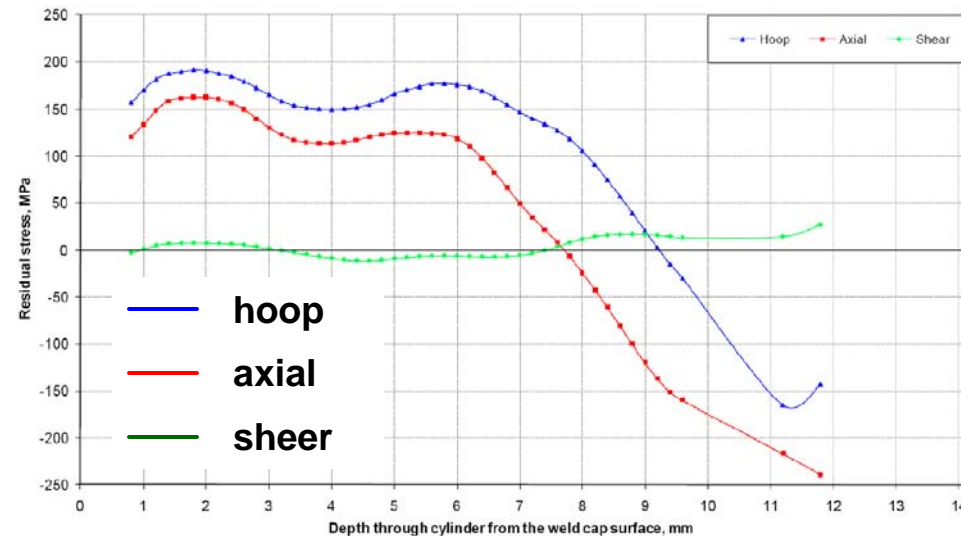
Phase I: Scientific Weld Specimens

Bulk Stress Measurement Results: Deep Hole Drilling

Weld Centerline



Repair Weld Centerline



Cylinder Specimen

- Smooth trends and reasonable magnitudes: e.g., -200 to 200 MPa
- Repair weld significantly affected the hoop stress

Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

Bulk Stress Measurement Results: Contour

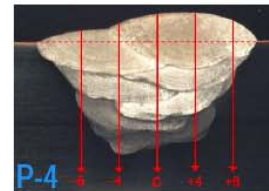
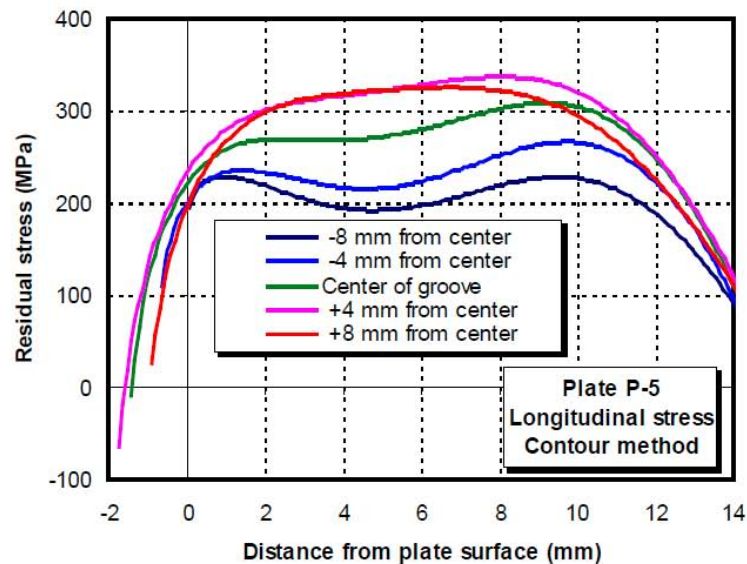
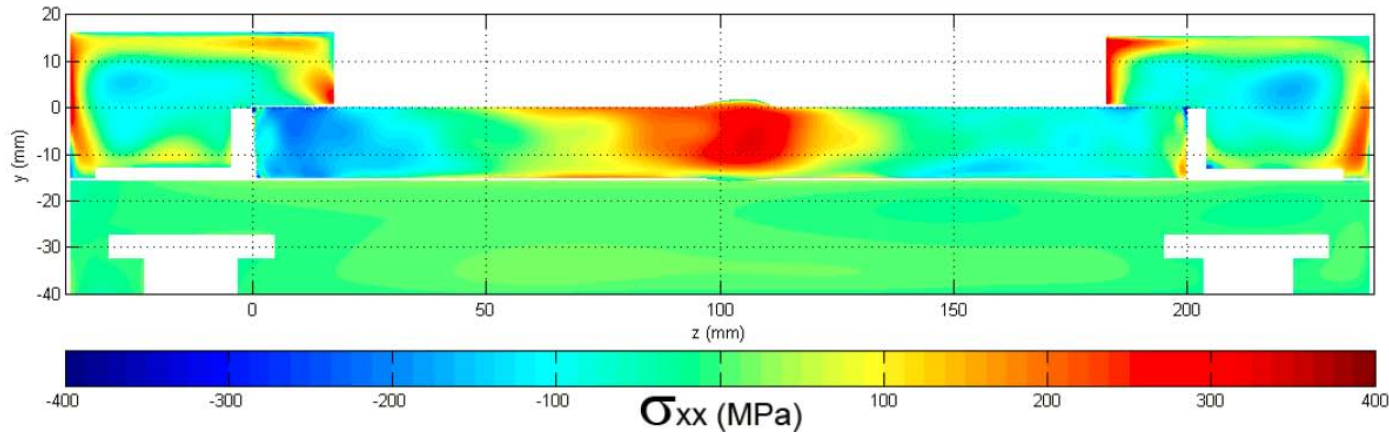
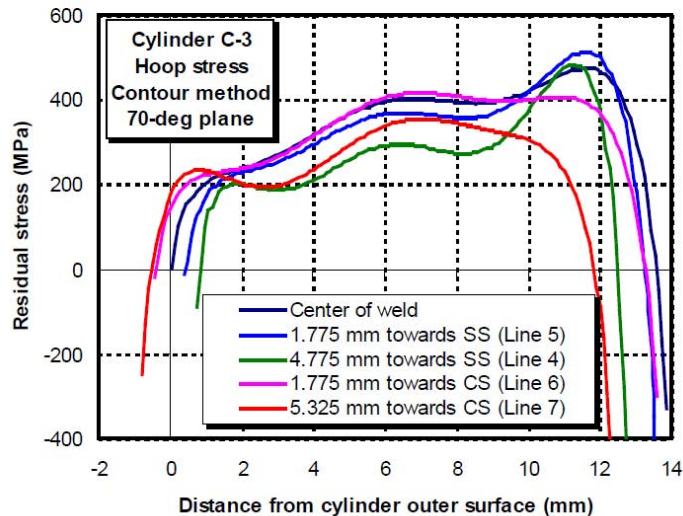
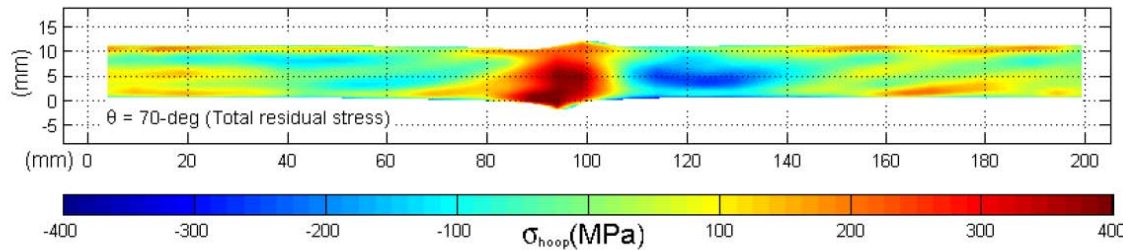


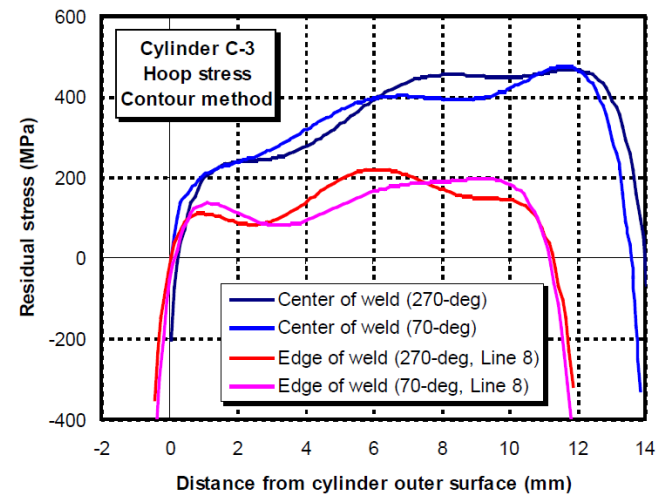
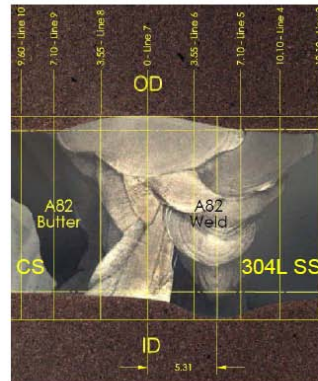
Plate Specimen

Phase I: Scientific Weld Specimens

Bulk Stress Measurement Results: Contour



Ring Specimen

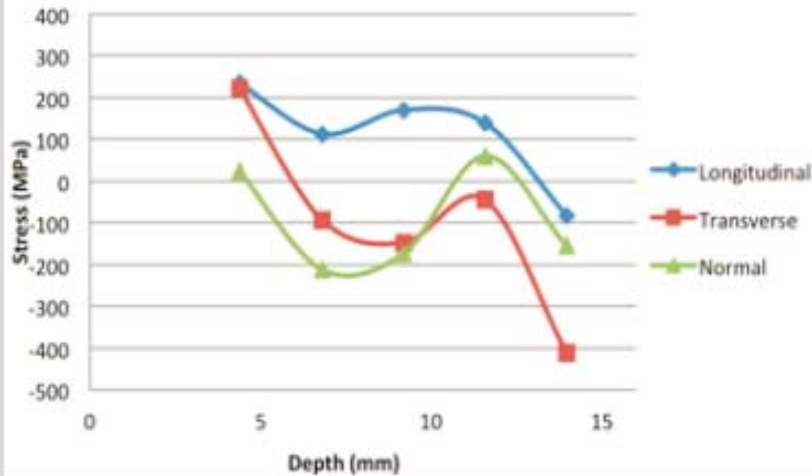


Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

Bulk Stress Measurement Results: Neutron Diffraction

P3 Stress Line 5 (MPa)



P3 Stress Line 3 (MPa)

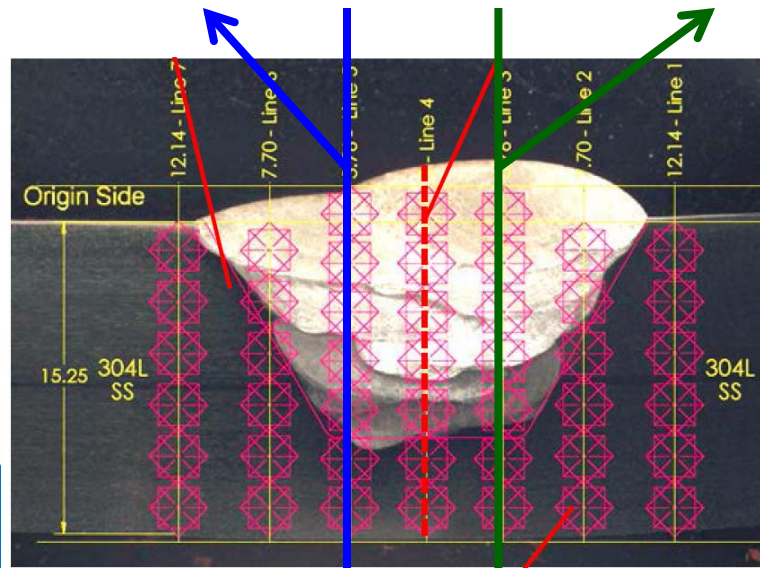
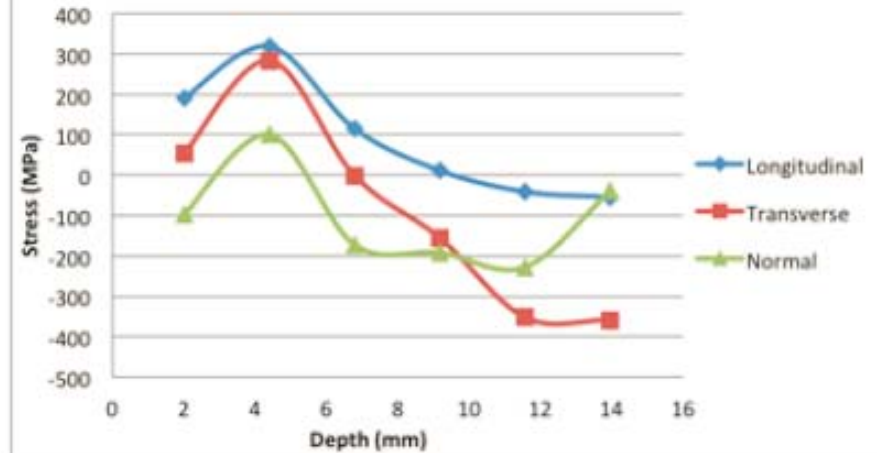


