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NUCLEAR REGULATORY COMMISSION

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ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

(ACRS)

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MATERIALS, METALLURGY AND REACTOR FUELS SUBCOMMITTEE

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WEDNESDAY

FEBRUARY 6, 2013

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ROCKVILLE, MARYLAND

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

COMMITTEE MEMBERS:

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

NRC STAFF PRESENT:

QUYNH NGUYEN, Designated Federal Official

MICHAEL BENSON

MICHAEL CASE

JAY COLLINS

DAVID RUDLAND

ROB TREGONING

ALSO PRESENT:

JOHN BROUSSARD

ZHILI FENG

*Present via telephone

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

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

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

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

MR. CASE: Good morning, gentlemen. My name is Mike Case. I'm the Director of Engineering in the Office of Research. And I think this is a great opportunity to talk about the Weld Residual Stress Validation Program today. I think it's a good opportunity because it's something that's important but not urgent. Often, we get together around things that are urgent, and you have a little bit of time --

CHAIR ARMIJO: Urgent but not important.

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

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

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

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

But I sort of look at $16 million, and I say, golly, it's kind of hard nowadays to do more. So as you make comments and help us with the program, just be sensitive to I've really kind of lost my ability to do more, at least until I, you know, sort of stabilize the budget situation. So if you can also give me help because you all also have outside contacts, like I know Bill works on the LTO program that DOE runs. So if there's ways that we can better leverage what we're doing, that would be a great insight, as well.

So thanks for that. You already recognize that --

MEMBER SHACK: You have some RELAP-7 --

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

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

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

So I just thought I'd start by giving a little bit of a purpose of why we're here. Mike alluded to the fact that we're going to be talking about the Residual Stress Validation Program. We recently completed four phases of this program and have published some documents and come up with some conclusions on that, so we want to give you an update of where we sit on that and what those conclusions are, where the gaps are, and things like that.

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

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

And so we're going to give you a little bit of background first to start off. I'm going to start with giving the background and a little bit about regulatory impact. And my colleague, Jay Collins, will help me in that situation. And then Mike will talk about our accomplishments with the first four phases of the Residual Stress Program, as well as the gaps which lead into what we have planned in the next year or so.

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

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

So back when the technical basis for the code act for the code was being developed, a series of experiments were done to try to characterize residual stress, and it was all based on the fact that there was a lot of IGSCC happening in the heat effect zones of dissimilar metal welds. Experiments were done by ANL, Bill Shack was heavily involved in those, as well as by EPRI, looking at stainless steel similar metal welds, and this plot of the data is a sampling of that. And the results from the analysis or from the experiments were that there are significant scatter in the data; but, within the heat effect zone and within the base metal of these particular welds, residual stresses are relatively uniform, relatively consistent between welds.

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

So like I mentioned, many of the issues of IGSCC were evaluated using these particular plots that I showed earlier. Effects of weld sequencing and all that stuff were not really included or investigated, mainly because those things are insensitive out in the base metal. They're a lot more sensitive when you get into the weld. So the dependence on things such as geometry and welding, weld bead size, weld parameters, weld sequence becomes much more important and a much larger impact on the residual stress when we're talking about the stresses that are in the middle of the weld relative to the stresses that are away from the weld.

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

As part of those investigations, both independently, we did residual stress numerical evaluations for those particular welds. This plot shows an example of that. And the differences here are relatively large; and, again, it shows just single analysis results between the industry which are the open symbols in this case and the NRC which are solid symbols. But you see that there are some scatter, and it could lead to very large differences in prediction of time to leakage and/or time to a rupture.

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

For no residual stress, the flaw shape is semi-elliptical and relatively uniform. However, as you get these more unusual residual stress fields, you notice the flaw length is much longer and the amount of cracked area is much greater. The difference in stability characteristics between a flaw like this and a flaw like this can be relatively large, depending on the toughness of the pipe, because there is a lot more cracked area. So it becomes very important to characterize the residual stress fields properly in order to understand what the limiting flaw size may be.

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

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

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

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

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

MR. RUDLAND: Yes --

CHAIR ARMIJO: Everything else --

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

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

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

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

CHAIR ARMIJO: That small.

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

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

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

A couple of years later, we came here again to talk about the xLPR program, and that was just recently, in the last year or so. And, again, that program is a modular-based probabilistic fracture mechanics code, and it's going to be used to assess the LBB systems that are currently in the fleet to GDC-4, and we had created a pilot study to demonstrate the feasibility. And the ACRS again wrote a letter on that and concluded that the models and the technology was good, but we needed to work on crack initiation, we needed a more realistic crack initiation model, and we wanted to make sure that we had proper characterization of residual stress and the treatment of uncertainties that we're able to properly account for those.

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

In parallel with that effort, the industry, through EPRI, developed MRP-287, which was a non-mandatory guidance for PWSCC flaw evaluation. They incorporated NRC comments informally but has not been formally reviewed by the staff. And that document gives some suggestions on how to conduct an acceptable residual stress analysis. It talks about geometry, materials, configurations, repairs, safe ends, weld beads, things like that. But the bottom line is that it recommends that the numerical procedures always be benchmarked and validated against experiments.

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

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

So from a regulatory standpoint, how can we be assured that the residual stresses that are being presented are conservative or representative even of really what's happening out there, and how can we be guaranteed that the residual stresses and the numerical procedures are validated or conservative with respect to uncertainties? Currently, we can't.

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

CHAIR ARMIJO: David, is there any work being done by yourselves or EPRI to kind of cut this off, this problem off at the fabrication stage to create a favorable compressive residual stress, particularly at the surface for BWSCC or IGSCC nucleates? If you could be assured of that, then if you never nucleate a crack, then you're not so concerned about through wall variability.

MR. RUDLAND: Right.

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

MR. RUDLAND: That's really a great question. So what we've done is, in this particular effort, we've come up with lessons learned, and those lessons learned help us inform. And then, through the code, we're trying to work with Section 3 code and incorporate procedures and best practices in weld fabrication to minimize residual stress. And so we're trying to go down that path, and I'll mention that, actually, in the next slide.

CHAIR ARMIJO: Okay.

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

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

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

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

MR. RUDLAND: Right. And in Section 3 right now, there are no rules that say you can't do those ID repairs the way that they did it in Vogtle. All right. So that's what we're trying to, through the code actions, change. And maybe it's a peening thing. Maybe it's just a different way of applying the repair that can minimize the stresses.

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

MEMBER BROWN: I'm not a metallurgist, so let me ask an ignorant question. Why try to get so refined if you've got -- you said, the method you talked about was relatively conservative, overly conservative. But if we build pipes and stick them together and weld them and they're overly conservative, why do we care if we make them less conservative with a more refined method? We don't want them to break, so, I mean, I have no problem with doing all the research. That's just fine. But these are huge pipes, lots of water, and the whole thing is predicated on trying to resolve some of the, you know, do we really have a validated leak before break type evaluation, you know, methodology or thought process. But if you know you've got a conservative design because you've made it beefier than it needs to be, based on your methodologies or your knowledge, is it a huge cost to do it that way, as opposed to a little bit more refined? Do you reduce the cost of building the plant by hundreds of millions of dollars? Or if it's $5,000, who cares?

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

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

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

MEMBER BROWN: Okay. But one other thought. Okay. Again, I'm not a metallurgist. So if you look at the conservative setup and you say, well, here, it may shut down for an inspection or do something more frequently than necessary, there's also a lot of uncertainty relative to, if you look at the seismic forces that the plant is supposed to endure or resist. And they're not huge but, yet, there are certainly circumstances where you've had higher, in areas of the country where there's been higher seismic forces applied to certain areas than, quote, within the analysis. I mean, it seems like a little bit of over -- this, again, is my thought process -- a little bit of overkill when that range is not necessarily bad.

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

So just, to me, you know, being a little bit, knowing we've got uncertainties in other areas where you have large forces applied and you look at the g-forces. I mean, just my thought -- that's why I had to ask the question. You've answered it, but it just seems to me there's other areas I would have applied instead of -- I'd be hesitant to go to something that reduces what, I guess my buddies here would probably say the deterministic uncertainty that's too high because you can do it better and be more refined. And that's all nice, but sometimes it doesn't matter.

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

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

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

MEMBER BROWN: But you can inspect for those.

CHAIR ARMIJO: Not so easily.

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

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

MR. RUDLAND: By indication. UT inspections.

CHAIR ARMIJO: Most of them are found by leaks.

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

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

MR. COLLINS: It's getting better.

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

CHAIR ARMIJO: Yes. But to Charlie's point, if the NRC could say it and there was ways to do it and you said, hey, we want all welds to be in a state of compressive stress as fabricated. Now, the ones that are out there are out there, and they're going to be whatever they are. But that would suit you because these cracks won't start in a state of compressive stress, but we're not doing that yet. And the industry isn't coming to you with fabrication techniques that says, yes, I welded all this way back and, after all is said and done, I do this additional process and it puts it all in compression. And if they could prove it, you'd be happy, I would guess.

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

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

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

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

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

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

CHAIR ARMIJO: Right.

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

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

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

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

MEMBER SHACK: Eighties.

MR. RUDLAND: -- when these were done.

MEMBER SHACK: We're not that old.

MR. RUDLAND: The residual stress measure techniques weren't as sophisticated as they are today, and so they created these through wall measurements in different ways. In Bill's particular case where it's just the closed symbols, you know, measurements were made by strain gauges, and then the wall thicknesses were machined away and the change in strain was measured and these stresses were inferred. And so for different measurements, you got a different set of curves. And so there's --

MEMBER SHACK: But those are different welds, too.

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

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

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

MEMBER BLEY: Okay.

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

MEMBER BLEY: You start up here --

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

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

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

MEMBER BROWN: To make it tensile.

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

MEMBER SHACK: Total stress may be --

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

So by the time you get down where the

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

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

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

MEMBER BLEY: Yes, that's right.

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

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

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

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

MR. RUDLAND: So, for instance, if you have a case like this where you end up with the cracks growing around the circumference much more than it's growing through the depth, you can end up with a very long surface crack, and it could possibly rupture. And in this case here, you have a very short crack that grows deep, and so it's going to probably leak because you have all this uncracked area to resist.

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

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

Okay. I'm going to swing just to the last slide before I let Mike take over. Some of the things that we already talked about I want to touch on again. You know, certain things we need to do to have confidence in using residual stresses in regulatory space. We have to try to reduce the uncertainty in the industry-submitted flaw evaluations by getting a little bit more confidence in the residual stresses. And we're doing that by working with the ASME code to incorporate some of these tiered approaches that we talked about into the code, as well as into 50.55(a).

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

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

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

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

MR. RUDLAND: Well, recently, we had,

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

MEMBER BLEY: Okay.

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

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

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

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

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

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

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

MEMBER SCHULTZ: Thank you.

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

CHAIR ARMIJO: Sure.

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

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

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

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

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

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

So the MOU, in general, sets forth terms of cooperative research. It's a high-level legal document. But then there are these addenda that address specific research topics. And the two that are of most relevance to today's talk are the extremely low probability of rupture addendum and the WRS Validation Program addendum. We're currently, the old WRS addendum has actually expired, and we're currently working on creating a new one.

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

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

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

CHAIR ARMIJO: It sounded really good.

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

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

MR. RUDLAND: Do you know the MRP number?

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

CHAIR ARMIJO: What was the title, Bill?

MEMBER SHACK: I have to -- validation of stress corrosion cracking initiation model for stainless steel and nickel alloys, 1025121.

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

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

MR. RUDLAND: We will definitely look into that.

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

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

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

MR. RUDLAND: Okay.

MR. BENSON: So in the MOU, in the MOU addendum I should say, there are specific tasks that are laid out and each organization is assigned a lead and sometimes it's co-led, depending on the task. But this slide just gives you an overall feel for how some of the work was split up between the two organizations. EPRI designed and fabricated some specimens and mockups for the weld residual stress measurement, and they also created finite element models. NRC did some finite element modeling, organized the finite element round robin studies that we're going to talk about, and we also designed and fabricated some mockups.

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

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

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

MR. RUDLAND: Especially the pressurizer nozzles. We didn't really know anything about the fabrication history at all. By cleaning up the surface on the ID, you were able to tell whether or not there were repairs. In some cases, there were small repairs. And I believe the same was for the cold leg nozzle, but I'm not sure. I don't think we had any of the fabrication history on the dissimilar metal weld.

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

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

CHAIR ARMIJO: Okay.

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

MR. RUDLAND: Oh, yes.

MEMBER SHACK: -- how big a variation that makes in residual stresses. I mean, is it comparable to the scatter you get from model to model? You know, Phase IV has one weld and, you know, a hefty amount of scatter between models, but if you took one model and you did four welds would scatter look the same?

MR. RUDLAND: Stay tuned.

MEMBER SHACK: Stay tuned.

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

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

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

The cylindrical specimens are shown in this slide. There was actually three different cylindrical specimens with increasing complexity. We started out with just welding stainless steel base metal to stainless steel base metal. And then we welded the carbon steel to the stainless steel base metal with the buttering layer. And then in the most complex specimen, we actually put in a safe-end.

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

MR. RUDLAND: Right.

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

MR. RUDLAND: That's right.

MEMBER BROWN: Why is it different?

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

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

MEMBER SHACK: Different materials and different environments.

CHAIR ARMIJO: Well, the 300 series stainless steels are the same, but the environment makes all the difference.

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

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

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

MEMBER BROWN: Carbon steel.

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

MEMBER BROWN: As opposed to?

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

MEMBER BROWN: Okay. Not the austenitic stainless.

MEMBER SHACK: Not the austenitic stainless.

MEMBER BROWN: Okay.

MR. BENSON: Okay. And then also, in the most complex cylindrical specimen, there was a weld repair, so there was a machine grooved, yes, a grooved machine into the specimen is shown in this diagram, and then weld metal would have been deposited back into the groove. During the welding, there was in-process characterization. Thermocouples were spot-welded to the specimens at different locations, and you get temperature history at those locations. And also laser profilometry was used to measure each individual weld bead. So you got the weld bead geometry, as shown on the left-hand side here.

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

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

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

And so I'm going to talk about some of these techniques in a little more detail, especially the ones that we ended up using in subsequent programs. So we'll talk first about diffraction-based techniques, and here you're really measuring the lattice spacing based upon the position of a diffraction peak. And then you also measure this reference lattice spacing, which depends on the experiment. And you calculate your strain that way, and then, if you measure three components of the strain, then you can calculate your stress through Hook's Law.

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

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

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

MR. RUDLAND: Back one slide. It will show you. So you can see that the x-rays go to, you know, not quite to a tenth of a millimeter probably, maybe a millimeter for the synchrotron stuff. Even neutrons themselves can't penetrate all that far, especially for some of the heavy components.

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

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

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

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

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

CHAIR ARMIJO: I was just wondering if

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

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

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

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

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

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

CHAIR ARMIJO: Okay.

MR. TREGONING: Rob Tregoning, staff. The ultrasonic technique, there's a lot of uncertainty in that because you measure velocity of the propagating wave, and it's dependent on stress, but it's a second order effect. So it's incredibly difficult to do that measurement, and there's a ton of uncertainty. So it was wise not to choose that, even though that is --

CHAIR ARMIJO: Especially for a big component.

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

CHAIR ARMIJO: Okay.

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

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

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

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

MEMBER BROWN: So you cut the specimen

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

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

MEMBER BROWN: That's through the weld.

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

MEMBER BROWN: All right. Thank you.

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

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

MR. RUDLAND: In some cases, it does, and so they have corrections for that. A lot of times, when they're making these cuts, you get plasticity ahead of the cut that's messing everything up. And so they go back and they're able to, through the finite elements, correct for that. So they realize that kind of stuff happens.

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

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

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

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

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

MEMBER BROWN: Yes, all right. Thank you.

MR. BENSON: Deep hole drilling is shown

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

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

MR. BENSON: Sure.

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

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

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

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

MR. RUDLAND: Right, right.

CHAIR ARMIJO: Okay. So that's just a

technique.

MEMBER BROWN: Do they glue it on?

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

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

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

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

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

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

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

CHAIR ARMIJO: And what is the thing

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

MEMBER SHACK: The diameter of the hole.

MR. RUDLAND: That's right.

CHAIR ARMIJO: The hole actually.

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

MEMBER SHACK: That seemed nifty enough in itself.

MR. RUDLAND: Right, right.

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

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

CHAIR ARMIJO: Okay, okay. Tricky.

MEMBER SHACK: Now, when I looked at the ASME paper, and there's not enough details there, so I can't claim I really understand what's going on. But it looks as though they do the analysis as though this is a set of laminar that are independent, and so they just do the analysis as though it was a sheet that they incrementally make out, which means that, again, you're going to have limitations on the kind of gradients that you can have. This is something that's in equilibrium but not compatible, so it's kind of a lower bound on the stresses, in a simple-minded way.

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

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

MEMBER SHACK: Are they a British company?

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

MEMBER SHACK: A spinoff from the University.

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

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

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

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

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

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

MR. BENSON: Any other questions? Okay. So that's a summary of some of the main measurement techniques that we've looked at. This slide here shows how the measurement techniques were applied for the plate specimens. This is a cross-section of the plate specimen. The purple diamonds are neutron diffraction measurements. If you want to use the contour method to get the component of stress parallel to the weld line, the longitudinal stress, you have to slice that plate parallel to the plane, like we're showing here. And if you want the contour measurement to give you the transverse stresses, you have to slice the plate along the dash line, as shown here.

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

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

MR. BROUSSARD: Yes, yes.

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

Now, we can begin to start looking at some actual data. This slide shows results from the surface stress measurements. We're showing residual stress versus depth from the surface. And one thing we point out here is we're getting relatively high values up around 1500 mega-pascals, so we start to really wonder if we believe that high stress.

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

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

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

MR. BENSON: That's right, yes.

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

MR. RUDLAND: Did we show kips?

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

MR. RUDLAND: About a factor of seven.

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

MR. RUDLAND: Yes, ksi is just kilopounds per square inch for stress and pascal is a millimeter square. So it's just an SI, mega-pascals --

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

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

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

MR. RUDLAND: Yes, yes.

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

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

MEMBER BROWN: It was less understandable than ever --

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

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

MEMBER BLEY: I finally understand why the transition has been so hard.

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

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

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

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

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

So we did the incremental hole technique because it is a technique that's used sometimes in near weld material, but we wanted to characterize what was going on. And I think that the variability that you're seeing is not necessarily indicative of what you're actually getting at the surface if you have a magic true residual stress-measuring machine. But it's more indicative of some of the variability in the process that you can get.

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

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

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

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

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

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

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

MR. BROUSSARD: Yes. I think, usually, in the diffraction techniques, well, I know for neutron, and probably for x-ray as well, it's more about, well, with neutron diffraction you're measuring differences in measure peaks kind of received scattered neutrons, and some of that error is more about the accuracy of the fit of the peak to the data. And so they plot how well they're able to predict the peak, the tip of the peak based on the normal distribution of the data that they have. And so that's what some more of those error bars are about, and it's not about, you know, comparisons to other measurement techniques and that sort of thing.

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

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

MR. BROUSSARD: As Dave mentioned, the problems with the diffraction techniques, one problem with the diffraction techniques is the large grain sizes of weld materials versus kind of a fine-grain base material. It does cause some problems when you have kind of large and irregular sized grains in these weld materials and very kind of oriented type grains, as well.

MR. BENSON: Okay.

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

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

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

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

MR. RUDLAND: They're destructive.

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

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

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

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

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

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

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

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

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

And for the modeling results, this is a bit of a strange result in that the Model B and the Model C, which are the red X's and the red solid squires, have the same hardening law, but you're getting in very large differences in the results. And it turns out that that results from the fact that you have these relatively small wall thickness in these small specimens. And it turns out that shrinkage effects become really important, and the assumptions that the modelers make have a bigger effect on the results. Generally, however, what you're going to see is that, if a modeler chooses this same hardening law, that the results are going to be much less scattered.

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

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

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

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

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

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

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

MEMBER SHACK: Well, Phase IV didn't

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

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

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

MR. RUDLAND: Yes, the purpose of, we started with Phase I before anything else, and the purpose of Phase I was to try to begin to learn where the issues were and the learn the process and develop things on a simple basis with supposedly simple specimens. I think, in hindsight, we probably should have chose some different things. For instance, the pipes that we chose I think were a little too thin-walled, so we had a lot of axial deformation that we probably should have stayed away from because it's not really relevant to what we were trying to do in the nuclear type of stuff. The clamped plate thing caused some issues, also.

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

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

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

MR. COLLINS: But one of the key things I thought you took from this was the deep hole drilling. The incremental deep hole drilling was at least giving you some consistent results through the thickness of the material versus what you were looking at from other items and, at least when you were looking at the finite element model, you were seeing the contours be similar as far as for this part. So it was giving you at least something of a basis for why we continue to move forward with the deep hole drilling, right?

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

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

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

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

MR. RUDLAND: Yes.

MR. BROUSSARD: Actually -- this is John

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

MR. RUDLAND: A lot worse.

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

MEMBER SHACK: This is easy --

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

MEMBER BLEY: Back to Bill's earlier comment about the little error bars on that early picture of neutron diffraction results, I take it that's because they do some simple statistics to do the error bars, rather than consider all the uncertainty that they're looking at.

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

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

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

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

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

CHAIR ARMIJO: Why does it do that?

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

MEMBER BROWN: How many layers was it?

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

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

MR. RUDLAND: Seven weld beads.

MR. BROUSSARD: And I think that's what you're seeing in some of this postprocessing of the results. Each bead is a big chunk of that cross-section, which is not necessarily characteristic of what we have in primary systems where we have, you know, 40 to 50 --

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

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

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

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

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

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

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

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

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

MR. RUDLAND: They do, they do.

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

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

MR. RUDLAND: For the cases where you're in a homogeneous type of material that has equi-axed grains, it's not. It's very easy. It's much easier. But these welds -- especially in these similar metal welds because you've got grains that are growing in the main weld, and then in the butter they're actually growing in the opposite direction. So that complicates things even more.

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

MR. RUDLAND: I would hold off --

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

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

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

MR. RUDLAND: That was kind of the, I mean, the point I was trying to make is that, in the future analyses that you'll see in a second, the elastic plastic gives similar results to the isotropic hardening, minus the waviness. And it's going to all depend on, it depends on a lot of things. Again, the elastic-perfectly plastic is a modeling choice, and the modeler has to be able to choose what is the yield strength of that material, right? So they've got to go back to the strain hard material and say, okay, where am I going to pick that yield strength? Do I look at flow stress, do I pick some number smaller or larger than the flow stress, and what's my rationale for that? That can lead to a lot of uncertainty because it becomes a modeling choice.

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

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

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

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

MEMBER SHACK: All of the --

MR. RUDLAND: And that's really what we're trying to get to. I mean, the same with the kinematic hardenings. It's the same way. I mean, the assumptions of how the yield surfaces evolve, and it's all assumptions right there. I mean, it's not necessarily true that these yield surfaces just expand or just translate. You know, they do a little of both and . . .

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

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

MEMBER BROWN: -- actual measurements.

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

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

MR. RUDLAND: And what you'll find out on the thicker welds, though, is that the isotropic doesn't necessarily bound because what it will do is it will bound, but it will bound in compression very conservatively also, which could lead, again, like we talked about earlier, to crack --

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

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

MEMBER BROWN: Yes.

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

MR. COLLINS: But I appreciate your original observation.

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

MR. RUDLAND: I believe the difference is, and, Mike, you can correct me if I'm wrong, are in the choices the modelers made in how to model the restraint of the plate. That's one of them because the plates are restrained, and John may have a comment on this. I'm not sure if I --

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

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

MR. BROUSSARD: Yes, so the differences between those two modelers was that the, we talked about how with this fairly thin wall cylinder you get kind of a change in the weld group geometry as each weld pass is deposited, and it's a lot bigger than what you really have in a normal dissimilar metal weld. It's all magnified. And so you wind up with some modeling assumptions, and the two different modelers use some different modeling assumptions on the size of each particular weld. And because each weld bead is a big chunk of the cross-section, you get, it kind of magnifies differences that aren't necessarily present. So that's why we did this Phase I, and then we kind of got some of these results and scratched our heads about them, and we said, you know what, we're not dealing with seven-pass welds in our particular issue, you know, in the components, in these primary system components; let's kind of table this and move on to thicker wall components where there's significant numbers of weld beads and see if some of these differences still exist or if it maybe improves things a little bit.

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

MR. FENG: Can I make a comment? This is Zhili Feng from Oak Ridge National Lab. I'm working with both the NRC and EPRI on this project, though mostly from the research side of the activity. And this is certainly something we need to do a lot more study on to that to find out what happened because some of the assumption is probably we had a lot of good experience on carbon steels, whereas the strength hardening behavior of material is not that great. But we move on to standard steel and nuclear alloys, there's a huge strain hardening behavior, and we probably didn't look that carefully, from a research point of view, past.

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

I also want to comment on this jumpiness of the prediction. To some degree, that is probably real because when they make a weld they are down to like a seven pass at the same time. When they make a one pass, that cool down to room temperature, and we put on the second pass and the third pass. When it goes through this process, it actually different weld process see different deformation behavior. So that you may see some in those kind of situations, either as a sudden pass and maybe a bigger pass. So it's probably going to have a very smooth curve. Smooth curve doesn't mean it has a good result.

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

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

MR. TREGONING: It's Rob Tregoning from

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

Normally, when you see weld residual stress programs, you're lucky if they have a measurement to compare with the theory that they do. You never see multiple measurements like this done in such a systematic way. Typically, they'll make assumptions on models. They won't systematically and parametrically vary them, as we've done here, to look at the influence of those assumptions. So, to me, that's really the uniqueness of this particular program, compared to -- look, we've been looking at weld residual stress modeling now for 25 years or 30 years or so, but none of them have really tried to understand uncertainty and variability and the effects that those things can have, ultimately, on your crack predictions, which is the ultimate end goal. This program is singular and unique in that aspect, and I think that's really the focus.

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

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

MR. RUDLAND: Okay. We've spent a lot of time on this particular slide, and there's a lot more similar slides to come uphill.

CHAIR ARMIJO: Okay.

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

MEMBER BLEY: What's the three curves?

MR. BENSON: Yes, the bottom here --

MEMBER BLEY: Oh, there we go.

MR. BENSON: Red is the measurements.

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

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

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

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

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

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

CHAIR ARMIJO: It turned out not to be.

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

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

CHAIR ARMIJO: Or just one weld.

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

MEMBER BROWN: The bulk measurement is the contour measurement?

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

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

MEMBER SHACK: You better put that one in quotes.

MR. BENSON: Yes. Near surface stress is

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

Okay. So any remaining questions on Phase I?

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

MR. BENSON: I did.

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

MR. BENSON: It was --

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

MEMBER SHACK: It's only surface remember.

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

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

MEMBER BLEY: Oh, okay.

CHAIR ARMIJO: That was x-ray?

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

MR. BENSON: That's right.

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

MR. BENSON: Yes.

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

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

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

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

MR. BENSON: We can go back to --

MR. BROUSSARD: I'm pretty sure that that is, you know, that the edges of those points are all the way up -- you know what, Mike? If you find that extra cross-section that shows the neutron diffraction lines, the x-ray diffraction points are at the top of the neutron diffraction. Yes. So those are the seven points you see. At the top of each of those columns of neutron diffraction is where the extra --

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

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

MR. BROUSSARD: That's right. It's all on the top surface of the weld there. So as you go across the top surface, we did these at numerous axial, at a couple of different axial locations, so along the length of the weld. And we got variability at the same location at different axial positions, even though it was a fairly continuous weld. So we did try our best to follow best recommended practice on these. We electropolished down to I think 15 microns to eliminate any very, very surface finish effects and that sort of thing. Obviously, these welds, you can tell, were not ground afterwards or anything like that. They were left in the as-welded condition. We tried to remove surface contamination and that sort of thing.

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

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

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

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

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

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

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

CHAIR ARMIJO: Thank you.

MR. BENSON: Okay. So Phase II now?

MEMBER BLEY: Are we taking a break, Sam?

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

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

CHAIR ARMIJO: Let's try and get back in session, please. Okay. So, Mike, I think we have a quorum, so there's no problem. Please go ahead.

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

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

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

MR. BENSON: We're going to talk a little bit about how we provided some of that information, but definitely, at the very beginning, they definitely had all the weld geometry. Some of the other information we held from them and then provided as they went along. So we'll talk about that.

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

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

On Slide 39, we show the measurement results, both before the stainless steel closure weld and after. And you can see these are axial stresses plotted versus distance from the ID, and you can see that close to the ID, as close as we could get, given the measurement technique, the deep hole drilling measurements did show that the stresses decrease after the closure weld for this particular geometry. But it turns out that the safe-end length can be an important parameter, so it's not necessarily guaranteed that every weld configuration will show this. But in this case, it did.

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

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

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

MEMBER SHACK: At least for the axial stresses.

CHAIR ARMIJO: The axial but not the hoop.

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

MR. RUDLAND: It's definitely not.

MEMBER SHACK: I was going to ask do you see a difference in the field? I mean, this would suggest you'd see more axial cracking than you would hoop cracking, and is that --

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

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

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

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

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

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

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

Slide 43 talks about, gets to the question that Sam asked: what type of information did we provide the modelers and how did we provide it to them? So, first of all, we postulated that the main sources of uncertainty might be welding heat input and material properties. And so we decided to do three analysis stages. In the first stage, we do not provide any thermocouple data or material property data. In the second stage, we provide that thermocouple data so they can tune their heat input models. And then, in the last stage, we provide material property data so everyone is using the same material properties. And the hope is, or the hope was that, as modelers got more information, that the modeling uncertainty would decrease. And we also modeled before and after the stainless steel closure weld.