Plate Specimen

Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

Finite Element Modeling

- Sequentially-coupled thermal-mechanical model
 - Temperature distribution in space and time is calculated first
 - Stress distribution in space and time is calculated second
- 2-dimensional plane strain or axisymmetric
 - True nature of the moving heat source is not modeled
 - A given weld pass, with associated heat input, is applied along the entire surface of the part simultaneously
- Weld pass geometry approximated by laser profilometry results

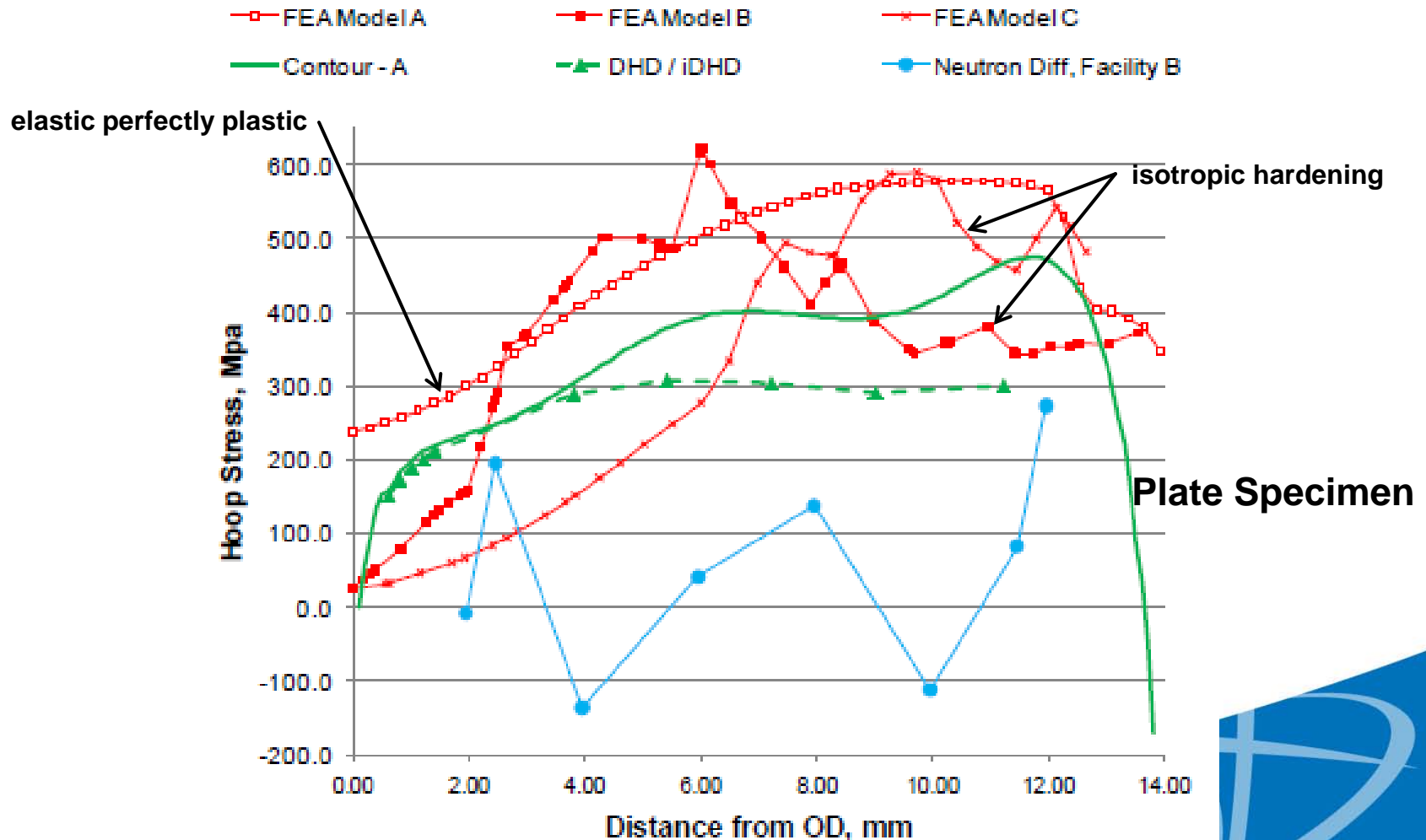
Phase I: Scientific Weld Specimens

Finite Element Modeling

- Thermal and mechanical properties as a function of temperature
 - e.g., specific heat, thermal conductivity, elastic modulus, thermal expansion
- Strain hardening law
 - Plastic deformation is expected
 - Elastic-perfectly plastic, isotropic hardening, kinematic hardening, mixed isotropic-kinematic hardening
- Heat input model
 - Goldak
 - “Tuned” to match the thermocouple measurements

Phase I: Scientific Weld Specimens

Model-Measurement Comparison: More Work to Do



Phase I: Scientific Weld Specimens

Data from a Pulsed Neutron Source

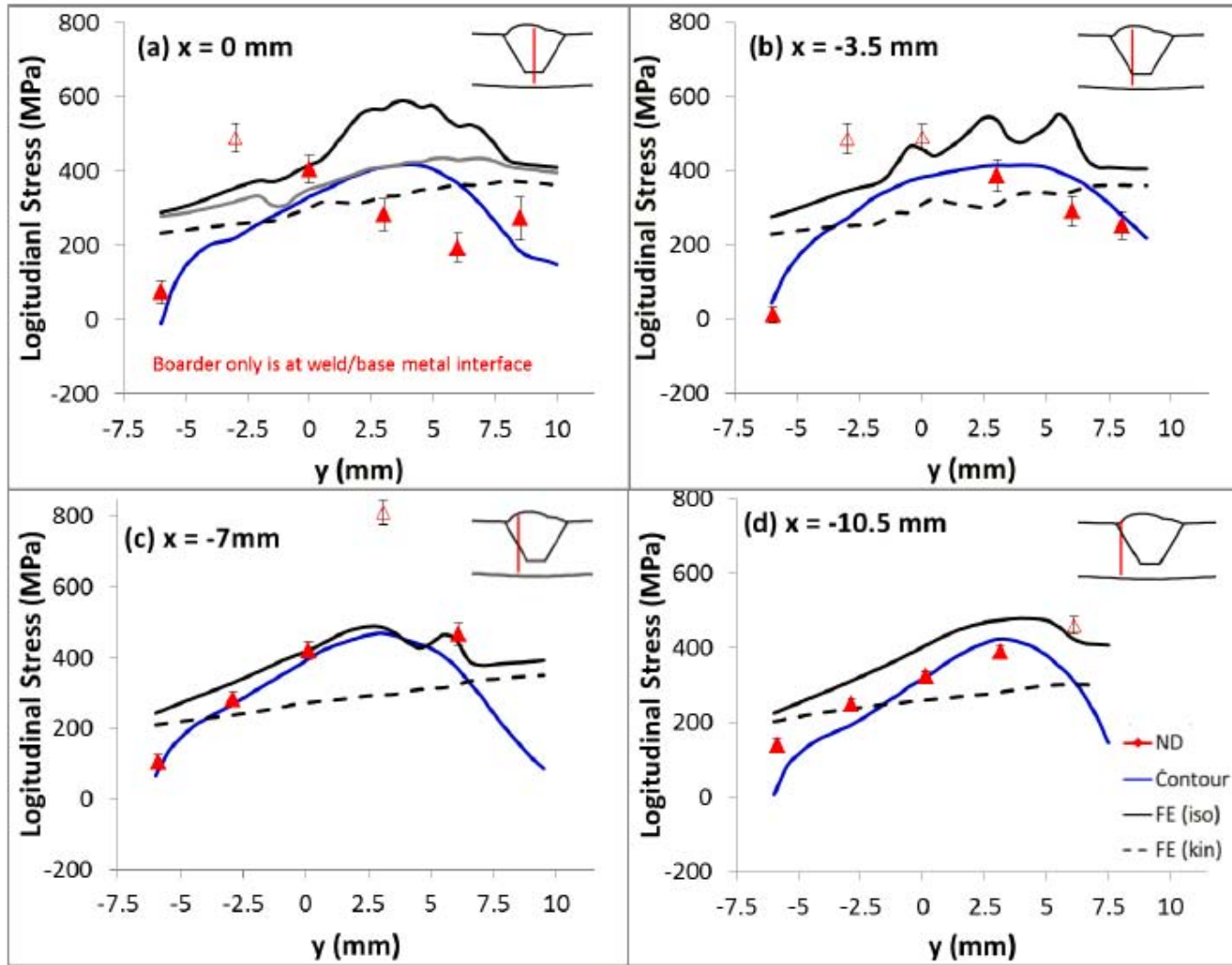


Plate Specimen

Phase I: Scientific Weld Specimens

Measurement Summary

- X-ray and neutron diffraction
 - d_0 varies spatially because of chemical concentration gradients near the weld
 - Texture and grain size effects
 - Less confidence in diffraction-based results
 - Attenuation of the beam can be an issue for thick components
- Strain relief
 - Near-surface results did not appear reasonable
 - For bulk measurements, less experimental difficulties than diffraction

Phase I: Scientific Weld Specimens

Conclusions

- Phase 1 of the program focused on simple weld geometries in order to develop measurement and modeling techniques
- Near-surface stress is experimentally problematic
- In general, mechanical strain relief techniques seemed most reliable
- Agreement between models and experiment seems feasible
- Modeling uncertainty is possible: hardening law

Outline

- Overview
- Phase I Work
- **Phase II Work**
- Phase III Work
- Phase IV Work
- Conclusions

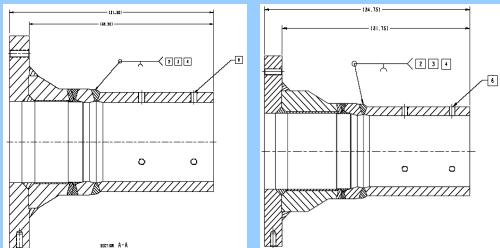
Phase II: Fabricated Prototype Nozzles

Overview

- Full-scale mockups
 - Two mockups: Only Phase IIa discussed here
 - Fabricated under controlled conditions
- Finite Element Round Robin
 - Double-blind: i.e., modelers did not have access to the measurement data
 - Obtain modeling results from a community of independent modelers
- Objectives
 - To validate WRS modeling with experiment
 - To assess WRS modeling uncertainty

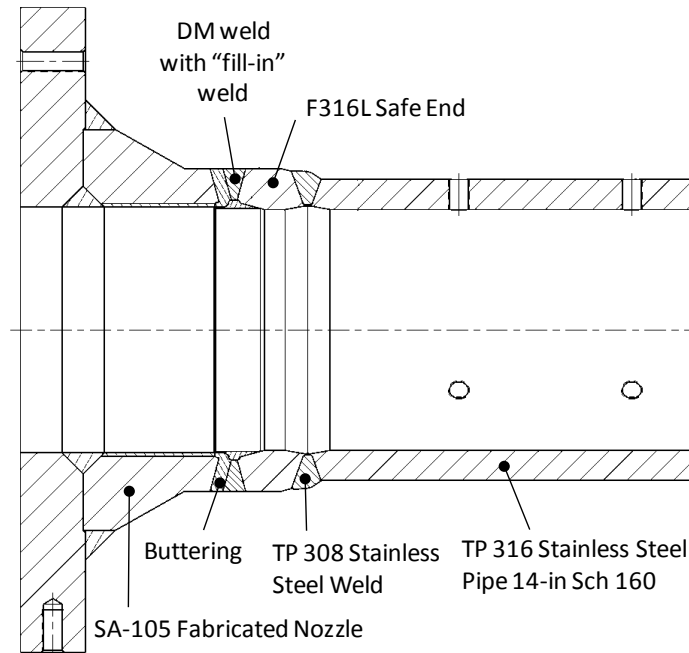
Phase 2 - NRC

- Fabricated Prototypic Nozzles
- Type 8 Surge Nozzles (QTY 2)
- Purpose: Prototypic scale under controlled conditions. Validate FE models.



Phase II: Fabricated Prototype Nozzles

Mockup Fabrication

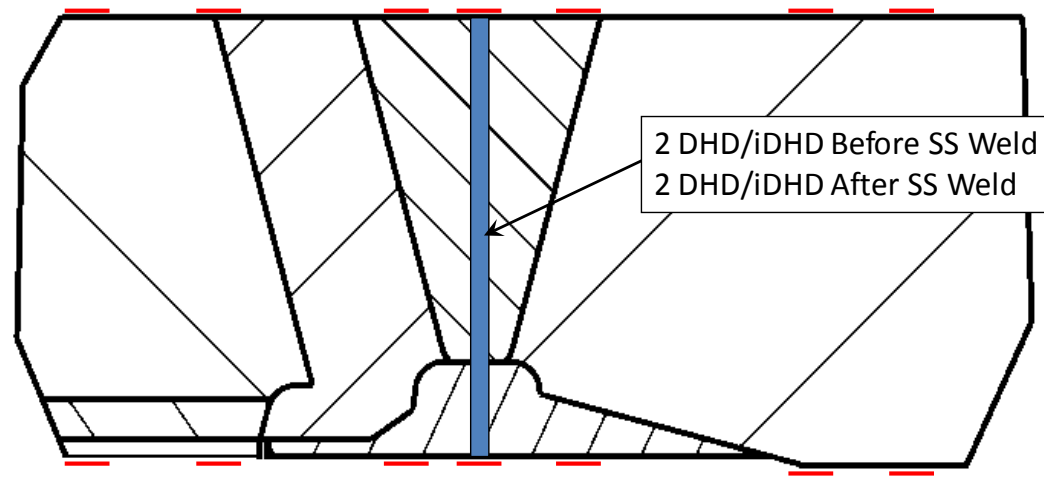


- Pressurizer surge nozzle
- Welding performed by automated gas tungsten arc welding
- Thermocouple and laser profilometry readings
- Rough dimensions: 31" overall length, 11" inner diameter

Phase II: Fabricated Prototype Nozzles

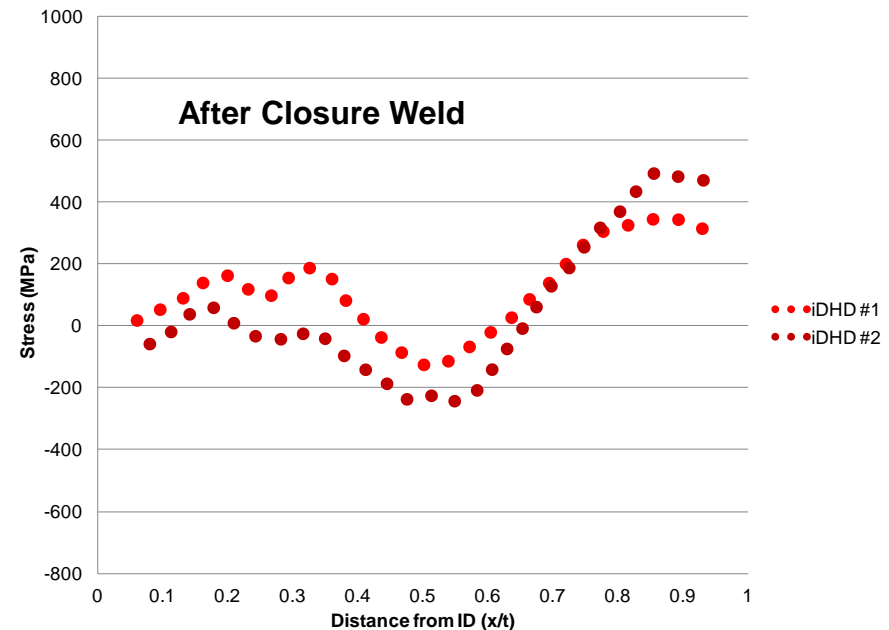
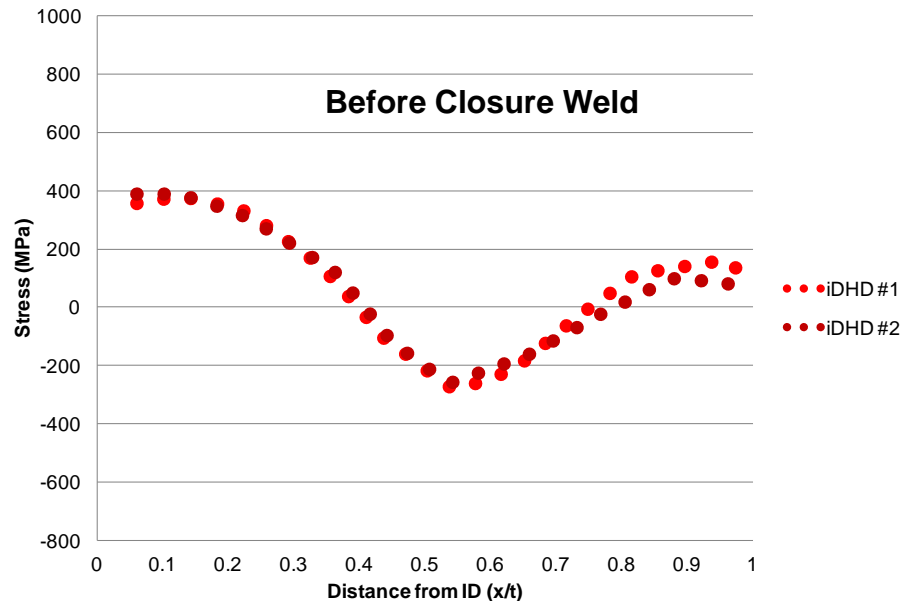
WRS Measurement

- Incremental deep hole and deep hole drilling - bulk
- Measurements taken before and after safe end to pipe weld was complete
 - Safe end to pipe weld can affect the stress field at the dissimilar metal weld



Phase II: Fabricated Prototype Nozzles

Stainless Steel Closure Weld Effect: Deep Hole Drilling

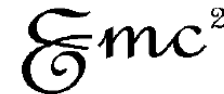


- Axial stresses shown here
- Safe end to pipe weld can potentially have a beneficial affect on inner diameter stress
- Safe end length can be an important parameter

Phase II: Fabricated Prototype Nozzles

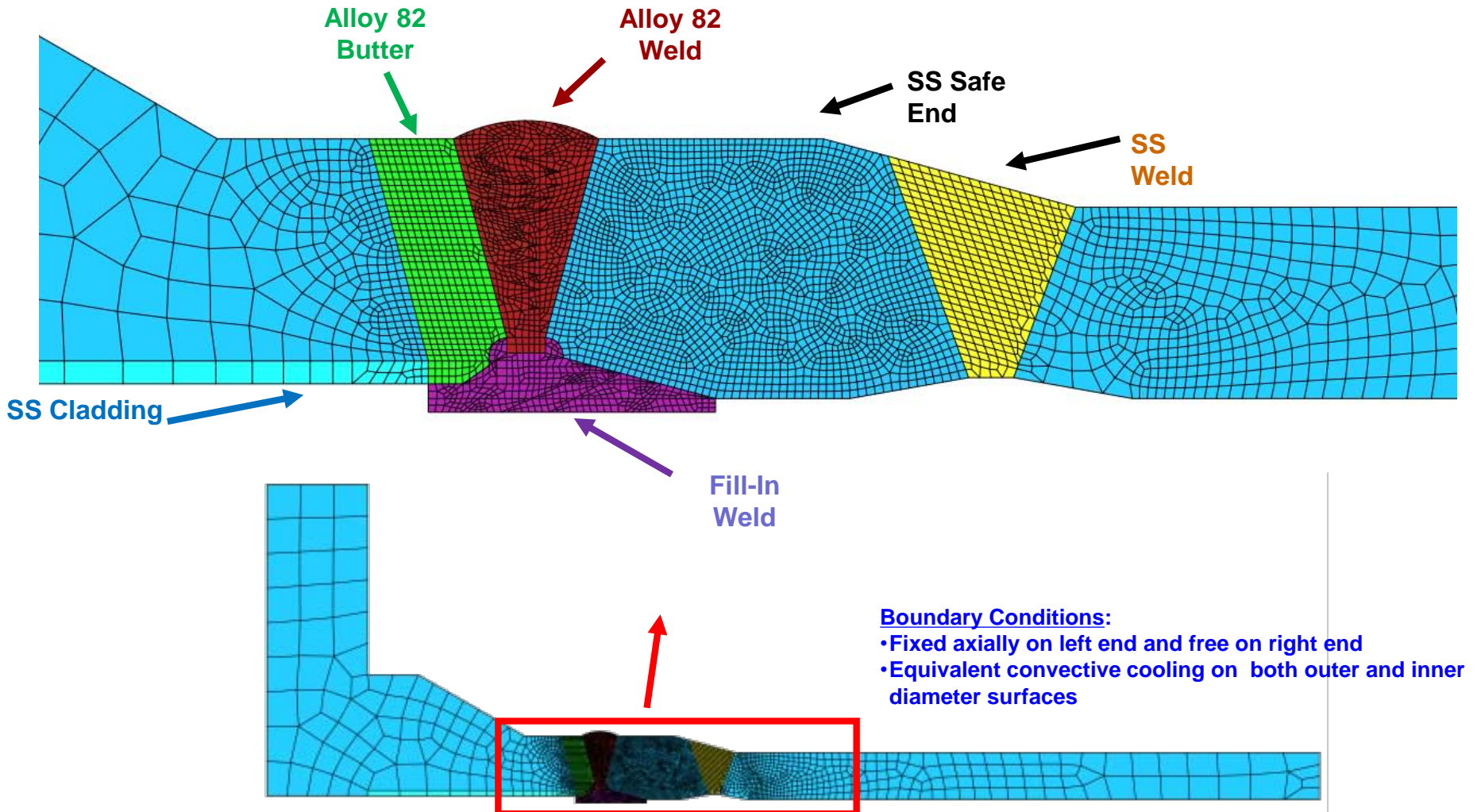
Finite Element Round Robin

- ANSTO (Australia)
- AREVA (USA and EU)
- Battelle (USA)
- Dominion Engineering (USA)
- Goldak Technologies (Canada)
- ESI Group (USA)
- EMC² (USA)
- Inspecta Technology (EU)
- Institute of Nuclear Safety System (Japan)
- Osaka University (Japan)
- Rolls Royce (UK)
- Structural Integrity Associates (USA)
- Westinghouse Electric Company (USA)



Phase II: Fabricated Prototype Nozzles

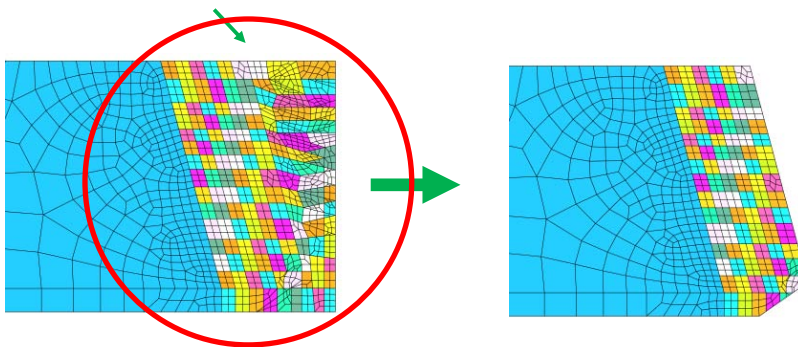
Example Model Geometry



Phase II: Fabricated Prototype Nozzles

Example Model Geometry

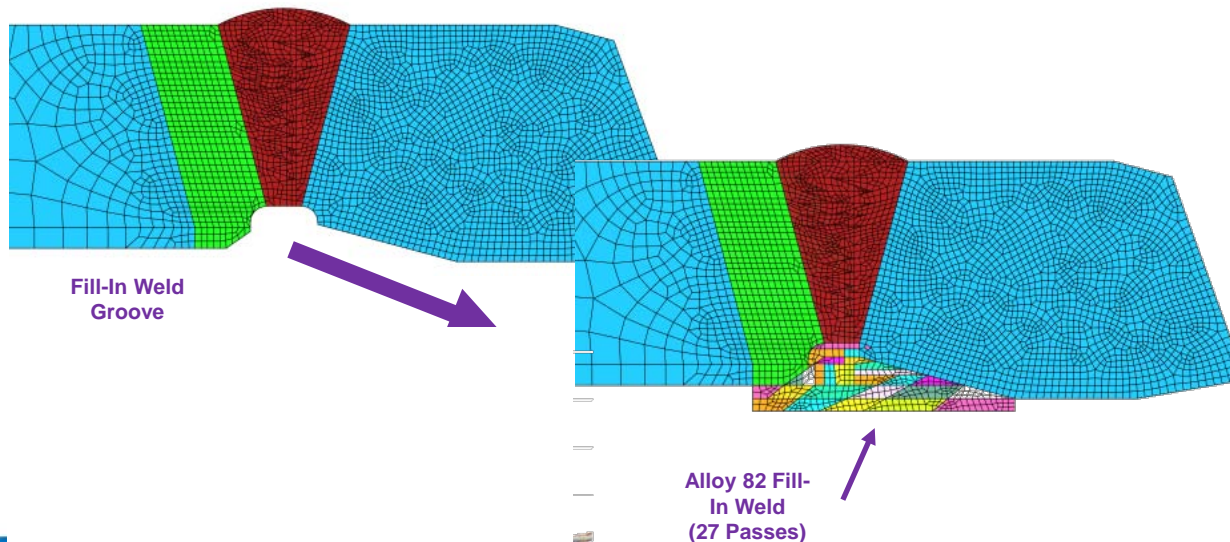
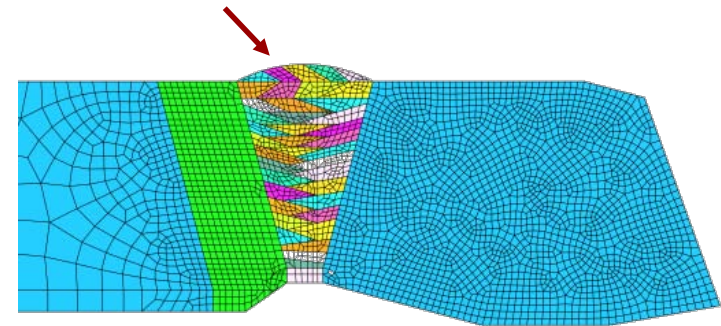
Alloy 82
Butter
(137 Passes)



heat treatment



Alloy 82
Weld
(40 Passes)