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

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

MEMBER BLEY: So do you know why providing the additional data didn't affect them? Did they already have similar information in their models, or did they account for those kind of things?

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

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

MEMBER BLEY: That's not surprising.

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

MEMBER BLEY: They did actually use the

data you gave them?

MR. RUDLAND: They did use the data. Well, you know, most of these modelers have their own databases of material properties.

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

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

MEMBER BLEY: Okay, okay.

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

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

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

MEMBER SCHULTZ: Oh, okay.

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

MEMBER SCHULTZ: All right. Thank you.

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

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

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

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

MEMBER SHACK: Just going back to the last one, at least not intuitively, which one of those is the most conservative one from a crack propagation point of view? You initiate faster, but you might stop the crack.

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

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

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

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

CHAIR ARMIJO: Okay. And these are axial stresses.

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

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

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

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

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

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

MR. COLLINS: Distance from how far it is away from this --

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

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

MEMBER SHACK: Optimized safe-ends.

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

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

CHAIR ARMIJO: Make it up some other way.

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

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

MEMBER BROWN: So you've got two incremental deep hole drilling sets, and they're done for both of these circumstances. Are they in different places? I mean, how do you -- okay. So you do them at different locations --

MR. RUDLAND: These two are 180 degrees apart.

MEMBER BROWN: Okay, all right.

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

MEMBER BROWN: And they map pretty well.

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

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

CHAIR ARMIJO: So additional incremental deep hole drilling?

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

MR. RUDLAND: The contour method.

CHAIR ARMIJO: Contour method.

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

MR. RUDLAND: Really slice it up, yes.

MEMBER SHACK: I mean, the nice about the deep hole is you can do the pre-stainless steel weld and still be able to do it --

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

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

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

MR. RUDLAND: By single analyst.

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

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

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

CHAIR ARMIJO: Have you tried it?

MR. RUDLAND: No, because, in reality, the materials aren't isotropically hardened. You know, it's some place in between kinematic and isotropic hardening, so it's going to be probably closer to the smoother curve than it is the jagged curve because it really isn't isotropic hardening.

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

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

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

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

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

MR. BENSON: And this slide just shows sensitivity studies with heat input, and the slide is really busy. But the easiest way to look at it, I found, was to pick out this orange line here, which is baseline post-stainless steel weld, and then this red line here at the bottom which is 25 percent of the heat flux of that baseline. And by varying that heat input, you can have some significant effect also on the results.

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

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

MR. BENSON: So higher --

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

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

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

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

MEMBER BROWN: The light blue is the

highest input, is the highest heat flux?

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

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

CHAIR ARMIJO: Yes, which is kind of interesting.

MR. RUDLAND: Right at the ID you mean.

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

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

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

MEMBER SHACK: Yes, right.

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

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

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

CHAIR ARMIJO: So that could make sense,

just there's no stress relaxation and --

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

MEMBER BROWN: Pre --

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

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

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

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

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

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

MR. RUDLAND: And I'll make one point is that, again, with this Phase III we knew nothing about these welds. We knew nothing about the weld processes for these welds at all. We were able to check the ID to see if there were some kind of repairs, but you will notice that the deep hole drills on certain parts of the wall thickness were different. Again, these were done at 180 degrees from each other. You'll see, if you look at the solid circle dots, there are some differences, again indicating that something is going on in that particular part, which isn't incorporated into the residual stress models because we just don't know what's there.

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

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

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

MR. RUDLAND: Because they curve, those lessons learned are learned after, were learned after, yes. So, in case, if you were able to read this, you'd see that some, again, used isotropic and some used kinematic in their analyses.

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

MR. RUDLAND: Yes.

MEMBER BROWN: So the Veqter nozzle two hoop and the --

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

MEMBER BROWN: Oh, okay.

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

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

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

MEMBER SHACK: All used axisymmetric.

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

MEMBER SHACK: It's just that axisymmetry becomes more problematic as the nozzle gets smaller, and this is, like, what? An eight-inch nozzle and you bound to it, yes.

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

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

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

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

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

MR. COLLINS: It goes to less than a half an inch of weld material on top, whereas a full structural weld overlay would be over the half-inch.

CHAIR ARMIJO: But it's a continuous weld?

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

MR. RUDLAND: Veqter did most of that.

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

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

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

MR. RUDLAND: Weld structural overlay is designed to basically replace the load-carrying capacity of the undersized weld. So the weld underside is degraded for some reason, and they put the overlay on with sufficient thickness to satisfy Section III, ASME Section III. The optimized is not. The optimized is thinner, takes credit for some of the weld, still provides enough residual stress mitigation to satisfy the mitigation of the PWSCC.

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

MR. RUDLAND: Good residual stresses but less weld.

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

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

MEMBER BROWN: Bigger through walled --

MR. RUDLAND: Yes, the thickness is larger.

MEMBER BROWN: The thickness is larger.

MR. COLLINS: With crack-resistant material.

MR. RUDLAND: Right. So they use a different material here than what's in the weld. They use a material that's got a higher resistance to PWSCC. So if the crack, for some reason, does make it all the way through the susceptible weld, it's going to not --

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

MR. RUDLAND: That's right.

MEMBER BROWN: Okay, thank you.

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

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

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

And then so we were looking at axial stresses in the previous two, but on Slide 62 I've just shown the hoop stresses. And there's actually a much more beneficial effect, according to our models, on the hoop stresses after the optimized weld overlay.

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

MR. BENSON: Yes.

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

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

CHAIR ARMIJO: You had at least 10 K compression?

MR. BENSON: No.

MR. RUDLAND: 10 K tension.

MR. BENSON: 10 K tension.

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

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

CHAIR ARMIJO: You can dance around that

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

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

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

CHAIR ARMIJO: Yes, sure, sure.

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

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

MR. COLLINS: It actually, in the calculation for holding the integrity of the pipe, it uses the outer quarter thickness of the material of the Alloy 82/182 material that would still be susceptible to cracking to go into those calculations, whereas the full structural weld overlay doesn't use that outer material.

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

MEMBER SCHULTZ: Thank you.

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

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

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

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

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

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

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

MEMBER SCHULTZ: I'd like to bring it up here. I'm struggling with the concept of saying that what we're looking at here is modeling uncertainty versus what I saw earlier that I appreciated, which was variability in the results of the modeling. The modeling uncertainty seems, to me, to be the strict comparison of the models of the data, and we saw many graphs or displays that showed the variability. And some of the models were, I presume, good in comparison to the data, and some were poor. But that doesn't mean that what I'm looking at is model uncertainty. I'm looking at the variability in the model, and I'd have to pour into the capacity of one particular model to identify its uncertainty versus the inability of the modeler or the inability of the model to effectively match the data. It's a little different than --

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

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

MR. RUDLAND: That's a good point. The analysis, at least in the round robin, the mean value matched the experiments pretty well. So from a mean standpoint of all of the analysis, we have little model uncertainty, I suppose, because the mean value matches the experiments rather well. And it's really that scatter from the individual modelers --

MEMBER SCHULTZ: Correct.

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

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

MEMBER SCHULTZ: Well, it's all, as you say, it's all good information. And given that a modeler is giving you a one-of-a-kind analysis, then it does, as you appropriately picked the word, inform you as to what confidence one may have at this point in time related to that prediction.

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

MEMBER SCHULTZ: That's right.

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

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

MR. RUDLAND: Right.

MEMBER SCHULTZ: But it's multi-variable.

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

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

MR. RUDLAND: Yes, thank you.

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

CHAIR ARMIJO: Yes, yes.

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

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

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

MR. BENSON: Yes. You're right, Sam. Our essential conclusion was things like contour measurement and deep hole drilling measurements are the ones we're going to stick with.

CHAIR ARMIJO: Okay.

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

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

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

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

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

MR. BENSON: So what are the knowledge gaps? First of all, commonly accepted procedures for developing a weld residual stress input to a flaw evaluation are lacking. And criteria are needed for weld residual stress acceptance and validation. No measurement data currently exists for various other weld geometries that we haven't looked at, such as J-groove weld. And the effect of partial arc repairs cannot be captured with axisymmetric models. So typical repairs in the field or certain portion of the circumference, we can't model that effect with the axisymmetric models.

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

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

MR. RUDLAND: Strain gauges.

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

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

MEMBER SHACK: Right.

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

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

MR. RUDLAND: Agreed.

MR. BENSON: So that data is being collected now. And then there's, like we mentioned, there's the Phase IIb mockup, which is pretty much similar to the Phase IIa mockup, except here we are using a manual welding technique. And this mockup is currently in England at Veqter, and they're finishing up deep hole drilling measurements. And then once that's finished, that nozzle will be shipped to our contractor in California who will do the contour and slitting measurements on that mockup.

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

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

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

So that will get at modeling uncertainty, and then welding uncertainty will be assessed by performing sensitivity studies on particular key inputs. So that's the work for xLPR. And then we're also keeping our eye on some international research programs.

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

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

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

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

MR. BENSON: Yes. Some of the topics went out to the end of 2014; is that correct, Paul? Is that what you remember? Yes, okay.

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

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

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

MR. BENSON: Potentially, yes.

MR. RUDLAND: We did in the first --

MEMBER SCHULTZ: I know in the first. I

hope that would continue.

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

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

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

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

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

MR. RUDLAND: That's a long answer.

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

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

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

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

MEMBER BROWN: Okay. For weld residual --

MR. RUDLAND: Right.

MEMBER BROWN: Okay.

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

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

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

MR. RUDLAND: That's right.

MEMBER BROWN: -- be more prescriptive?

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

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

MR. RUDLAND: No, I sure hope not.

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

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

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

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

MR. RUDLAND: No.

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

MR. RUDLAND: No.

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

MR. RUDLAND: No.

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

MR. COLLINS: Like right now, well, I mean, right now it's not in the code. So, I mean, when we see something come in, usually they're asking for reason, right? They're asking for an extension of an inspection frequency or something of that nature. So we want to have the confidence in whatever they're providing. And, unfortunately, at this point, since we don't have this established criteria out there, there's uncertainty when we go to talk to them about what we need to have. Like, for instance, that tiered level approach, that 50 percent weld repair that's initially in there for their initial calculation. And then if they want to better define their residual stresses, then we have to work through that process. And we look at the sensitivity to how close they are in months to what they're asking for. Do they actually have, are the calculations saying it's 120 months and they're only asking for 50 versus does the calculation show 58 months and they're asking for 50? Then we have to better redefine and look at some of the uncertainty analysis.

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

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

MR. COLLINS: No.

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

MR. COLLINS: I think that's a pretty good general statement. Even the requirements currently in the code for the various different inspection programs are based upon the idea of a deterministic calculation at some point along the line. There's other factors that feed into, probabilistic and things of that nature have their opportunities. But the base deterministic calculation, especially for relief requests that come in for, like you were saying, a licensee wanted to change inspection frequency or they've missed coverage and the flaw size might be larger in an area because they can't get full volumetric inspection coverage. Those are things we handle more so on a basis.

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

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

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

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

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

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

CHAIR ARMIJO: No one called in?

MR. NGUYEN: Correct.

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

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

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

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Outline

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

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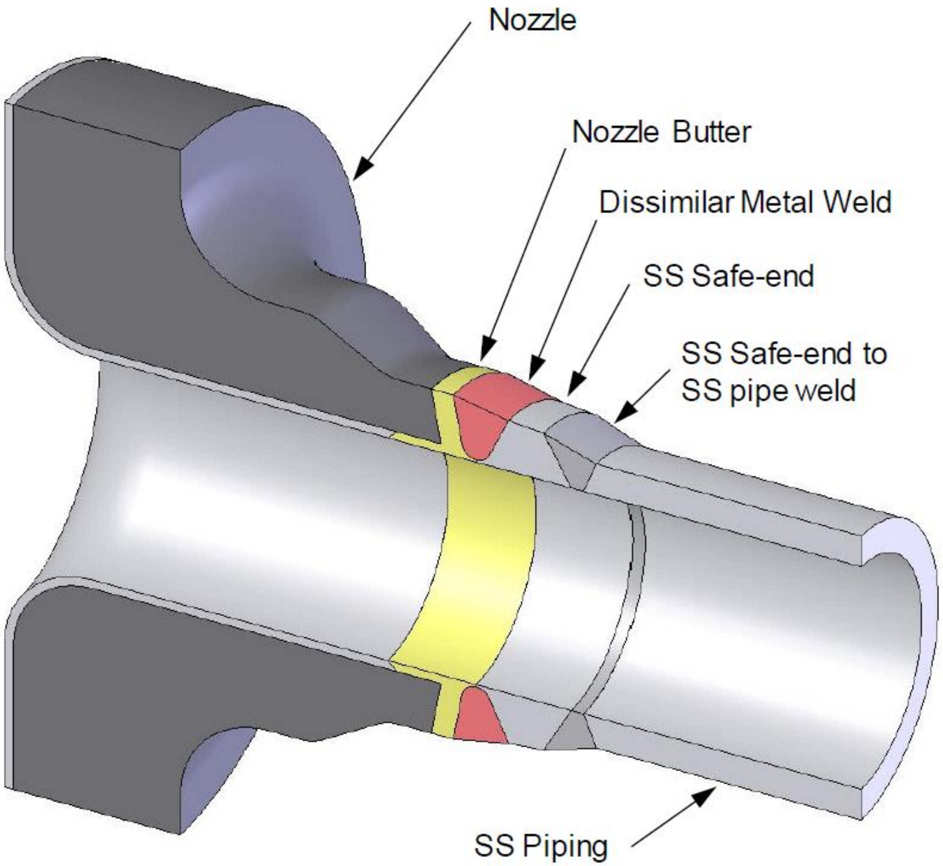
WRS Validation Program Overview

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

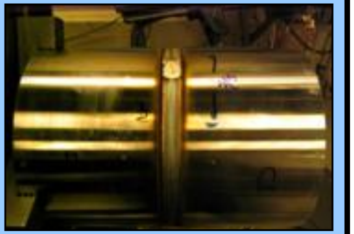
WRS Validation Program Overview

Research Phases

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

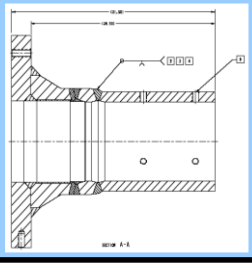
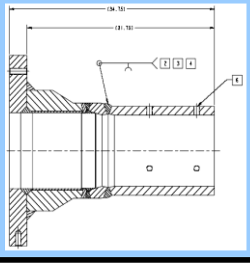
Phase 1 - EPRI