Fill-In Weld
Groove

Alloy 82 Fill-
In Weld
(27 Passes)

Phase II: Fabricated Prototype Nozzles

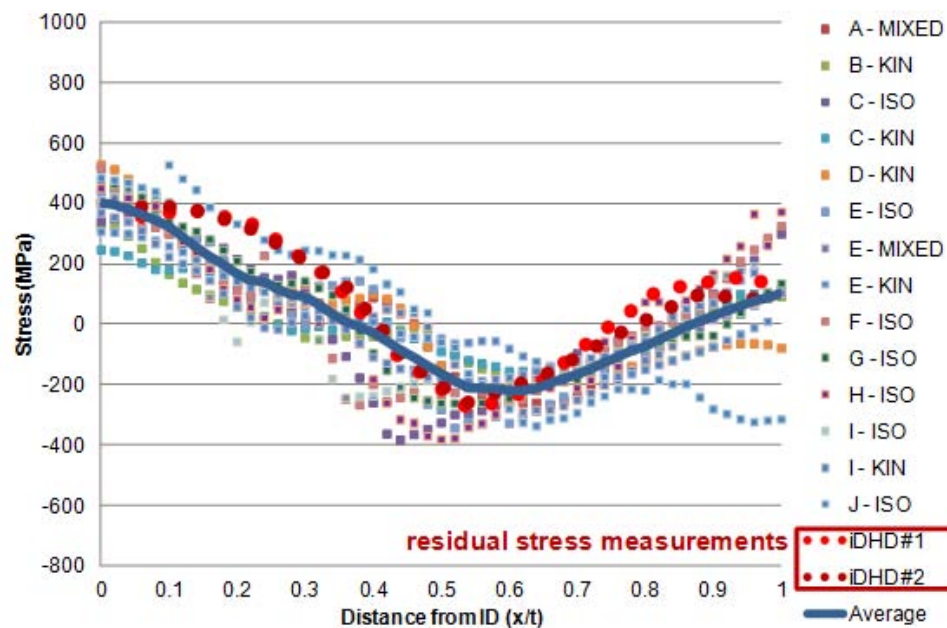
Analysis Stages: Can We Reduce Uncertainty?

- Postulated sources of uncertainty: welding heat input and material properties
- Three analysis stages
 - No thermocouple data or material property data supplied
 - Thermocouple data only supplied
 - Thermocouple and material property data supplied
- Models completed before and after the stainless steel closure weld

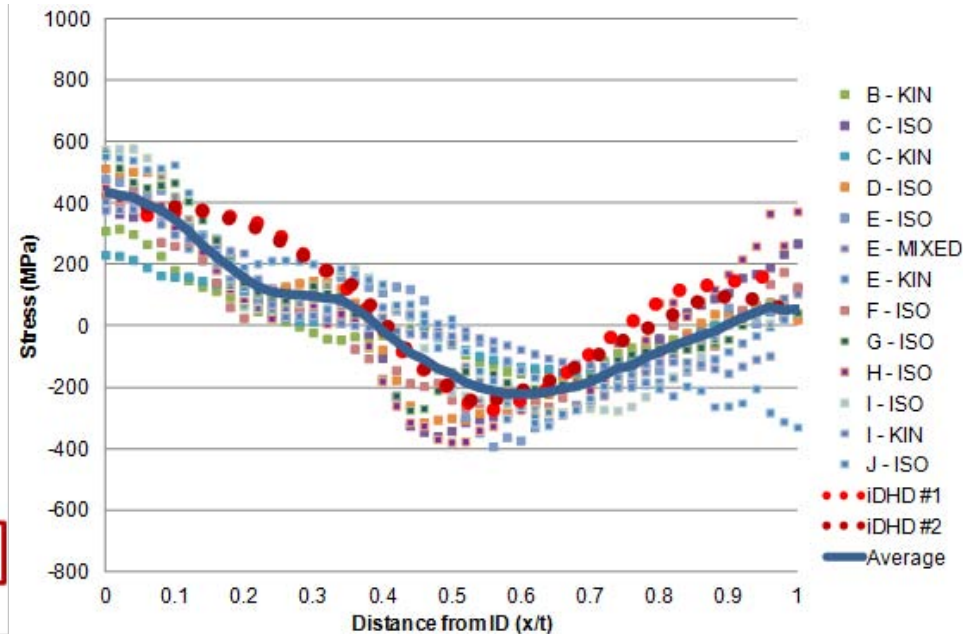
Phase II: Fabricated Prototype Nozzles

FEA Round Robin Results

Pre-stainless steel weld
No material properties
No thermal couple data

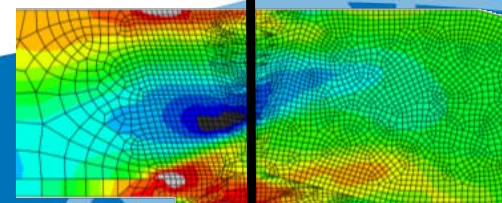


Pre-stainless steel weld
Supplied material properties
Supplied thermal couple data



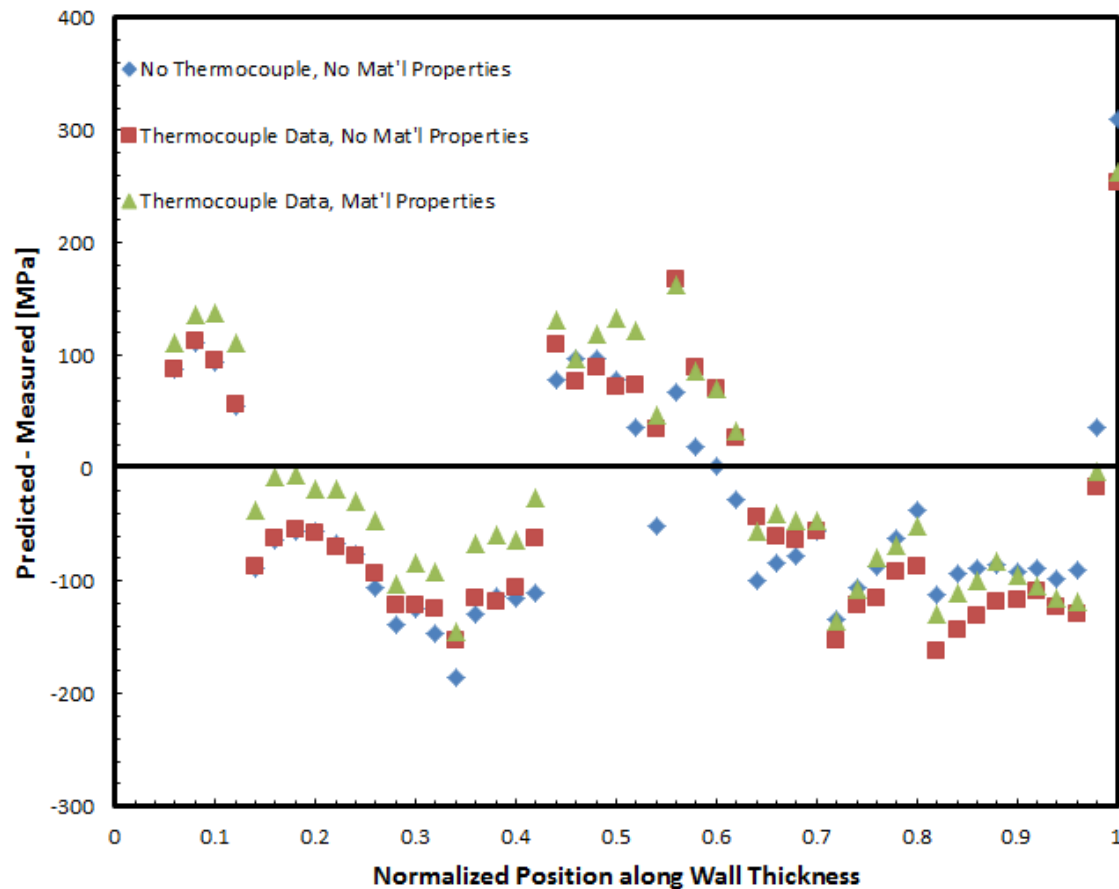
- Axial stresses shown here
- Variety of hardening laws employed
- Modeling uncertainty is the same

Axial Stress



Phase II: Fabricated Prototype Nozzles

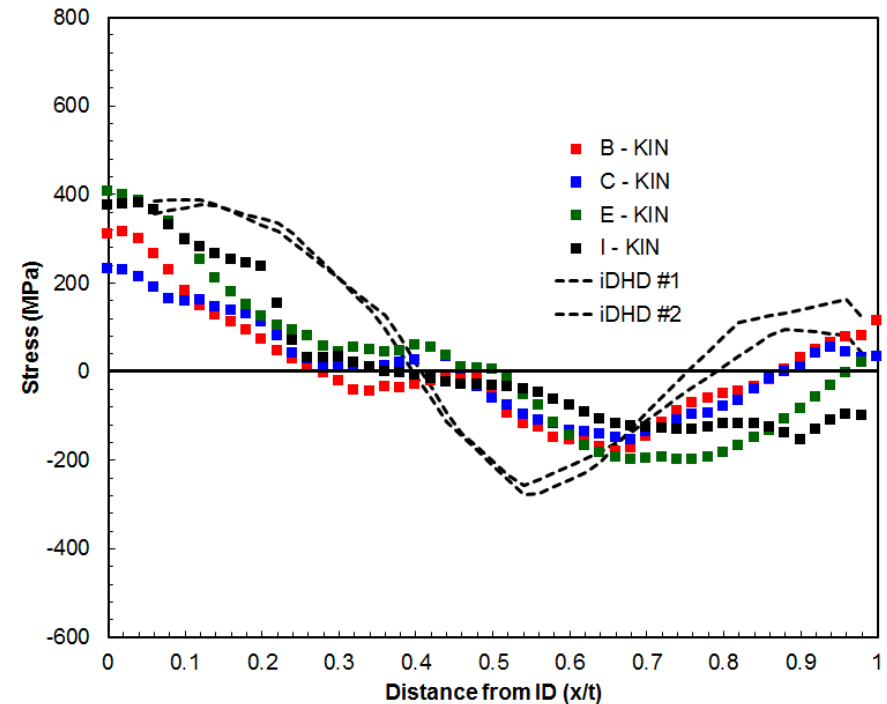
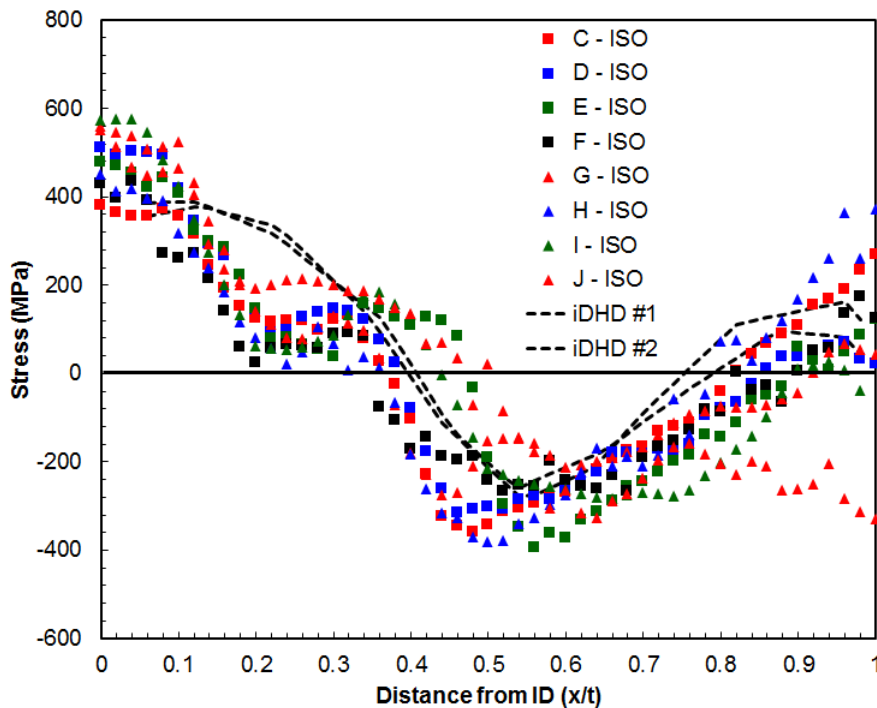
FEA Round Robin Results: Single Modeler



Hoop Stress
Pre-stainless steel weld
Supplied material properties
Supplied thermal couple data

Phase II: Fabricated Prototype Nozzles

FEA Round Robin Results: Separate Hardening Law

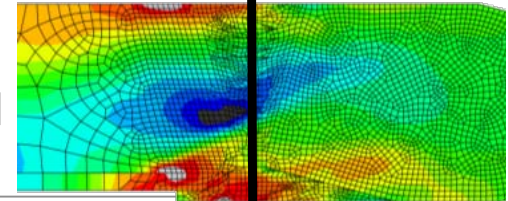


Axial Stress
Pre-stainless steel weld
Supplied material properties
Supplied thermal couple data 46