- **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

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

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

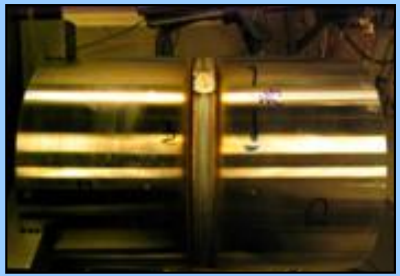
Phase 1 - EPRI

•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
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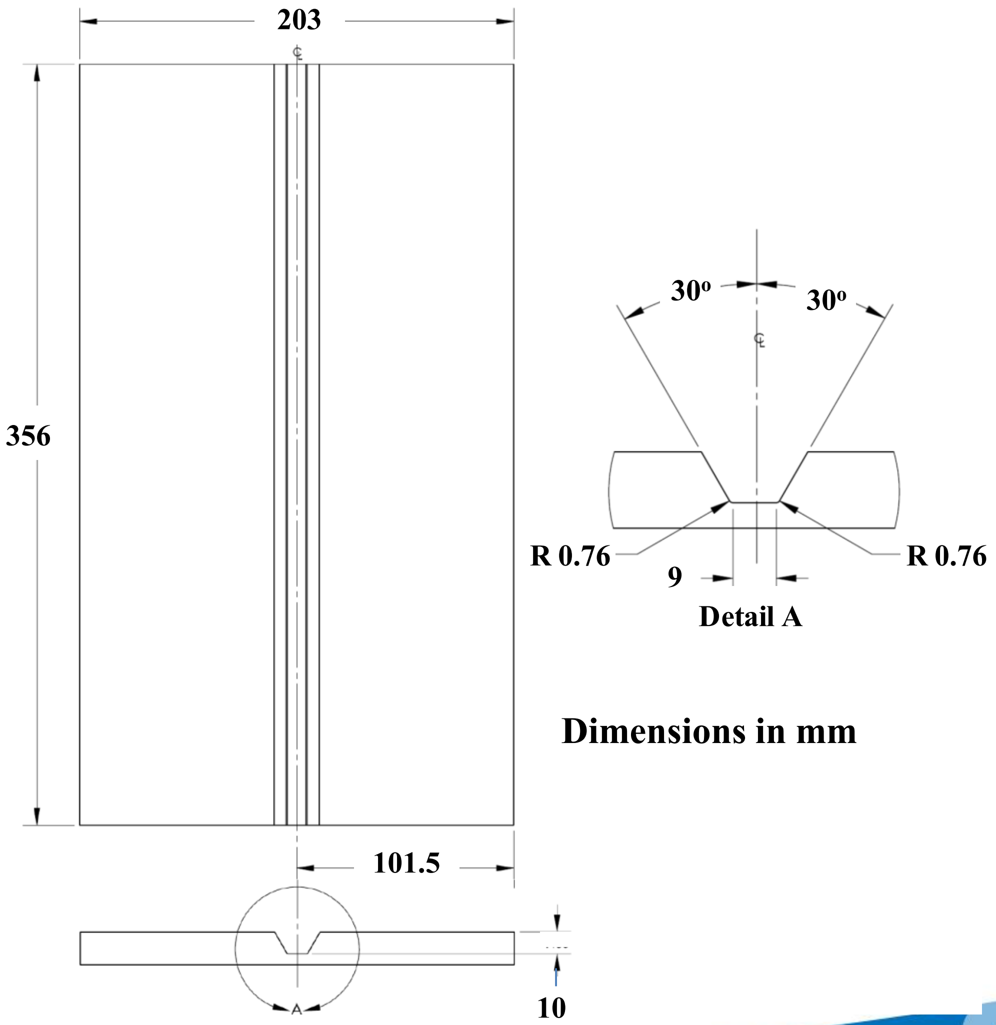
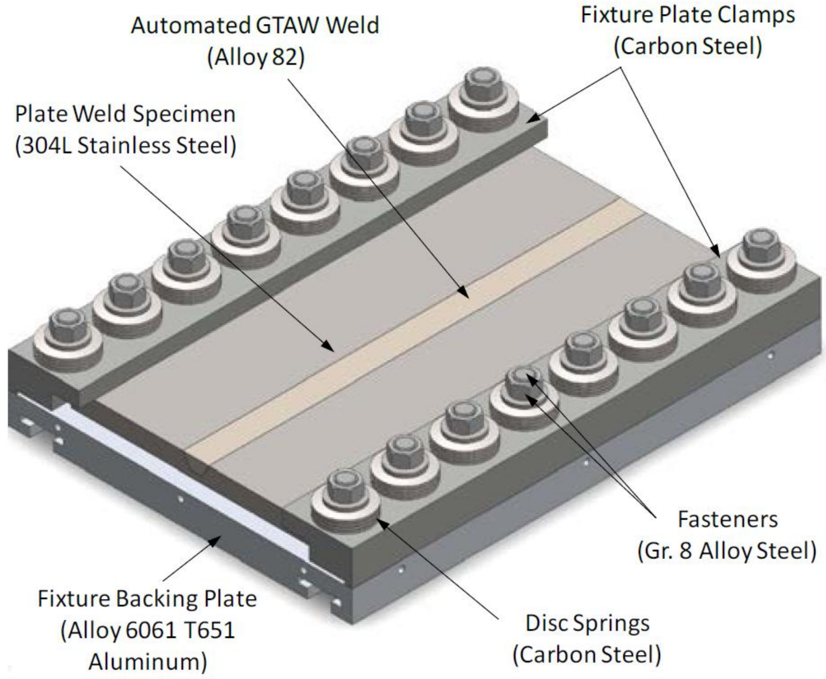
Phas

Phase I: Scientific Weld Specimens

Plate Specimens



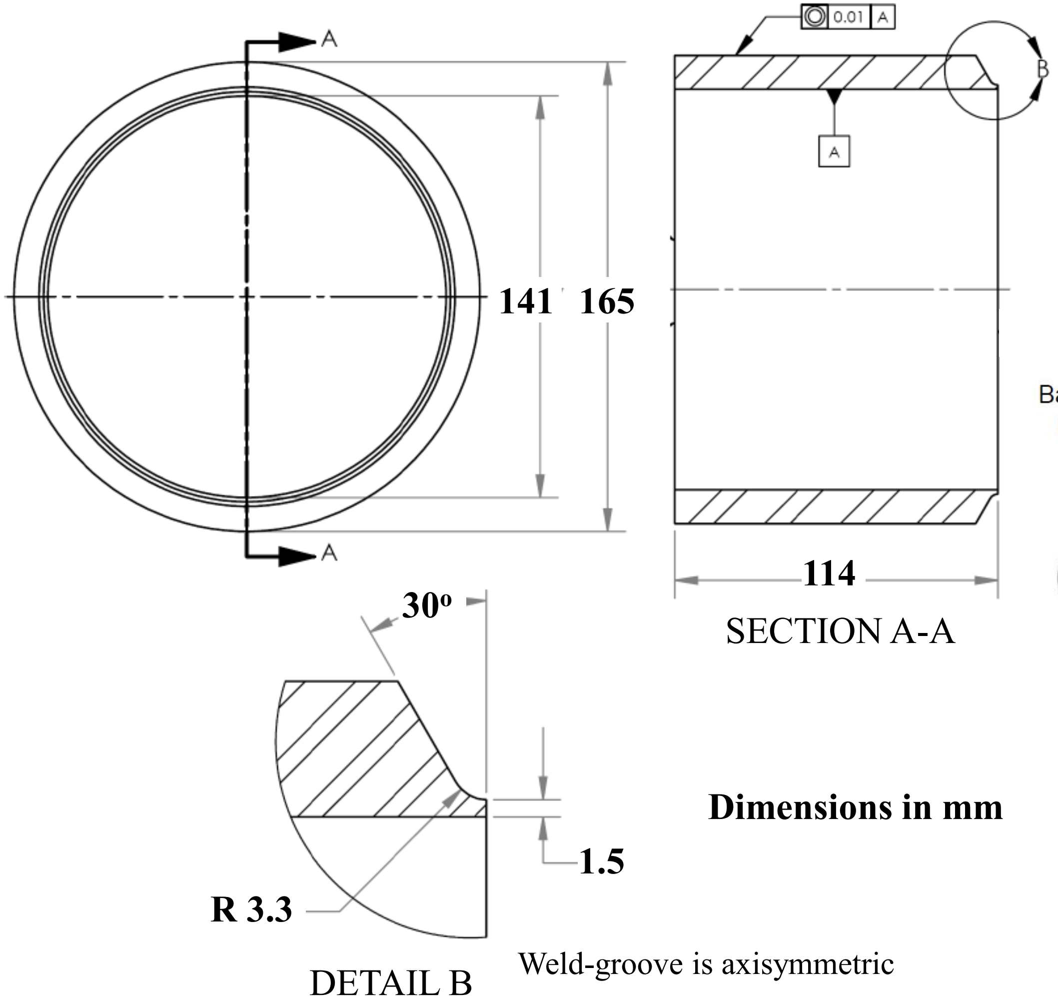
Dimensions in mm



Source: MRP-316, EPRI, 2011

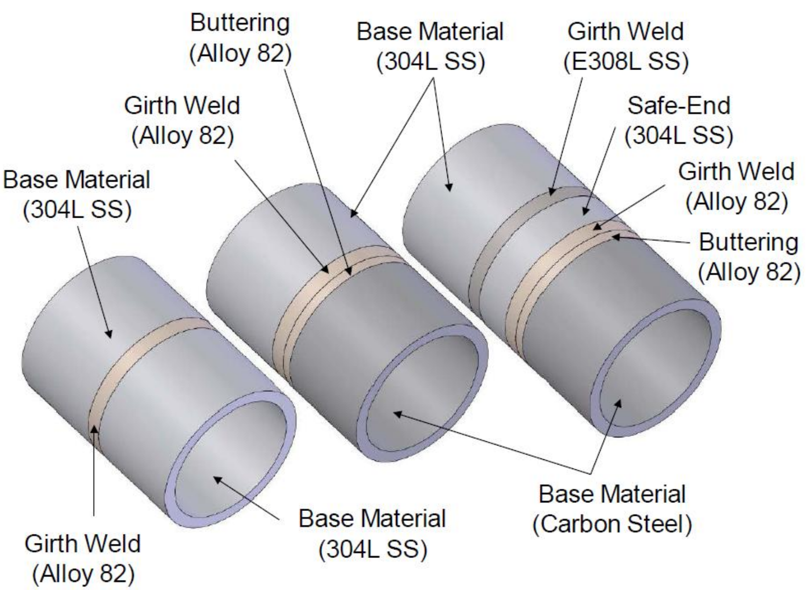
Phase I: Scientific Weld Specimens

Cylindrical Specimens



Dimensions in mm

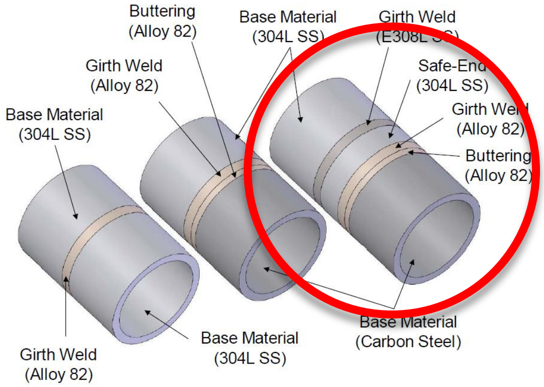
Weld-groove is axisymmetric

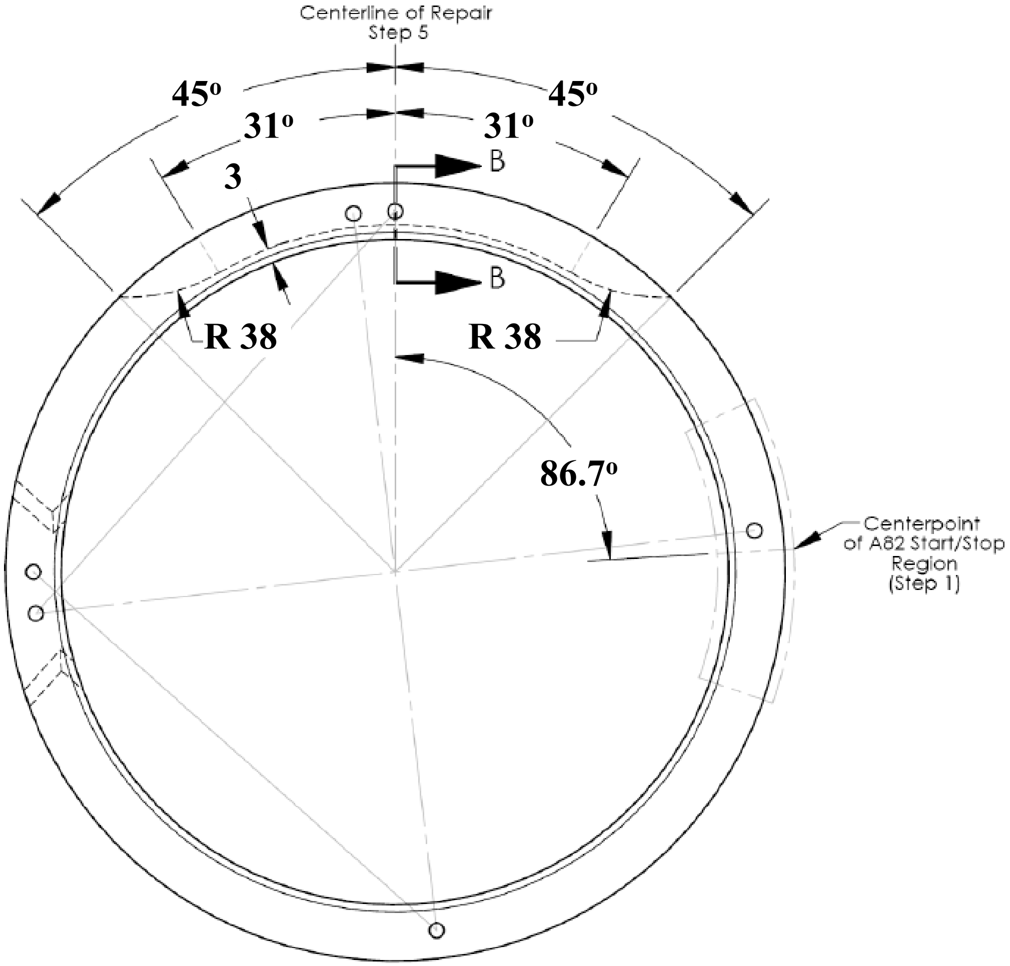


Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

Weld Repair



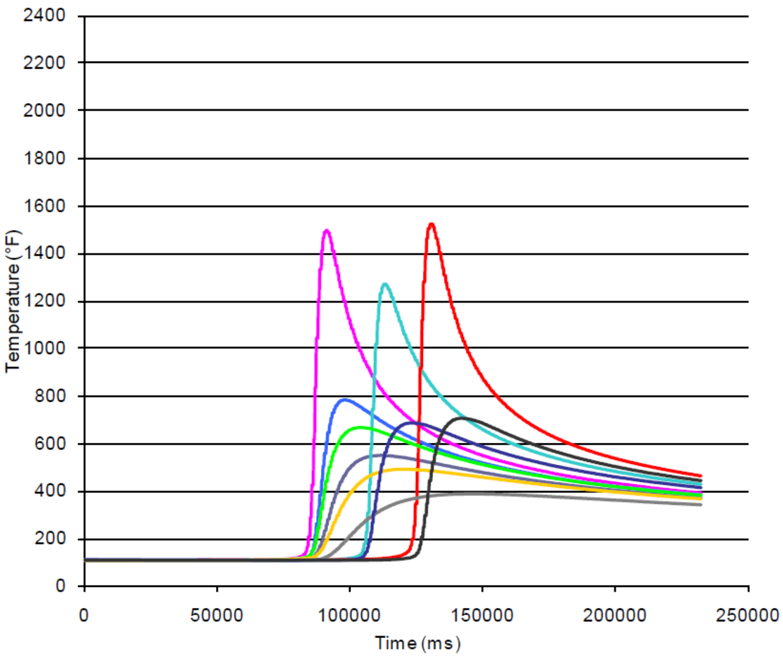


Source: MRP-316, EPRI, 2011

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

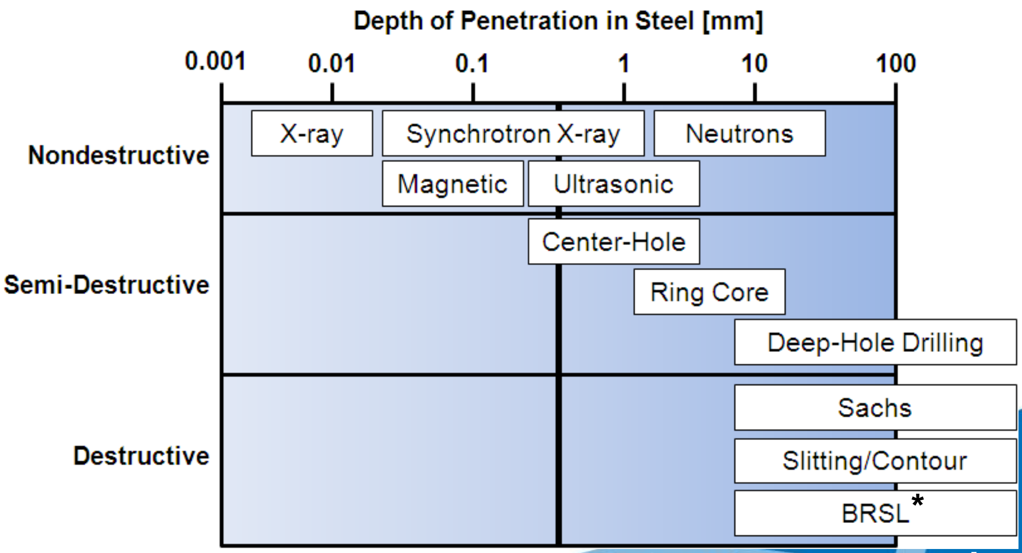


Source: MRP-316, EPRI, 2011

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

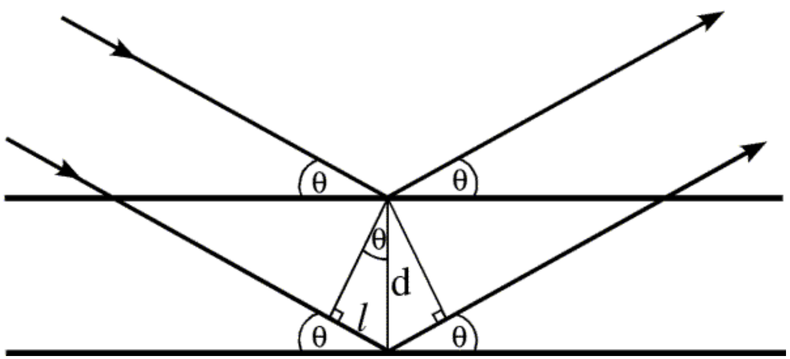
Diffraction Techniques

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

- Measurement of lattice spacing, based upon the position of diffraction peaks

- Relies upon proper measurement of reference lattice spacing

- X-ray: surface, neutron: bulk



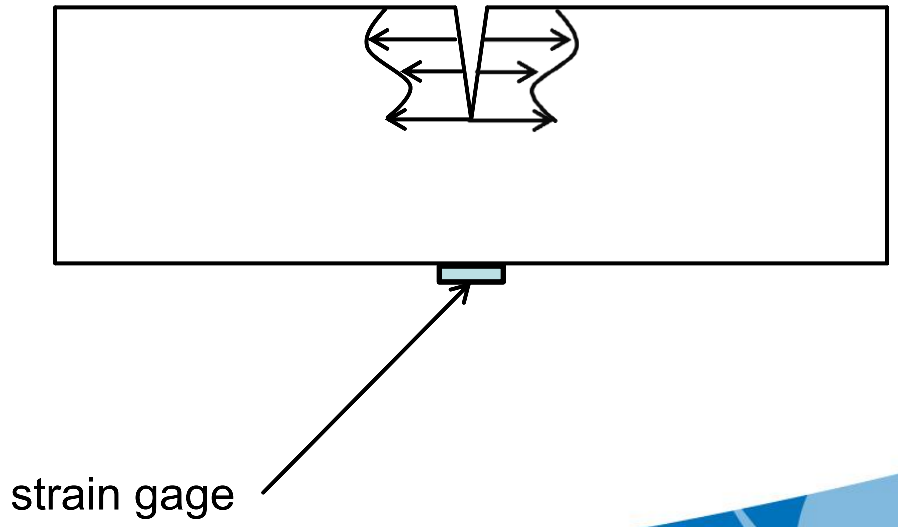
$$\varepsilon_{ii}^{hkl} = \frac{d_{hkl} - d_{hkl,0}}{d_{hkl,0}}$$

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

Phase I: Scientific Weld Specimens

Strain-Relief Techniques

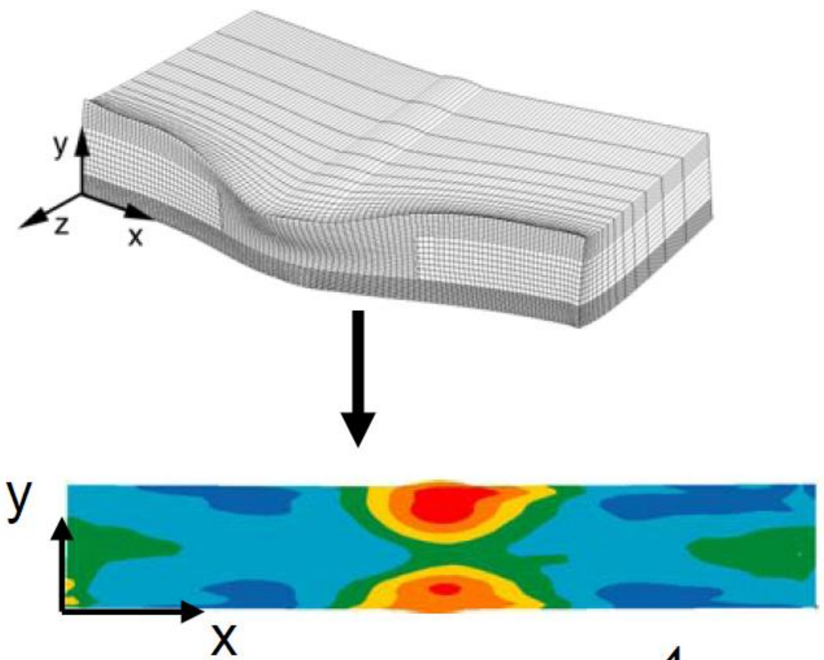
- Incremental slitting: near surface



Phase I: Scientific Weld Specimens

Strain-Relief Techniques

- Contour method: bulk

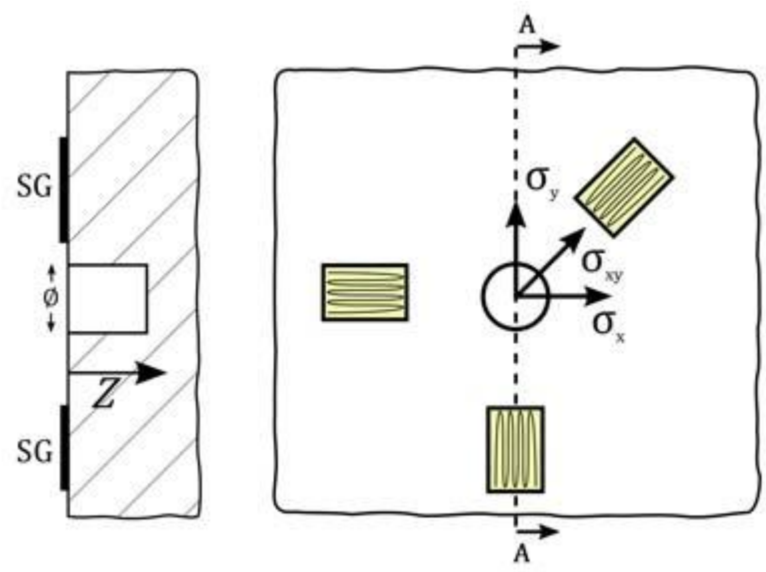


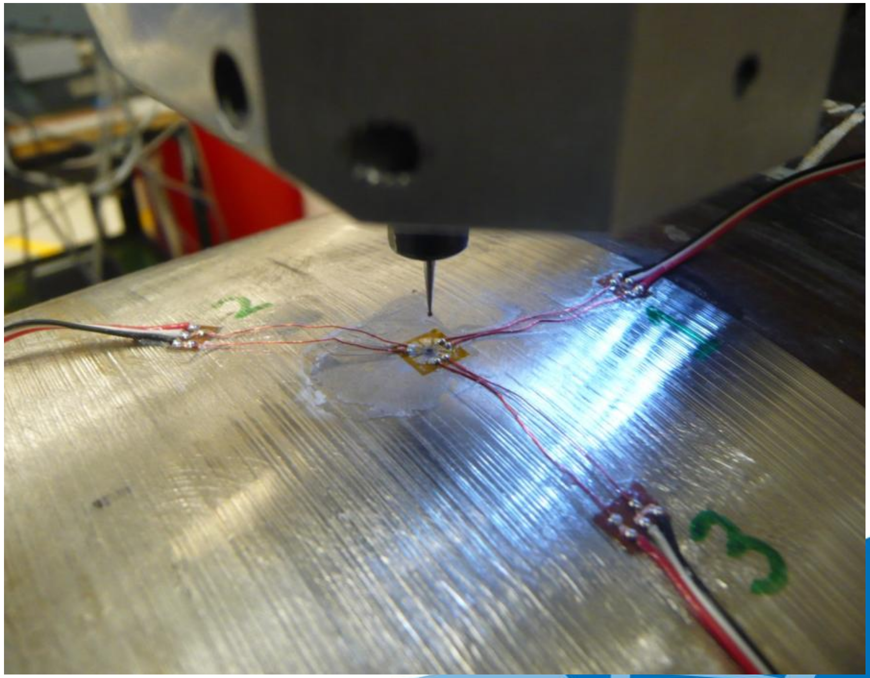
Source: Hill Engineering

Phase I: Scientific Weld Specimens

Strain-Relief Techniques

- Incremental center hole drilling: can be near-surface



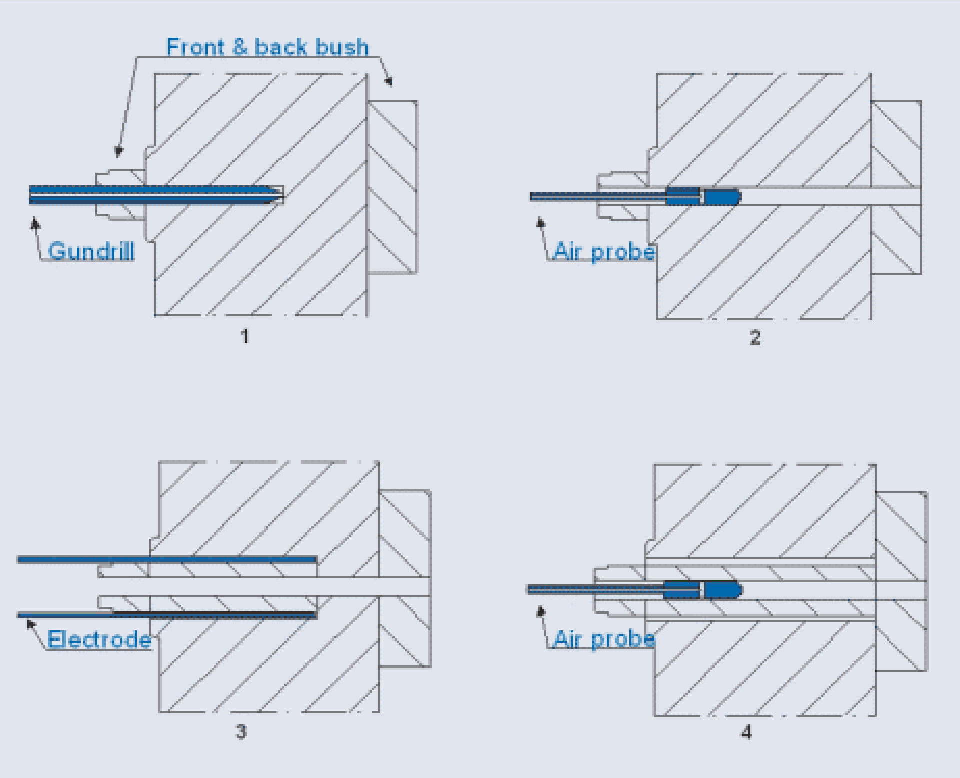


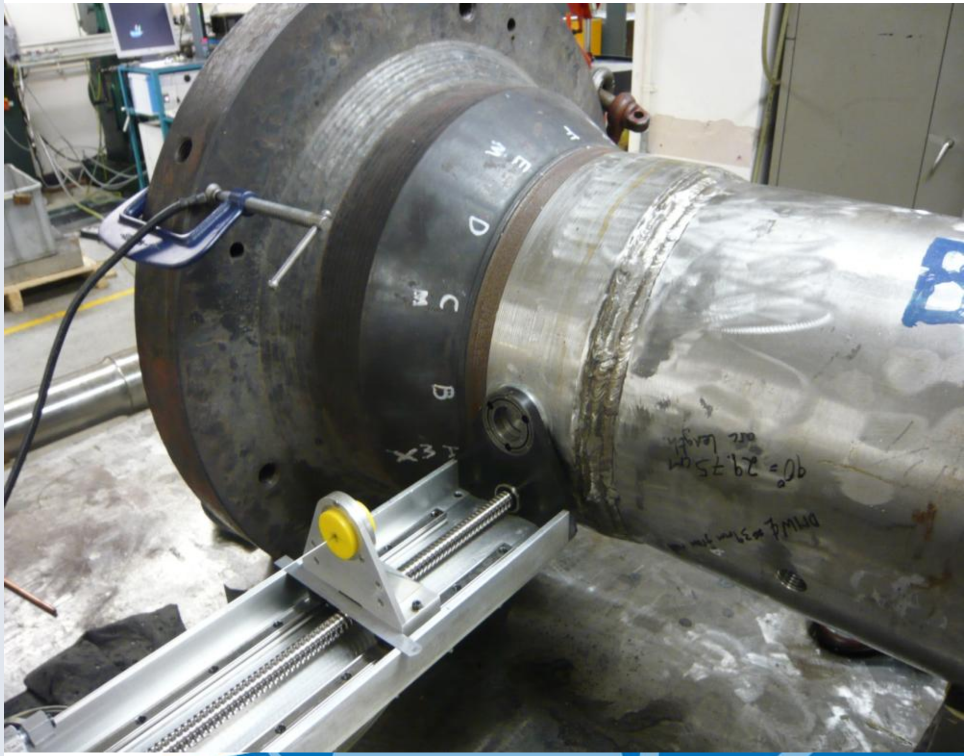
Source: VEQTER, Ltd.