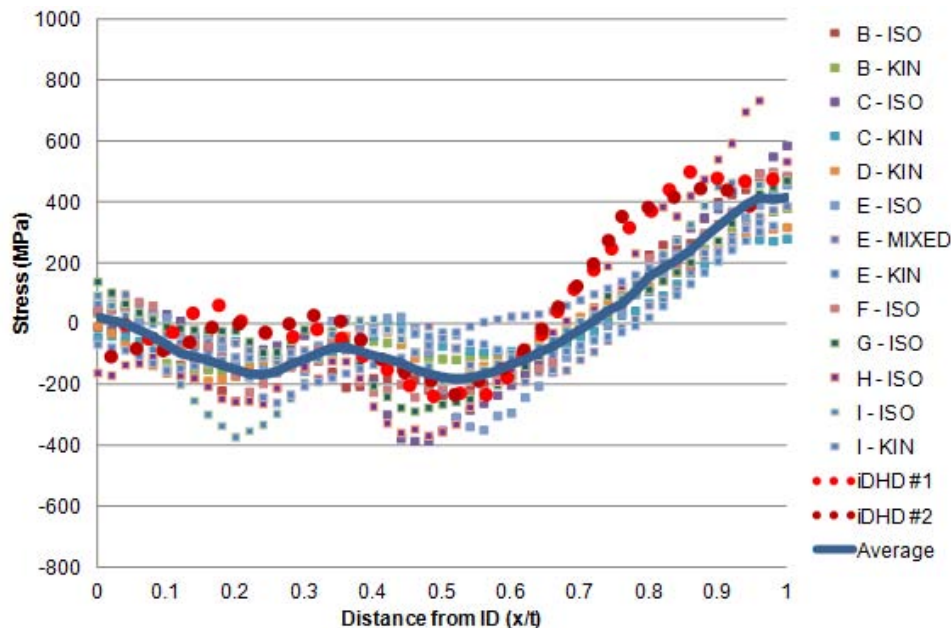
Phase II: Fabricated Prototype Nozzles

FEA Round Robin Results

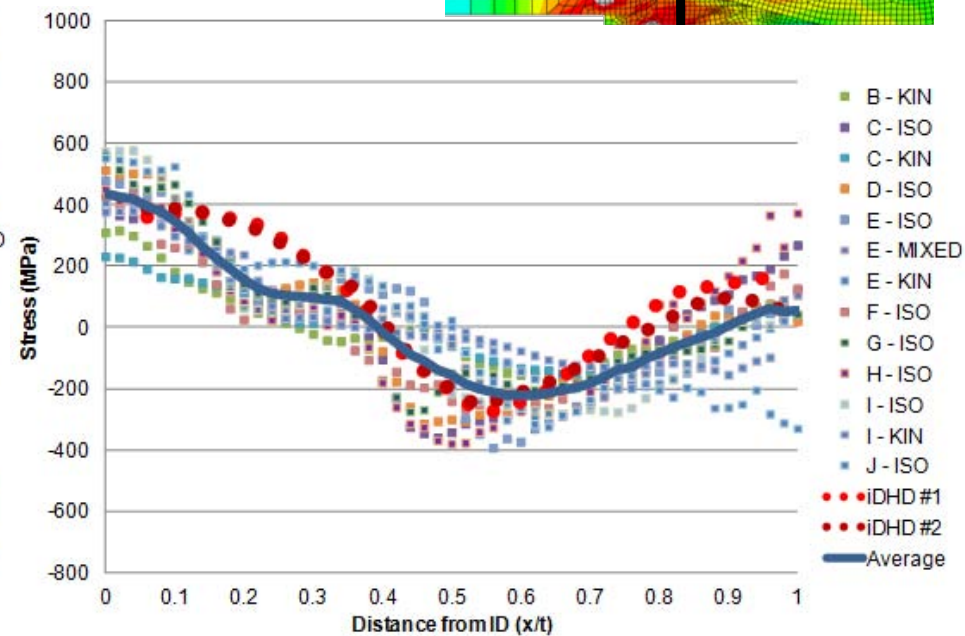
Axial Stress



Including stainless steel weld



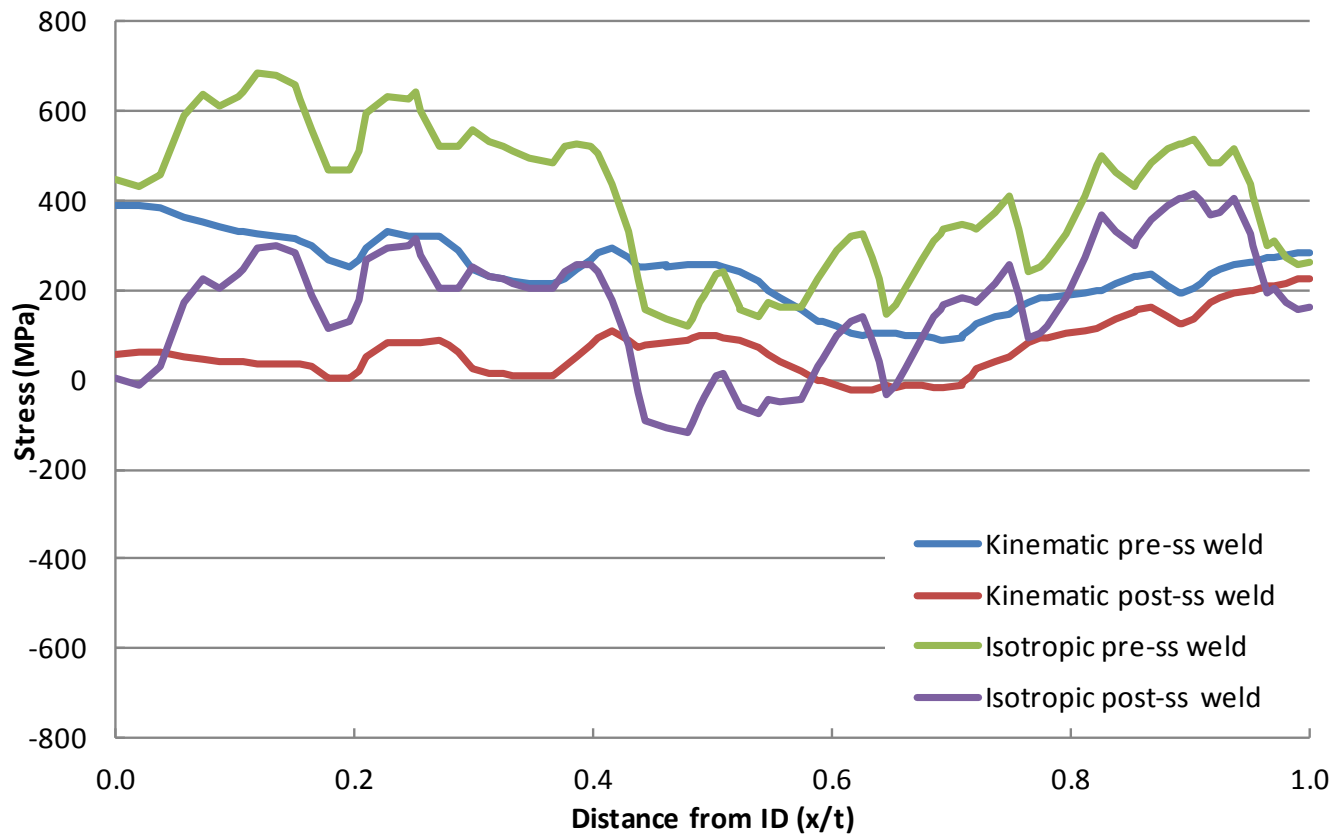
Pre-stainless steel weld



- Axial stresses shown here
- Models show beneficial affect of stainless steel weld for the welding geometry modeled here

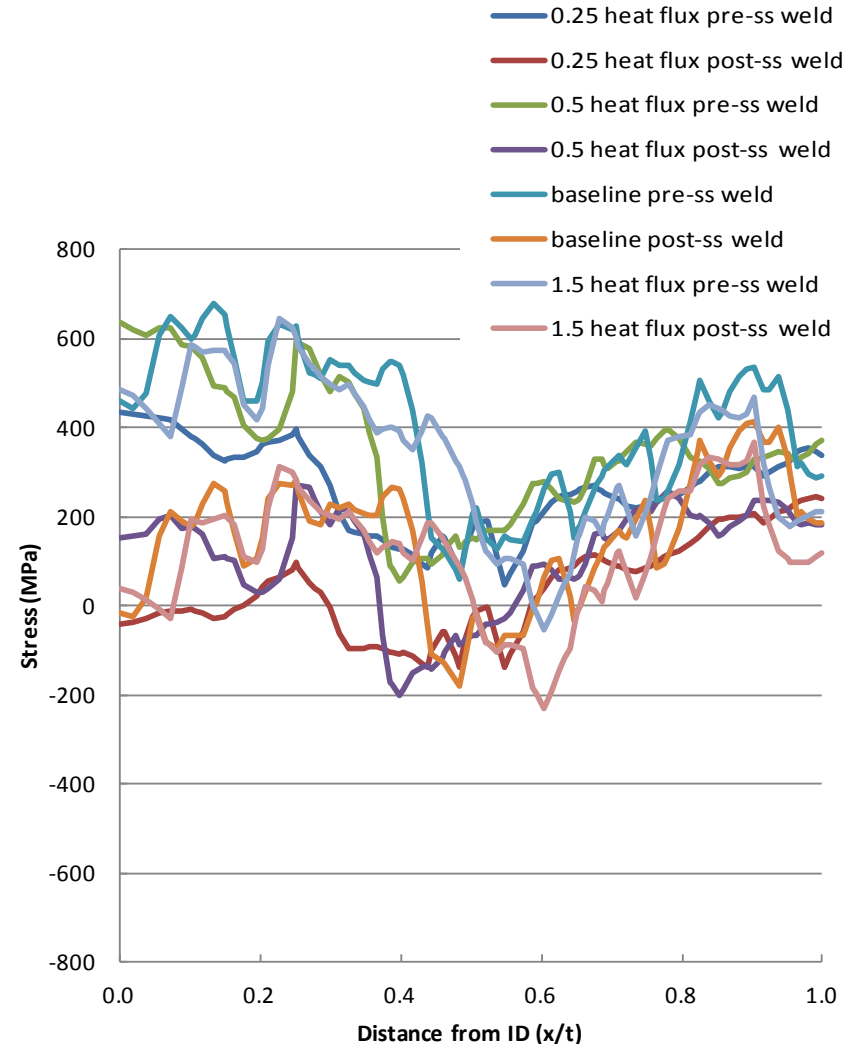
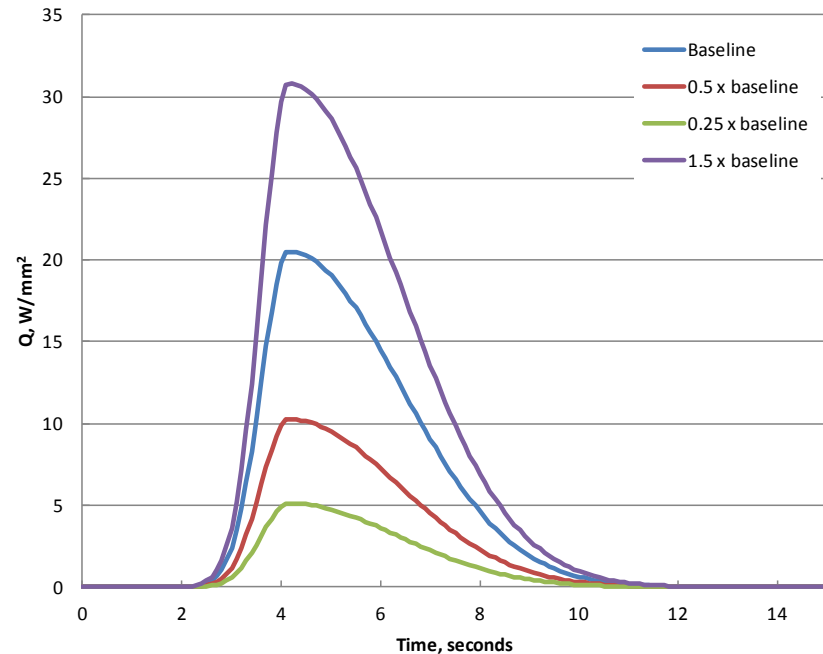
Phase II: Fabricated Prototype Nozzles

Sensitivity Studies: Hardening Law



Phase II: Fabricated Prototype Nozzles

Sensitivity Studies: Heat Input



Phase II: Fabricated Prototype Nozzles

Observations from Phase II Work

- While modeling and measurement results show reasonable agreement in magnitude and profile shape, there is significant model-to-model variability
- Providing thermocouple data and material property data did not decrease modeling uncertainty
- Weld uncertainty
 - Process sequence
 - Arc efficiency (may be reduced by thermal couple data)
 - Material properties
- Modeling uncertainty
 - Choice of hardening law (largest affect on Phase II models)
 - Mesh density, post processing

Outline

- Overview
- Phase I Work
- Phase II Work
- **Phase III Work**
- Phase IV Work
- Conclusions

Phase III: Cancelled Plant Nozzles

Overview

- Full-scale components
 - Actual pressurizer nozzles fabricated for intended service
- Finite Element Round Robin
 - Double-blind: i.e., modelers did not have access to measurement data
 - Obtain modeling results from a community of independent modelers
- Objectives
 - To validate WRS modeling with experiment
 - To assess WRS modeling uncertainty

Phase 3 - EPRI

•Plant Components

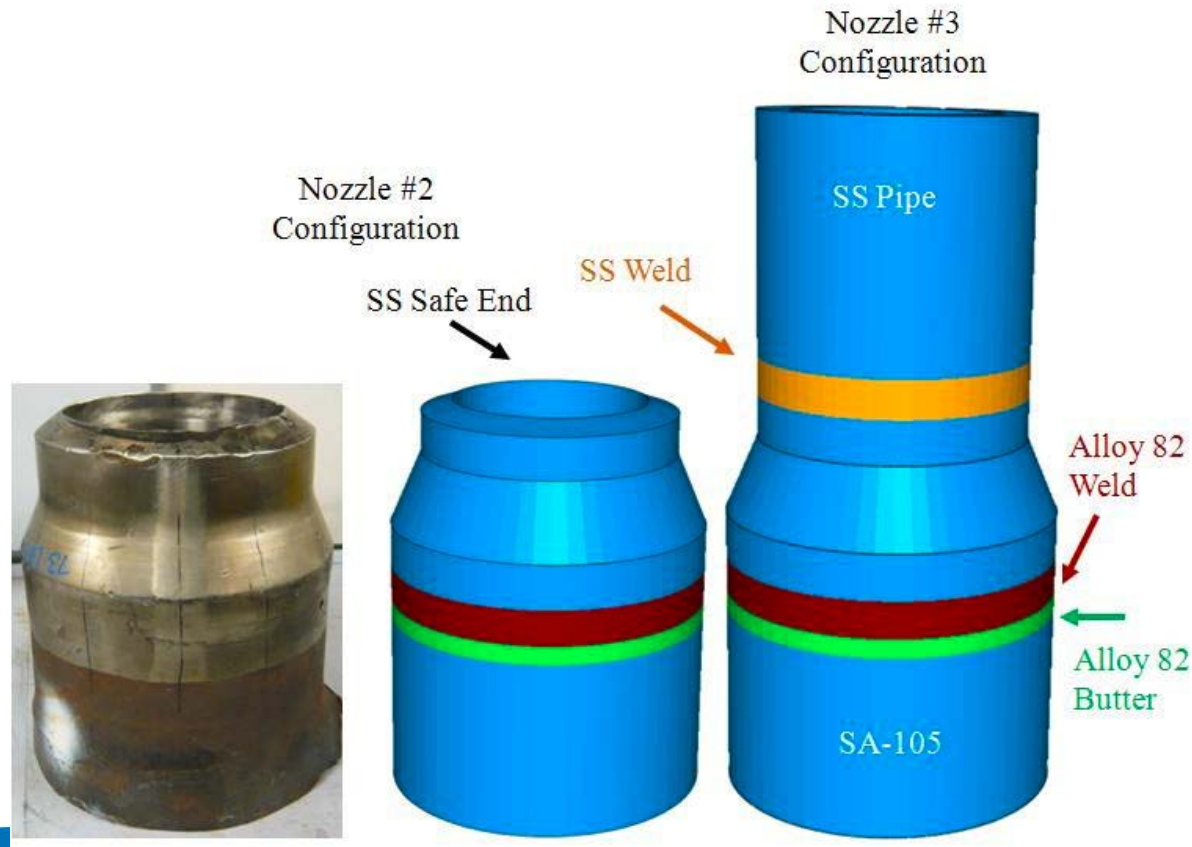
- WNP-3 S&R PZR Nozzles (QTY 3)
- Purpose: Validate FE models.



Phase III: Cancelled Plant Nozzles

Overview

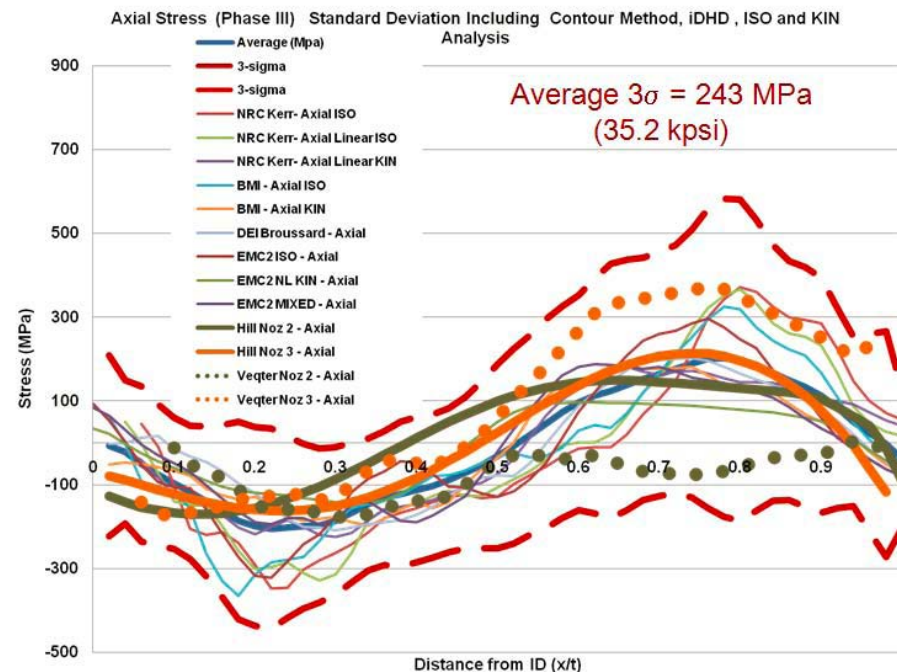
- Two nozzles required in order to apply the destructive contour method to both cases
- Outer diameter = 200 mm, Phase IIa was 350 mm



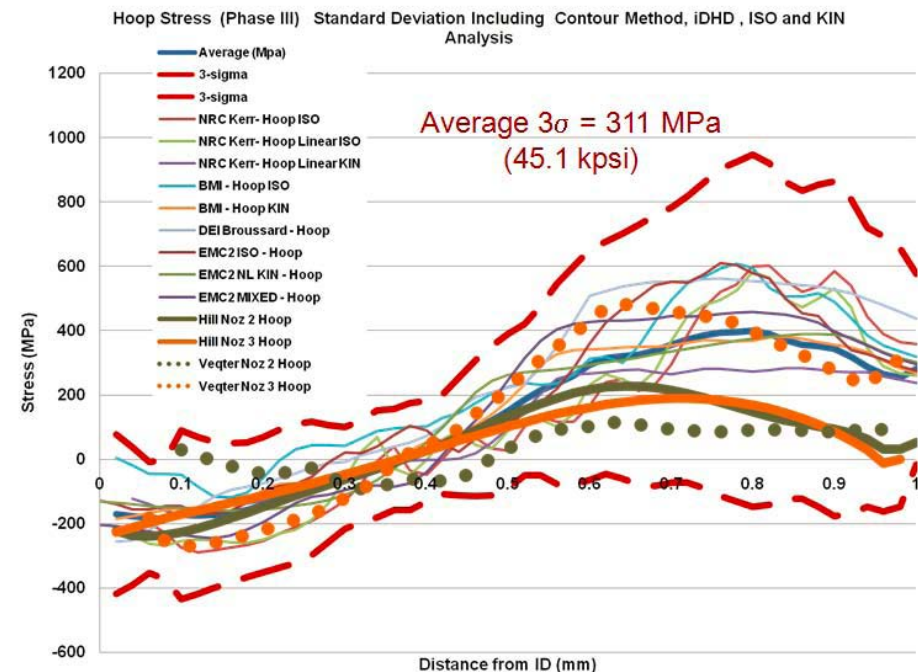
Phase III: Cancelled Plant Nozzles

Overview

Axial Stress Post safe end weld



Hoop Stress Post safe end weld



- Spread in modeling results evident in the Phase III results
- Phase 3 average $3\sigma = 243$ MPa, Phase 2a average $3\sigma = 278$ MPa

Phase III: Cancelled Plant Nozzles

Observations from Phase III Work

- Measurement and modeling results show similar trends
- Spread still evident in Phase III modeling results
- Uncertainty between Phase III and Phase II results is comparable, maybe slightly less

Outline

- Overview
- Phase I Work
- Phase II Work
- Phase III Work
- **Phase IV Work**
- Conclusions

Phase IV: Cancelled Plant Nozzles

Overview

- Full-scale components
 - Actual cold leg nozzle fabricated for intended service
- Finite Element Round Robin
 - Double-blind: i.e., modelers did not have access to measurement data
 - Obtain modeling results from a community of independent modelers
- Objectives
 - To validate WRS modeling with experiment
 - To assess WRS modeling uncertainty
 - To assess weld overlay effectiveness

Phase 4 - EPRI

- Plant Components
- WNP-3 CL Nozzle (QTY 1)
- RS Measurements funded by NRC
- Purpose: Effect of overlay on ID.