Phase I: Scientific Weld Specimens

Strain-Relief Techniques

- Deep hole drilling: bulk

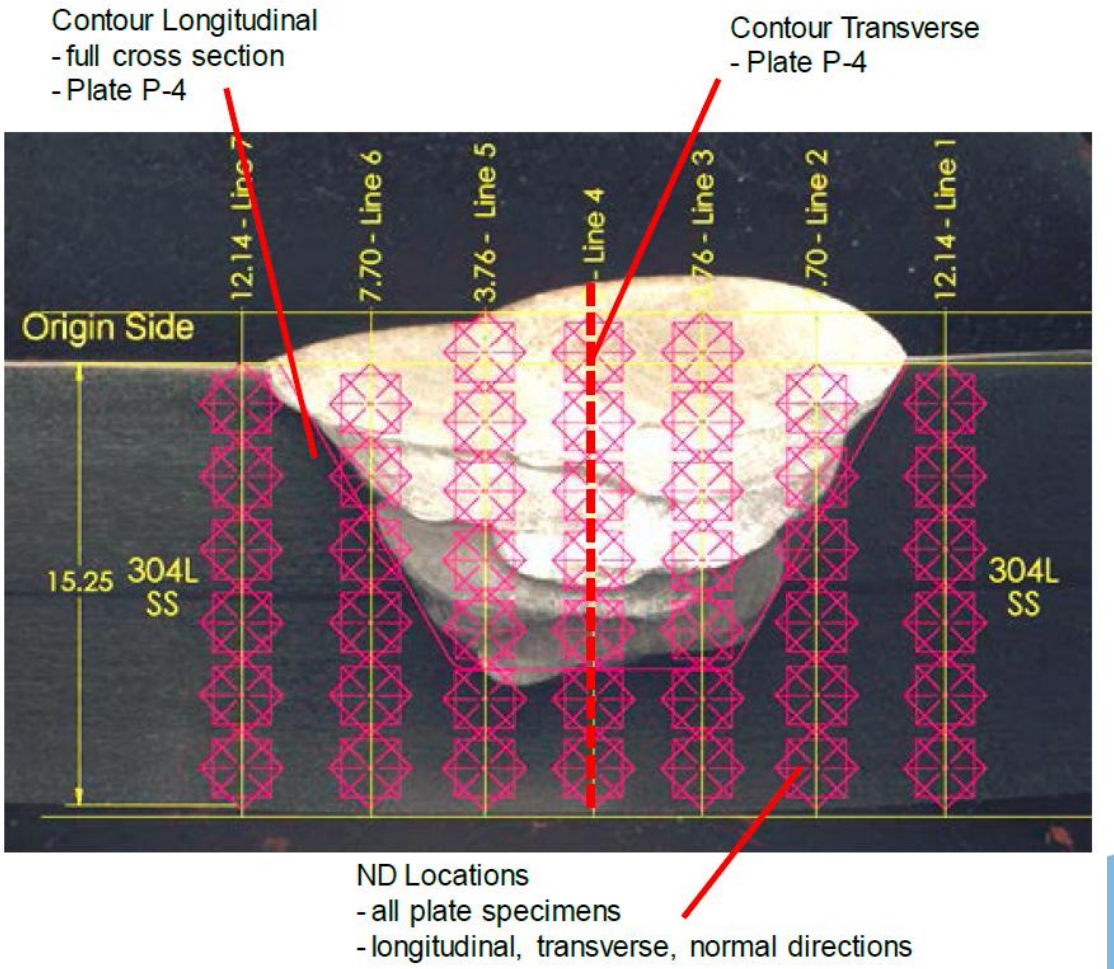




Source: VEQTER, Ltd.

Phase I: Scientific Weld Specimens

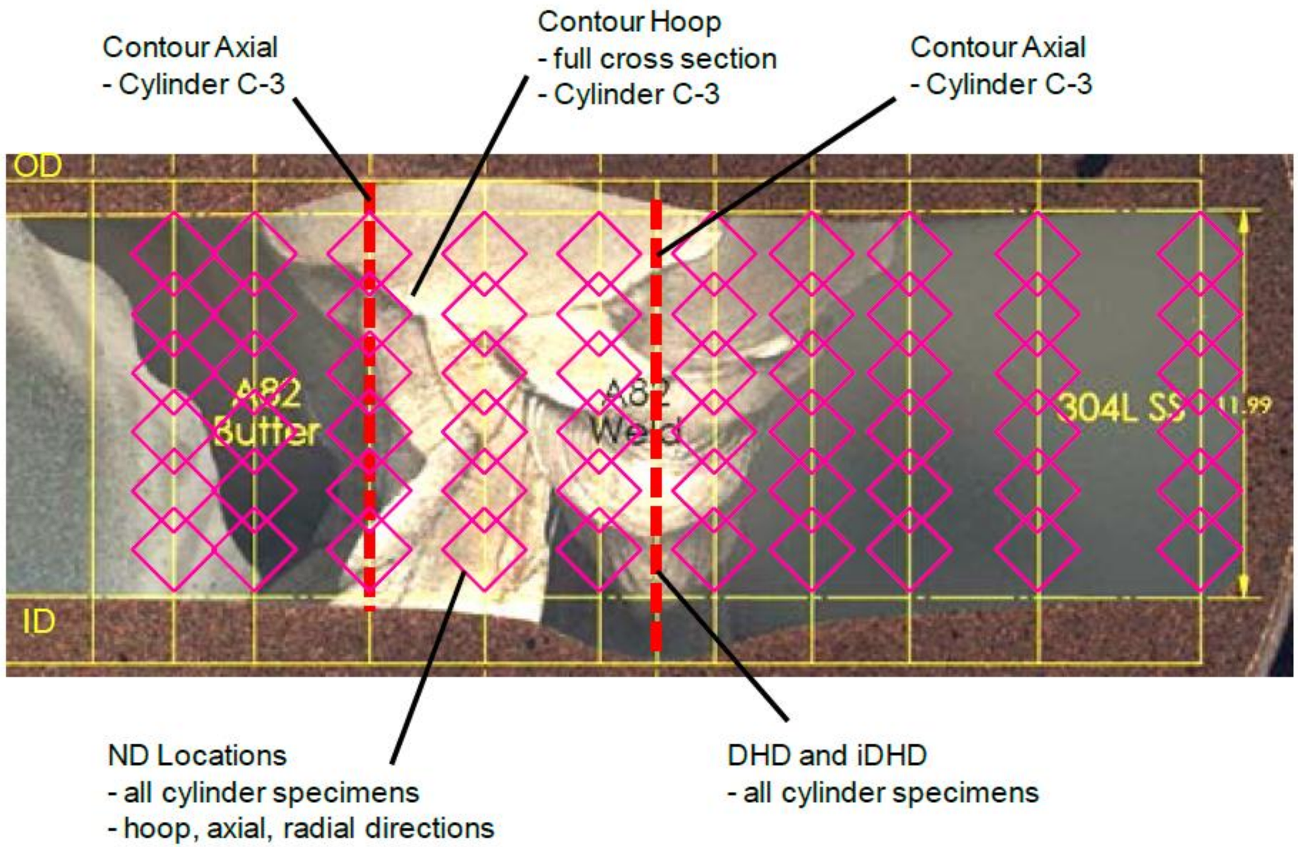
Measurement Summary: Plate Specimens



Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

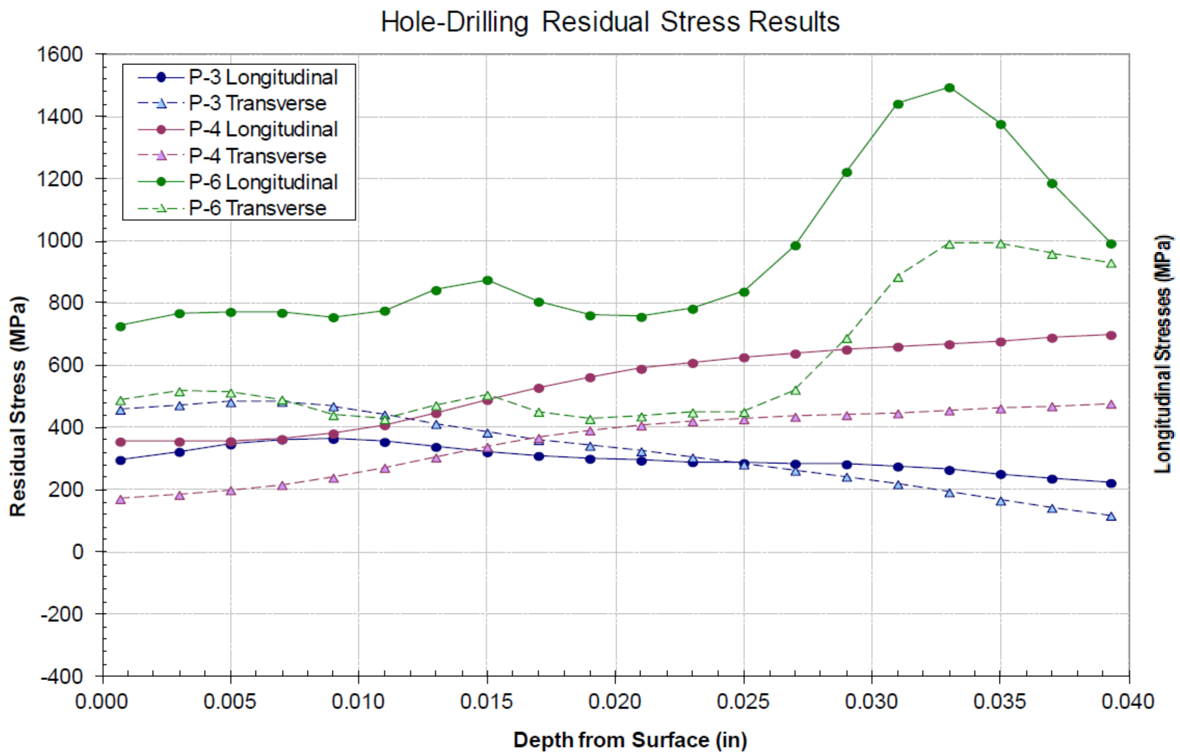
Measurement Summary: Cylinder Specimens

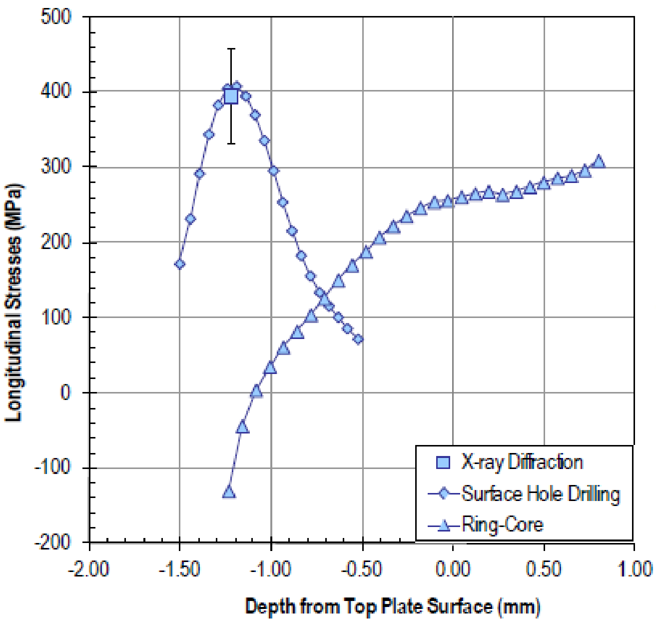


Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

Surface Stress Measurement Results





- 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

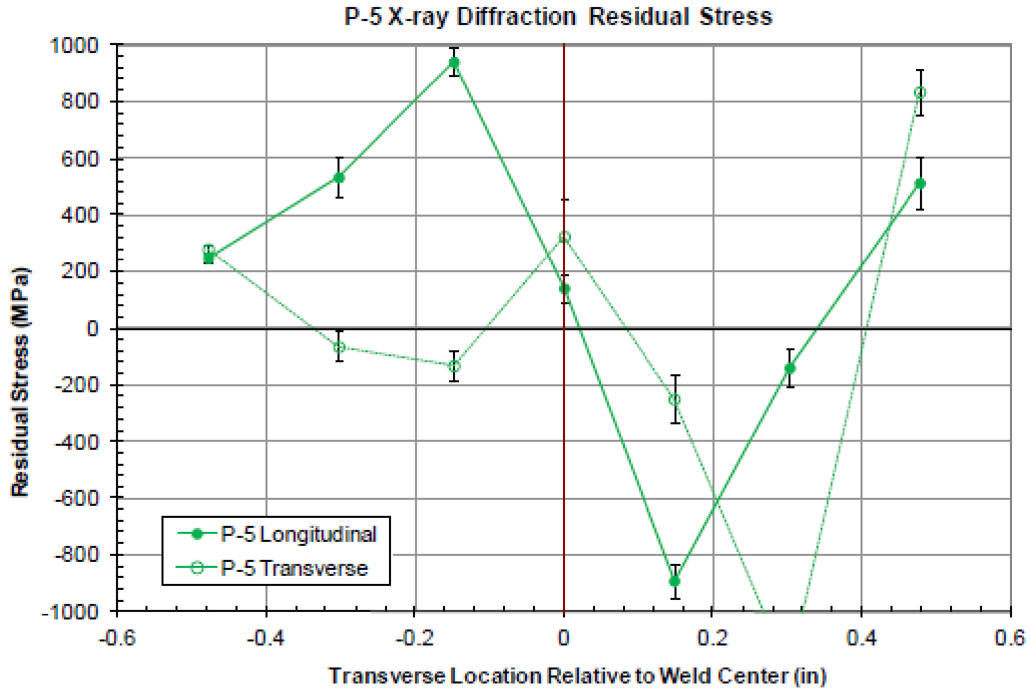


Plate Specimen

- 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

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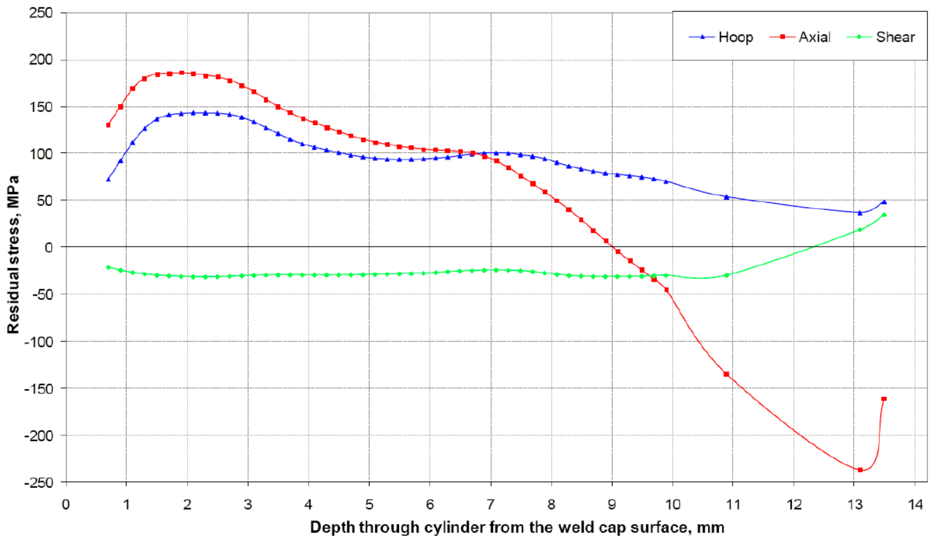
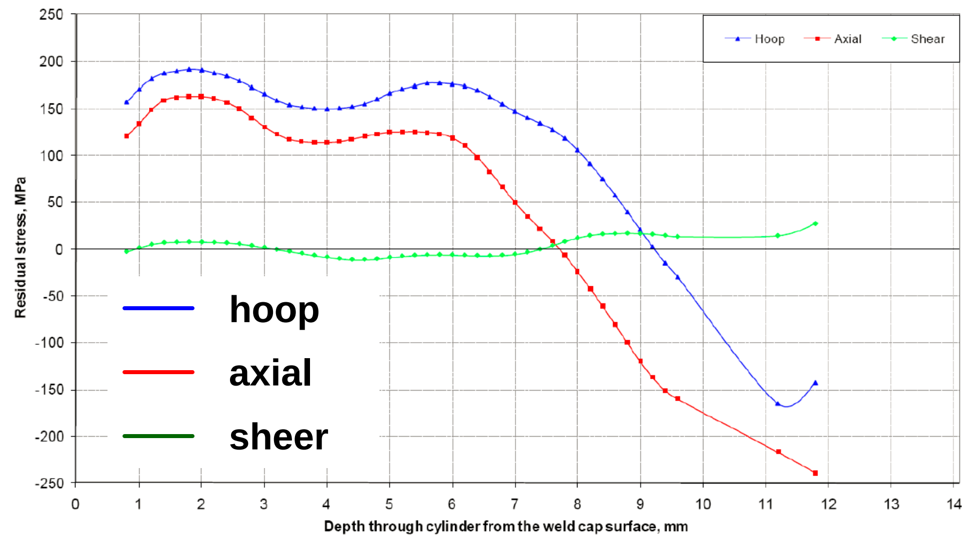
Weld Centerline



Repair Weld Centerline



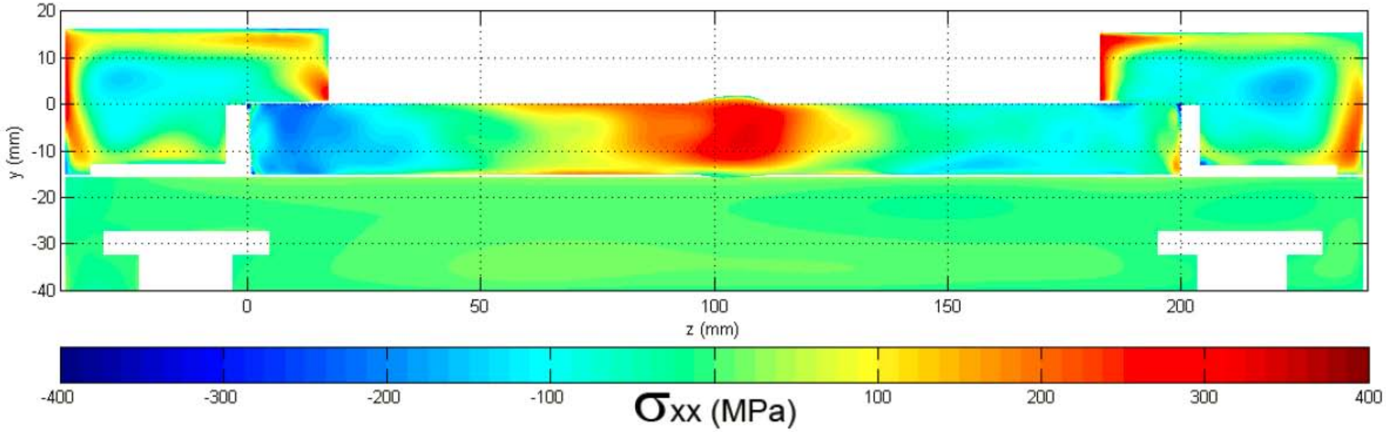
Cylinder Specimen

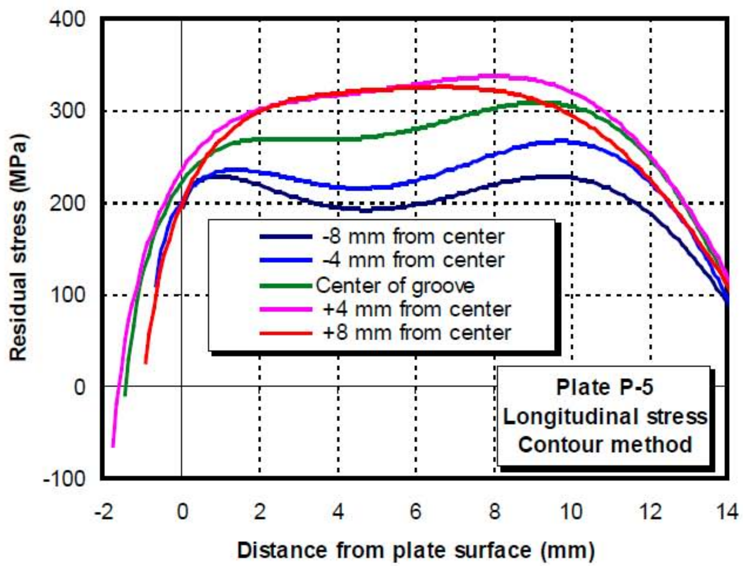
- Smooth trends and reasonable magnitudes: e.g., -200 to 200 MPa
- Repair weld significantly affected the hoop stress

Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

Bulk Stress Measurement Results: Contour





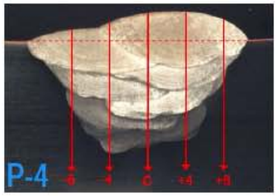
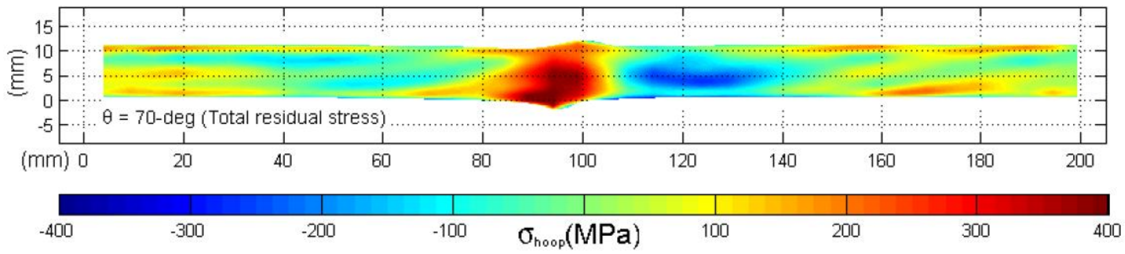
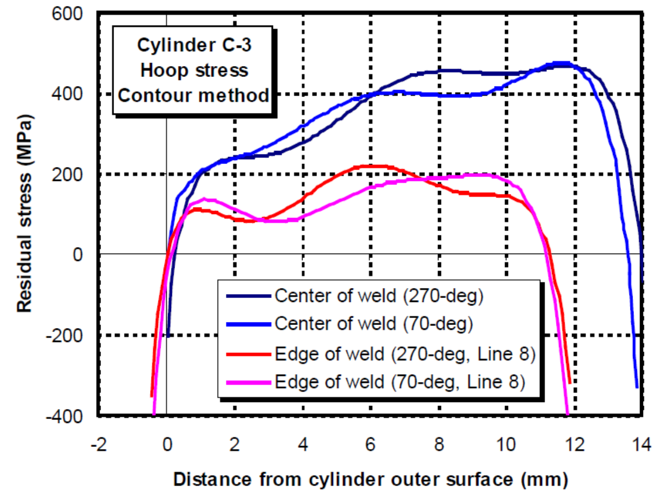


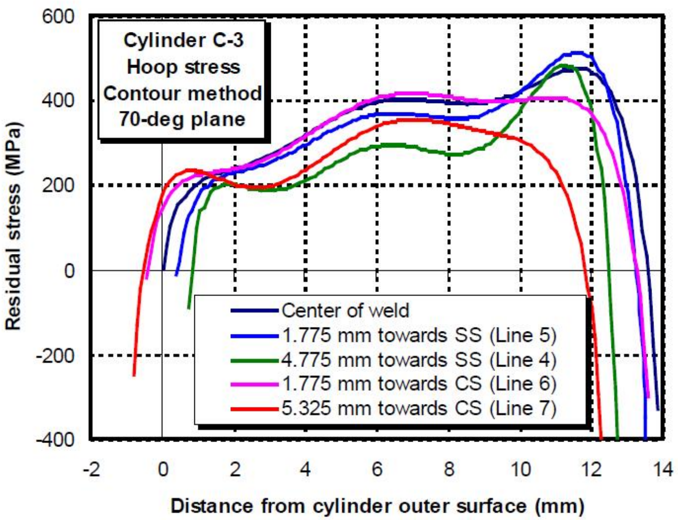
Plate Specimen

Phase I: Scientific Weld Specimens

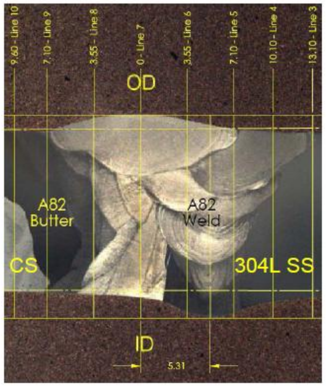
Bulk Stress Measurement Results: Contour







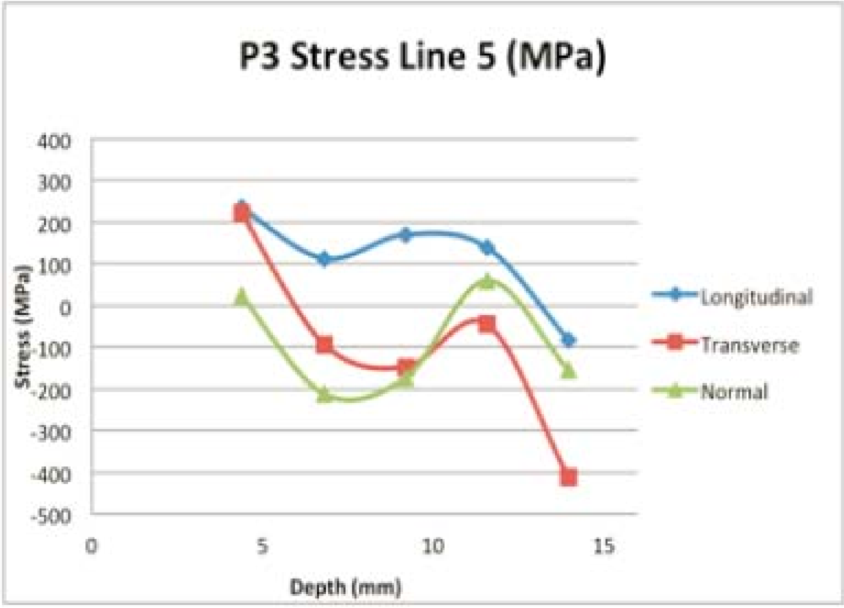
Ring Specimen



Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

Bulk Stress Measurement Results: Neutron Diffraction



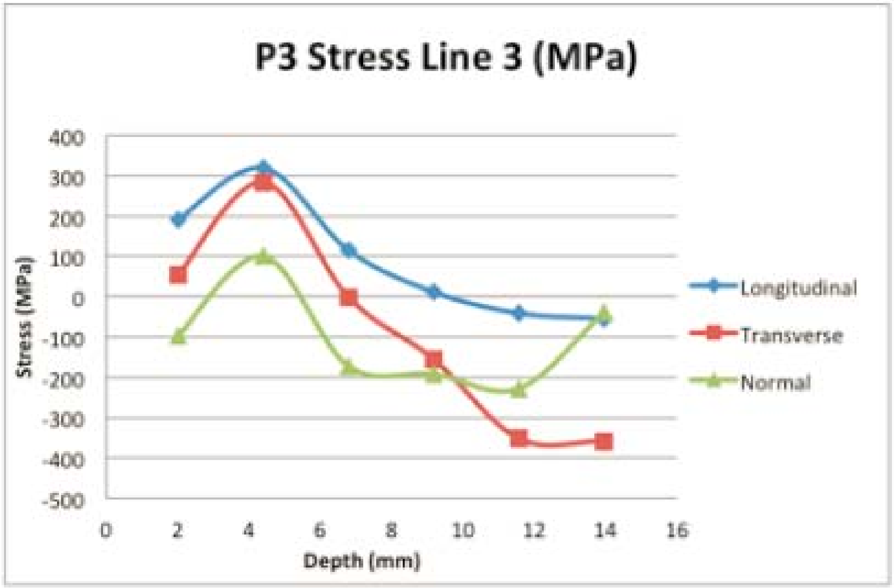
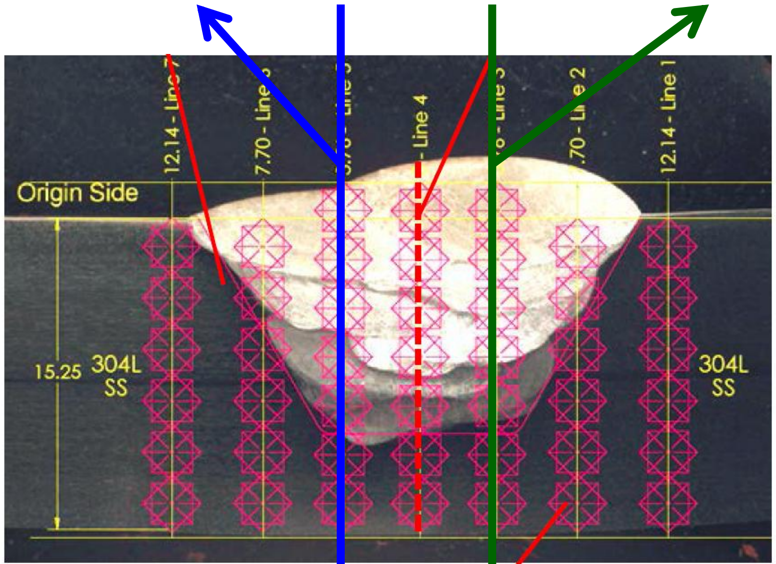