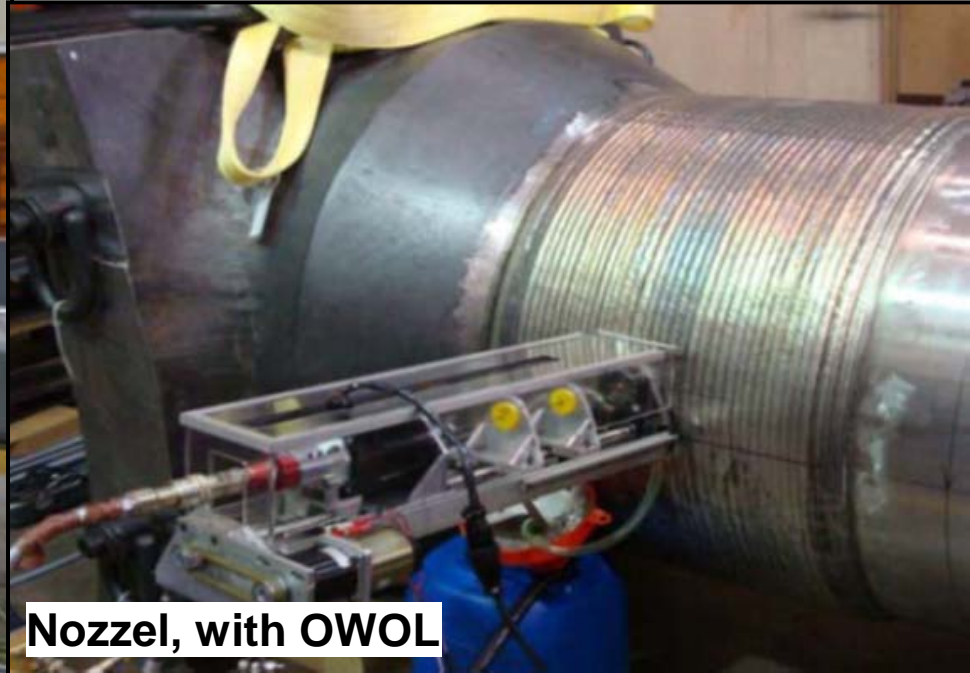


Phase IV: Cancelled Plant Nozzles

Mockups



Nozzel, without OWOL

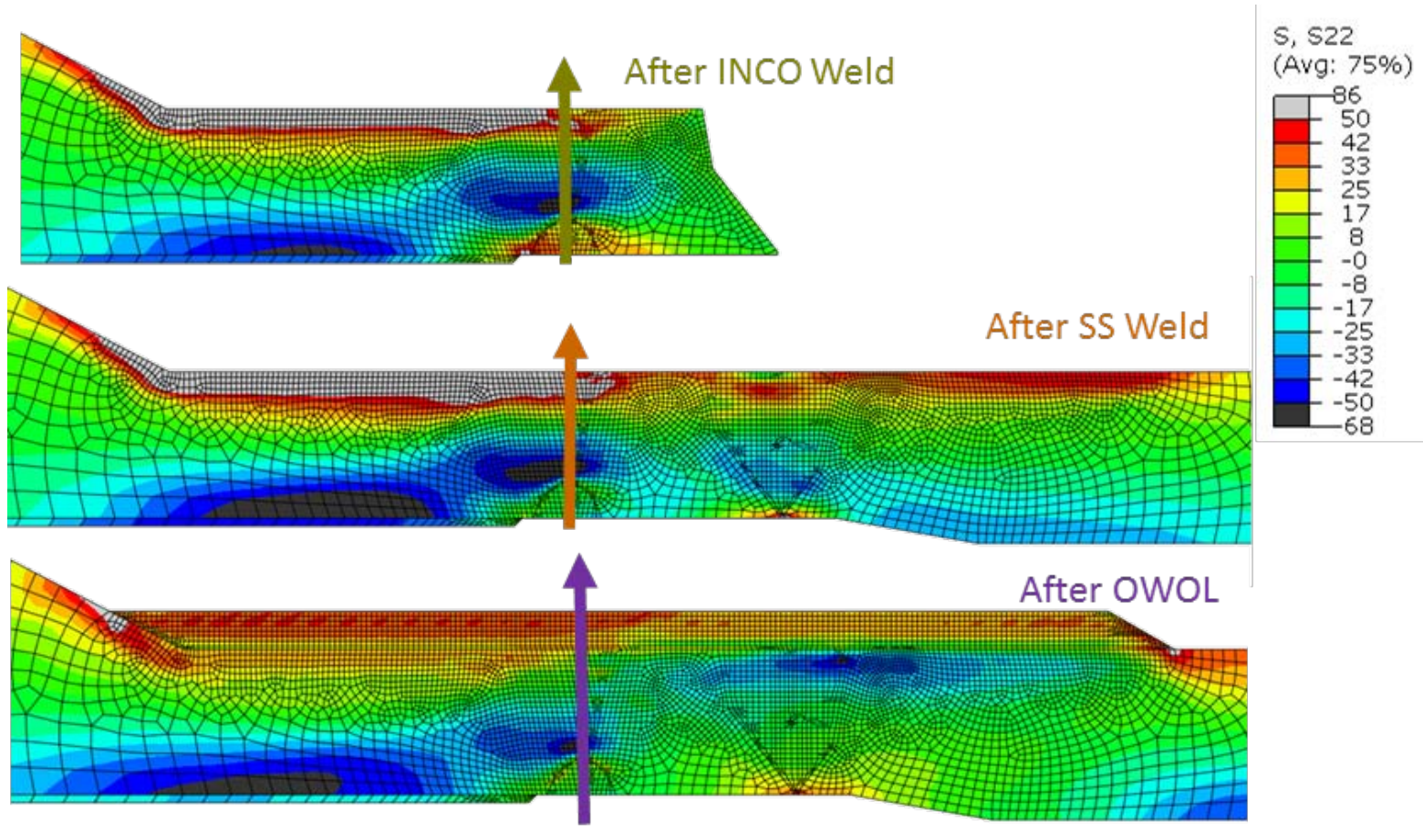


Nozzel, with OWOL

- Investigation of a mitigation technique: Optimized Weld Overlay (OWOL)

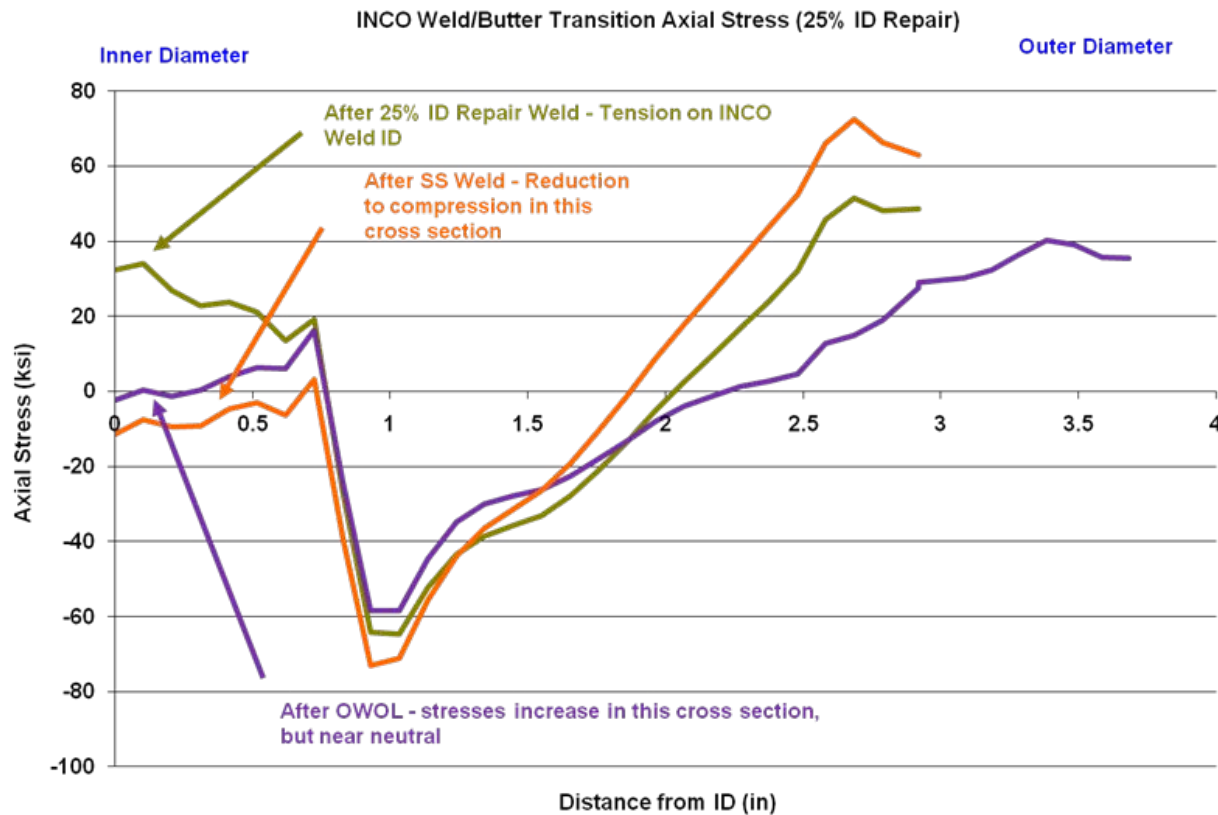
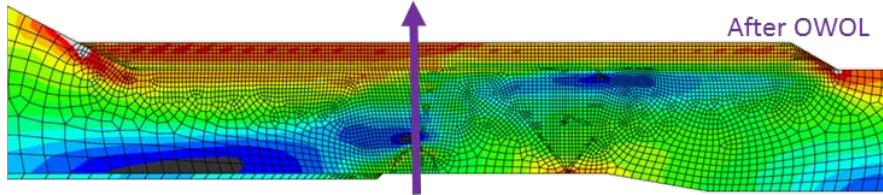
Phase IV: Cancelled Plant Nozzles

Results: Axial Stresses



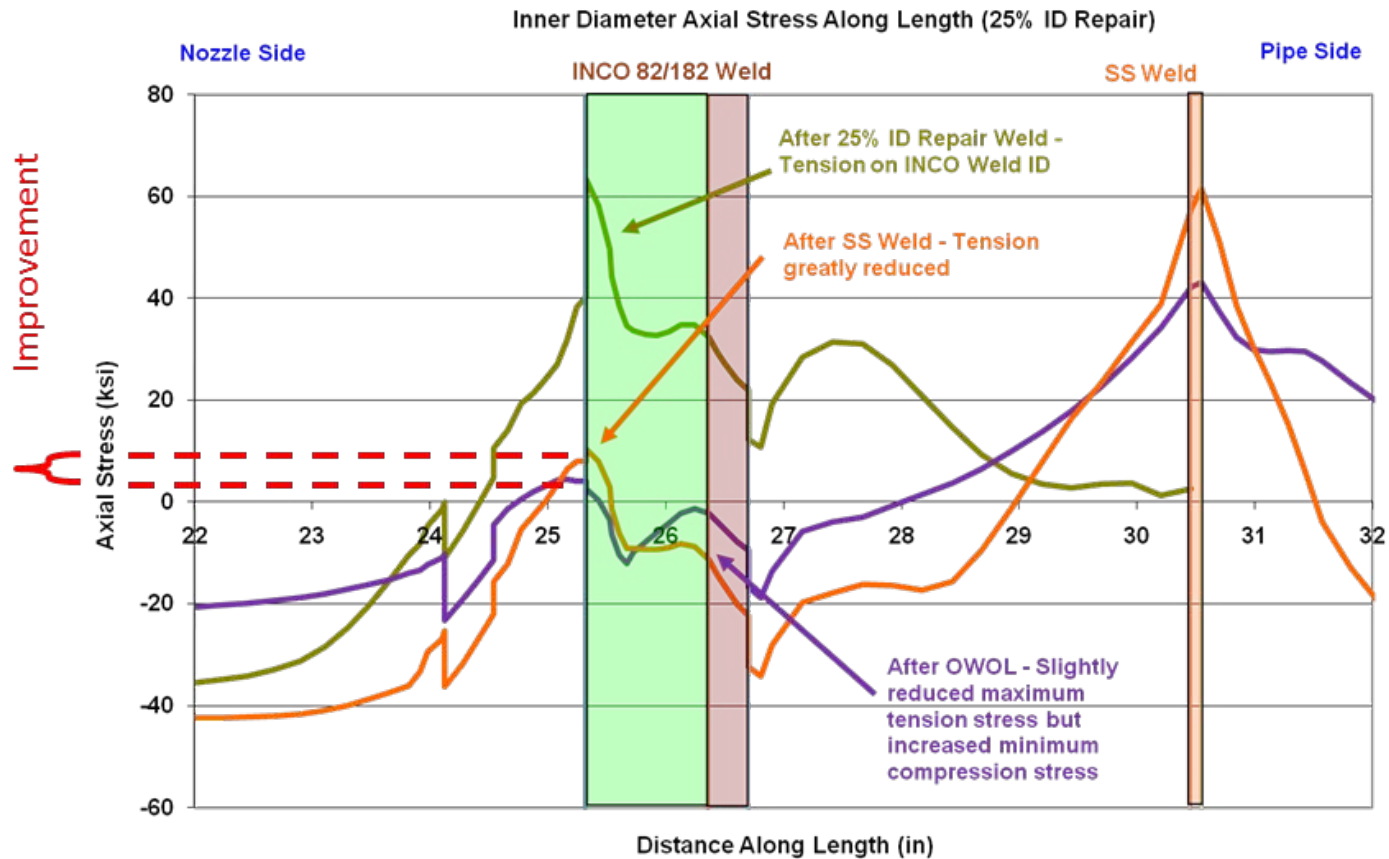
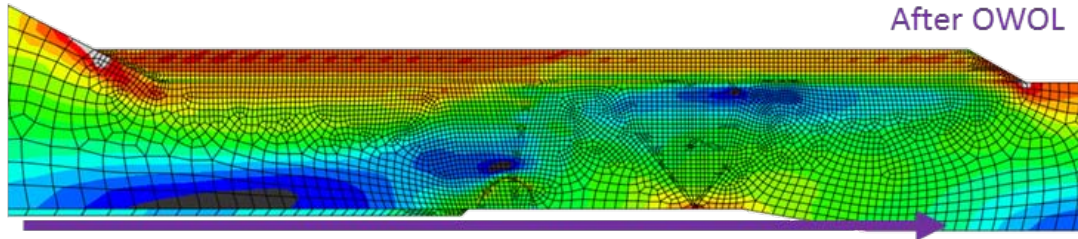
Phase IV: Cancelled Plant Nozzles

Results: Axial Stress, Midweld, Through Thickness



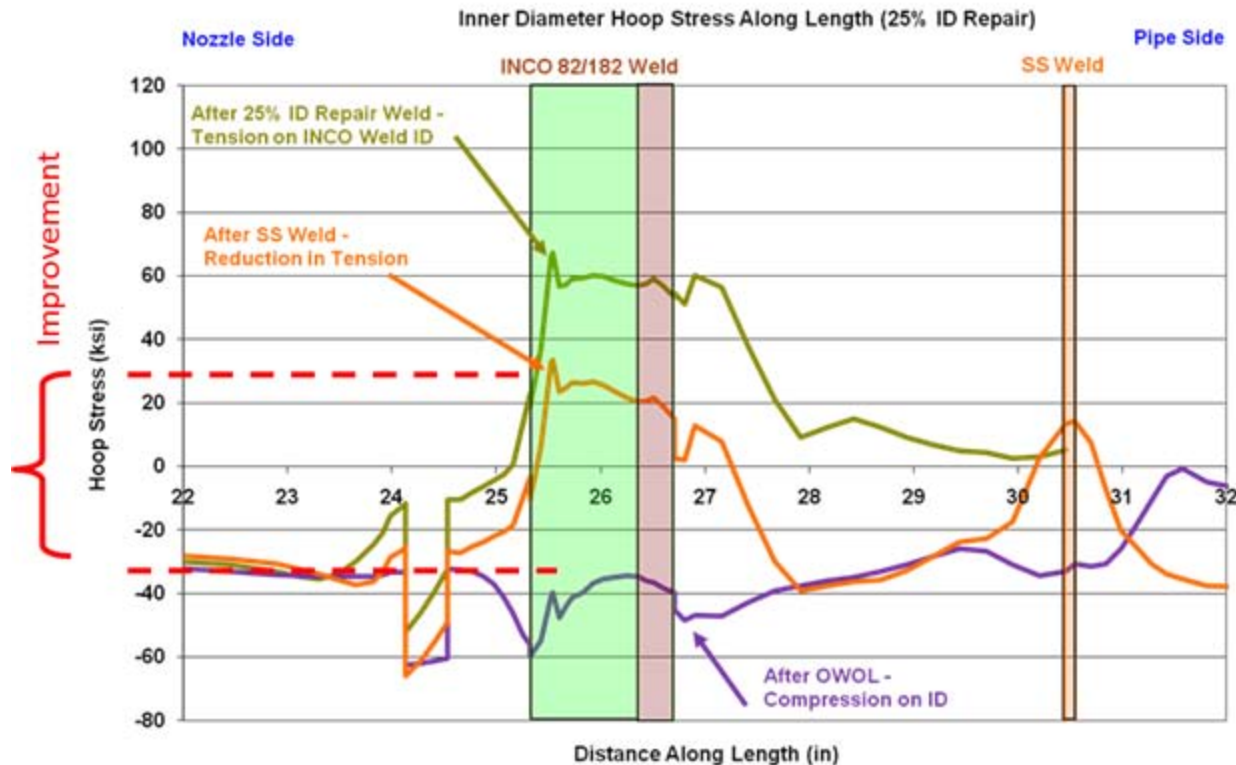
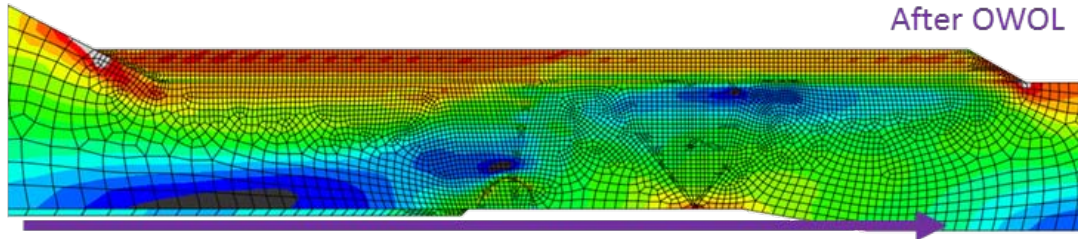
Phase IV: Cancelled Plant Nozzles

Results: Axial Stress, ID, Transverse to Weld



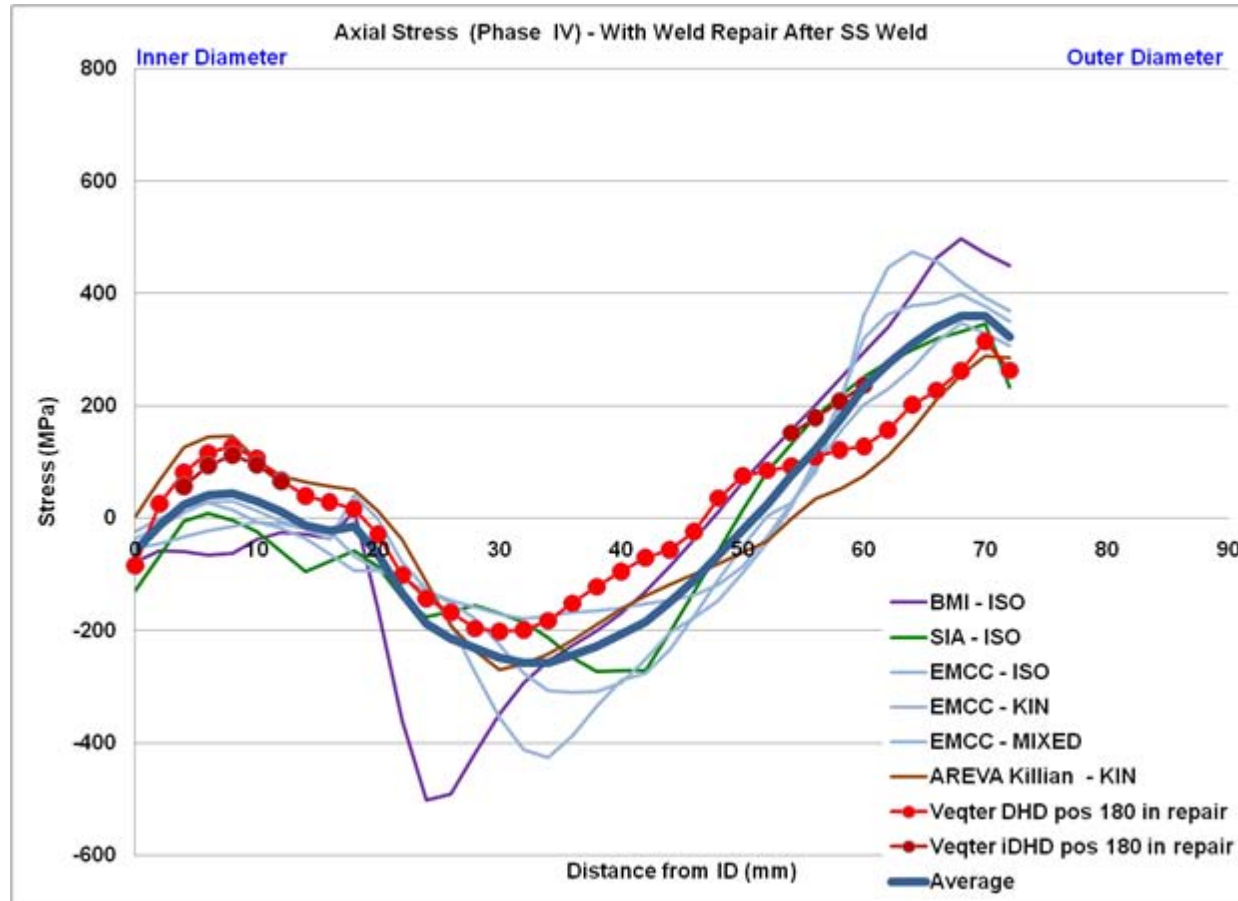
Phase IV: Cancelled Plant Nozzles

Results: Hoop Stress, ID, Transverse to Weld



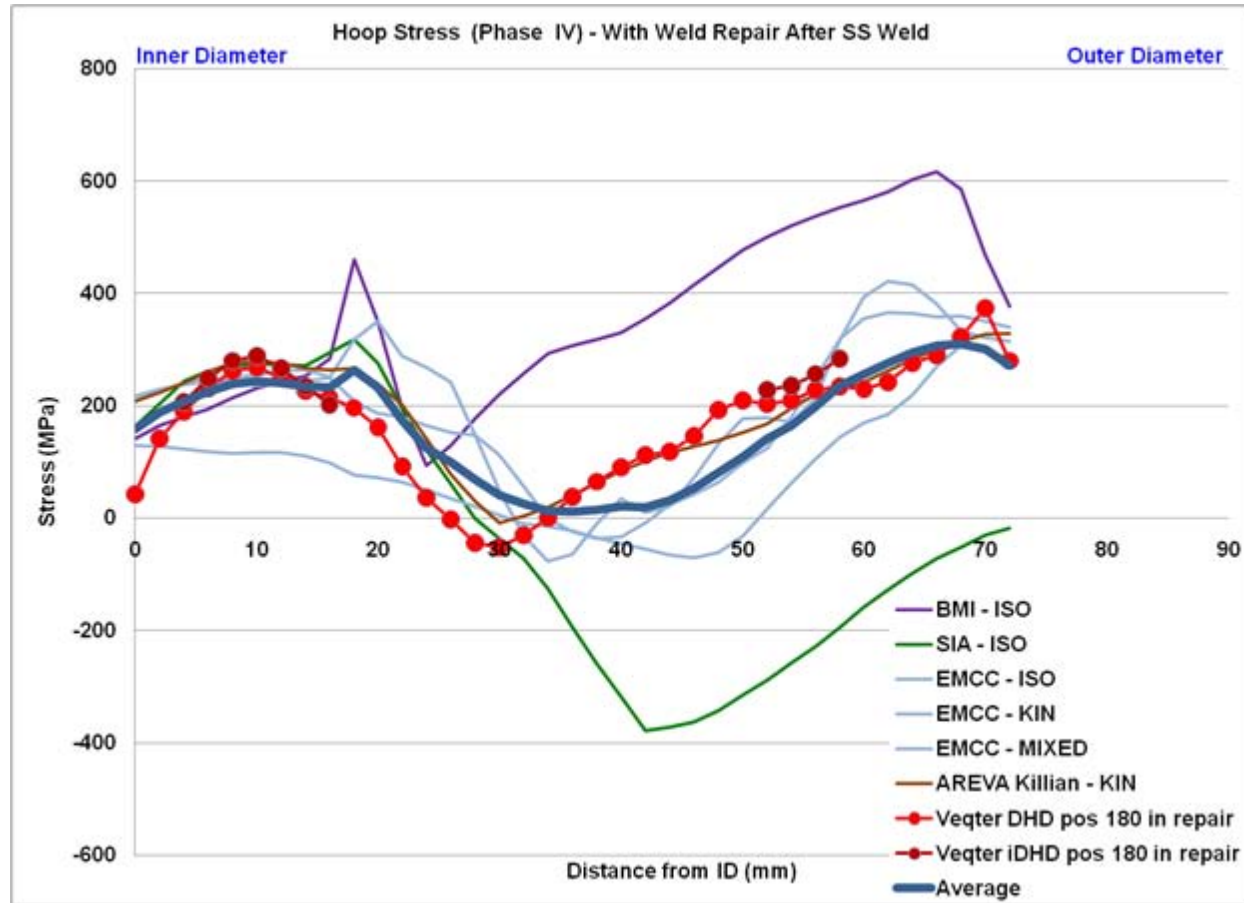
Phase IV: Cancelled Plant Nozzles

Results: Axial Stress



Phase IV: Cancelled Plant Nozzles

Results: Hoop Stress



Phase IV: Cancelled Plant Nozzles

Observations from Phase IV Work

- The modeling and measurement results showed improvement of the residual stresses at the ID location after OWOL was applied
- Modeling uncertainty still exists, but general agreement between models and measurements

Outline

- Overview
- Phase I Work
- Phase II Work
- Phase III Work
- Phase IV Work
- **Conclusions**

Conclusions

- Accomplishments
 - Double-blind WRS modeling validation by prototypic nuclear component mockups
 - Beneficial effect of OWOL confirmed by modeling and experiment: led to safety evaluation input
 - Sources of uncertainty have been identified
- Sources of uncertainty
 - Weld uncertainty
 - Process details (bead sequencing and heat input)
 - Material properties
 - Modeling uncertainty
 - Hardening law
 - Finite element details: e.g., mesh density, post processing
- Lessons learned from xLPR and the WRS Validation Program to reduce modeling uncertainty

Conclusions

- Opportunities to improve understanding of WRS:
 - No procedures in place to reduce the modeling uncertainty
 - Some sources of uncertainty not well quantified: sensitivity studies
 - No current acceptance criteria for WRS input in place

WRS Validation Program

Future

Michael Benson
U.S. NRC RES/DE/CIB

**ACRS Meeting of the Subcommittee on
Materials, Metallurgy, & Reactor Fuels**
February 6, 2013
Rockville, MD

Introduction

- This talk :
 - Recaps the current accomplishments of the WRS Validation Program
 - Describes the knowledge gaps
 - Introduces potential future research activities of the WRS Validation Program

Accomplishments

State of Knowledge

- Modeling uncertainty is uncomfortably large
- Sources of uncertainty have been identified
 - Choice of hardening law
- Despite the large analyst-to-analyst scatter, axisymmetric finite element models agree with measurements

Accomplishments

Knowledge Gaps

- Commonly-accepted procedures for WRS input development are lacking
 - Can we reduce the modeling uncertainty?
- Criteria are needed for WRS acceptance and validation
 - How do we determine where a WRS input falls in the uncertainty band?
- No measurement data exists for j-groove weld configurations
- Affect of partial-arc repairs cannot be captured with axisymmetric models

Future Activities

List of EPRI/NRC Joint Research Activities

- Development of new Memorandum of Understanding Addendum for cooperative NRC/EPRI WRS Research
- Phase IIa mockup (NRC)
 - Original mockup already discussed in the previous talk
 - Contour and slitting measurements
- Phase IIb mockup (NRC)
 - Similar to Phase IIa, fabricated by manual SMAW welding
 - Deep hole drilling, contour, and slitting measurements
 - FE Round Robin: Use lessons learned to reduce modeling uncertainty
 - FE Round Robin: Apply developed guidelines, MRP-317

Future Activities

List of EPRI/NRC Joint Research Activities

- Draft of ASME Code best practices for weld residual stress inputs to flaw evaluations (NRC/EPRI)
- Development of 3-D moving arc analysis (EPRI/NRC)
- Development of Improved Hardening Laws (EPRI)

Future Activities

List of EPRI/NRC Joint Research Activities

- Validation of Upper-Head J-Weld WRS Model (EPRI)
- Validation of Lower-Head J-Weld WRS Model (EPRI)
- WRS Inputs for xLPR (NRC/EPRI)
 - Modeling uncertainty assessed by having multiple analysts independently modeling the same problem
 - Welding uncertainty assessed by performing sensitivity studies on material properties, weld sequencing, and heat input
- International WRS Research Programs (NRC/EPRI)

Summary

- Weld residual stresses have regulatory significance
 - Important input to engineering evaluations involving nuclear safety
 - Large uncertainties exist
- Future activities
 - Validate finite element modeling for other weld geometries
 - Develop codified guidelines for formulating WRS inputs
 - Reduce modeling uncertainty by considering hardening law and finite element modeling details
 - Quantify the uncertainty through sensitivity studies
 - Recommend acceptance criteria for regulators