Plate Specimen



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

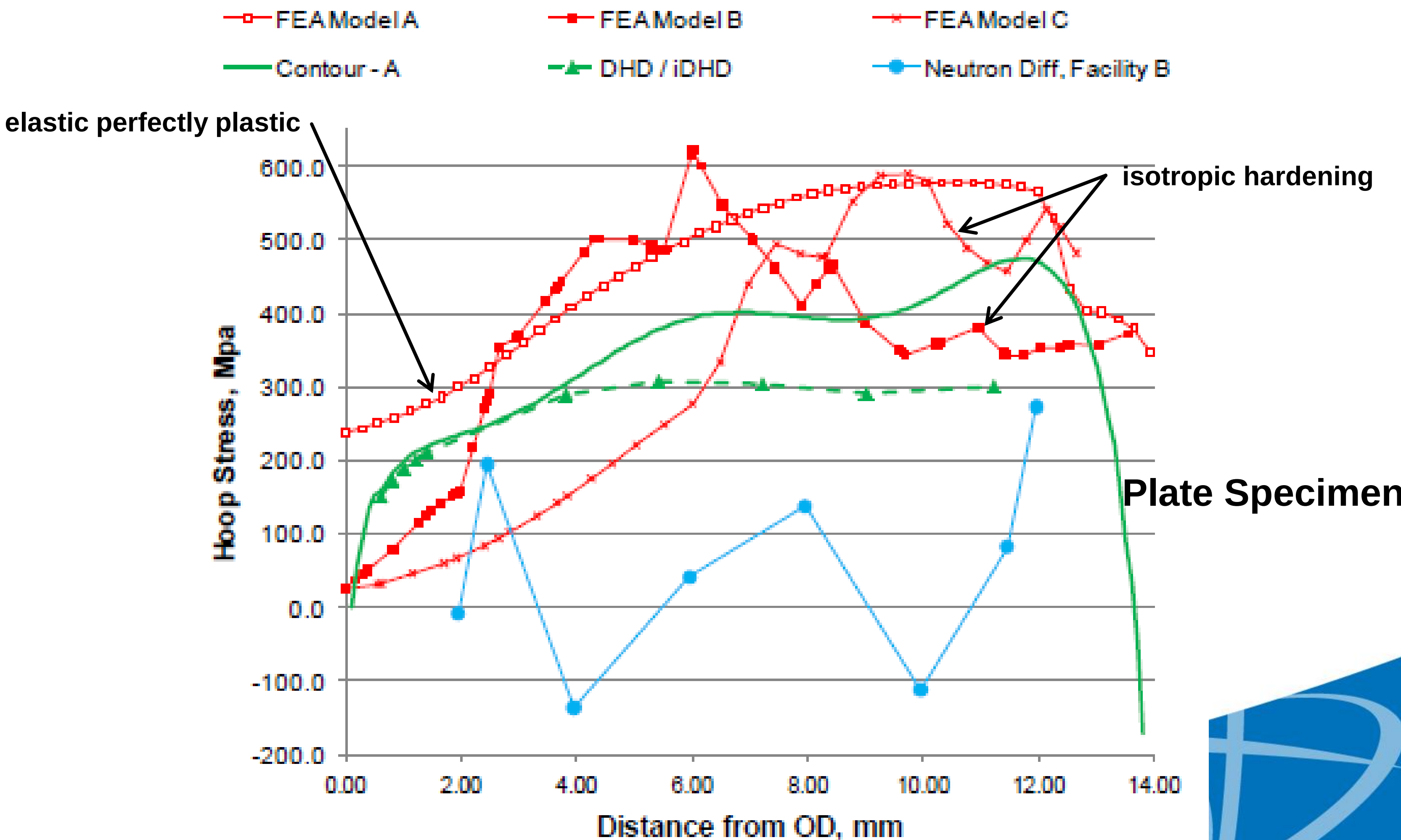
Phase I: Scientific Weld Specimens

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



Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

Data from a Pulsed Neutron Source

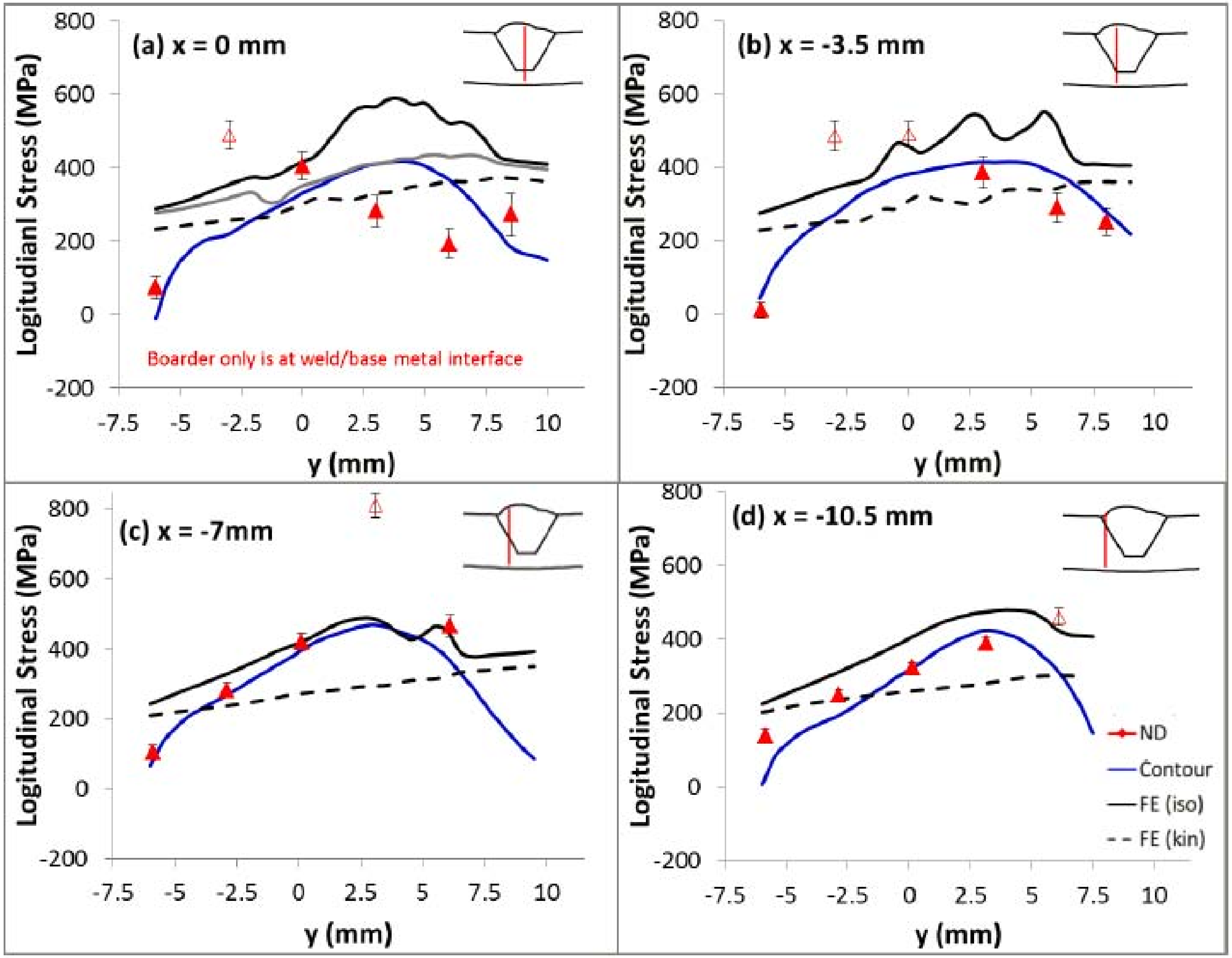


Plate Specimen

Source: MRP-316, EPRI, 2011

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

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- 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

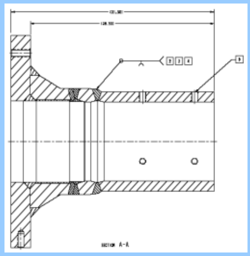
ic Weld Specimens
: Restrained Plates (QTY 4)
: Small Cylinders (QTY 4)
Develop FE models.

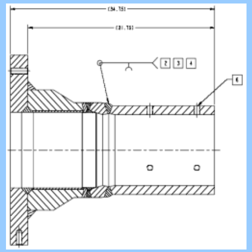
Phase 2 - NRC

•Fabricated Prototypic Nozzles

•Type 8 Surge Nozzles (QTY 2)

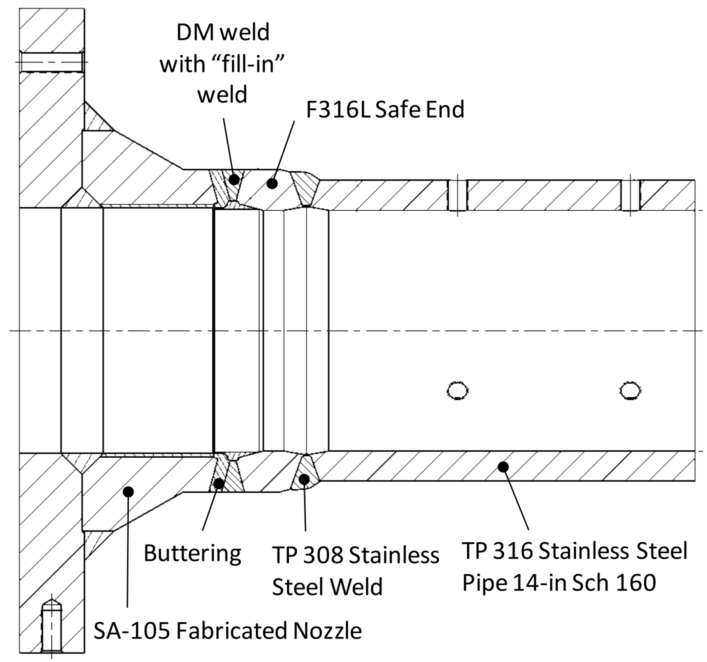
•Purpose: Prototypic scale under controlled conditions. Validate FE models.





Phase II: Fabricated Prototype Nozzles

Mockup Fabrication

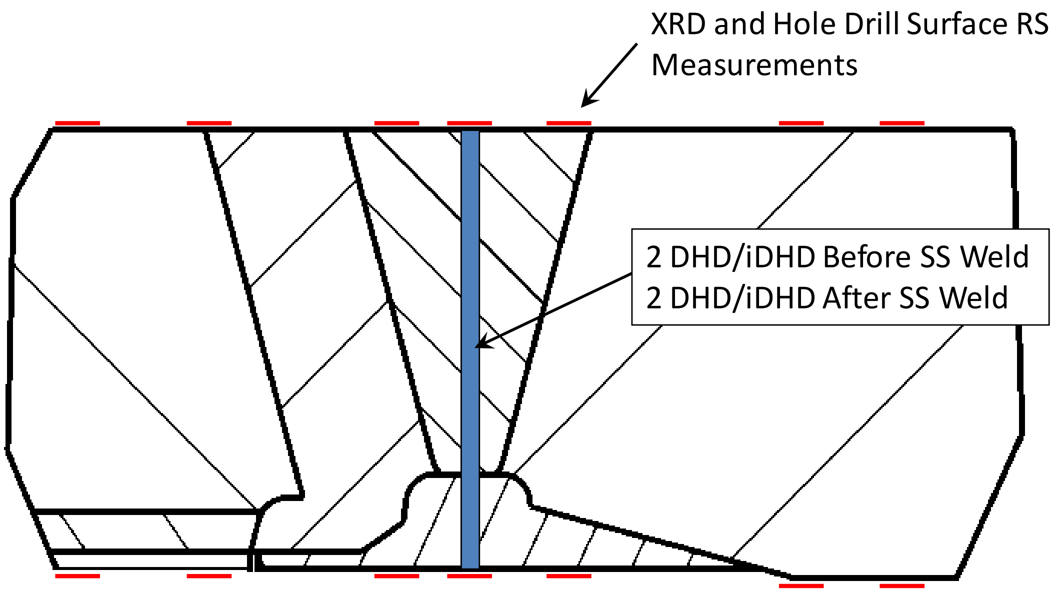


- Pressurizer surge nozzle
- Welding performed by automated gas tungsten arc welding
- Thermocouple and laser profilometry readings
- Rough dimensions: 31" overall length, 11" inner diameter

Phase II: Fabricated Prototype Nozzles

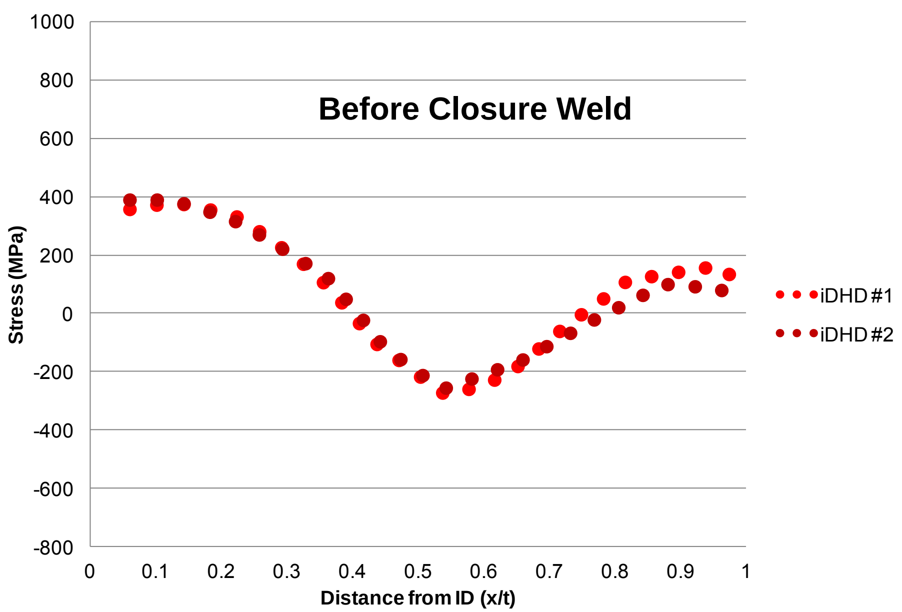
WRS Measurement

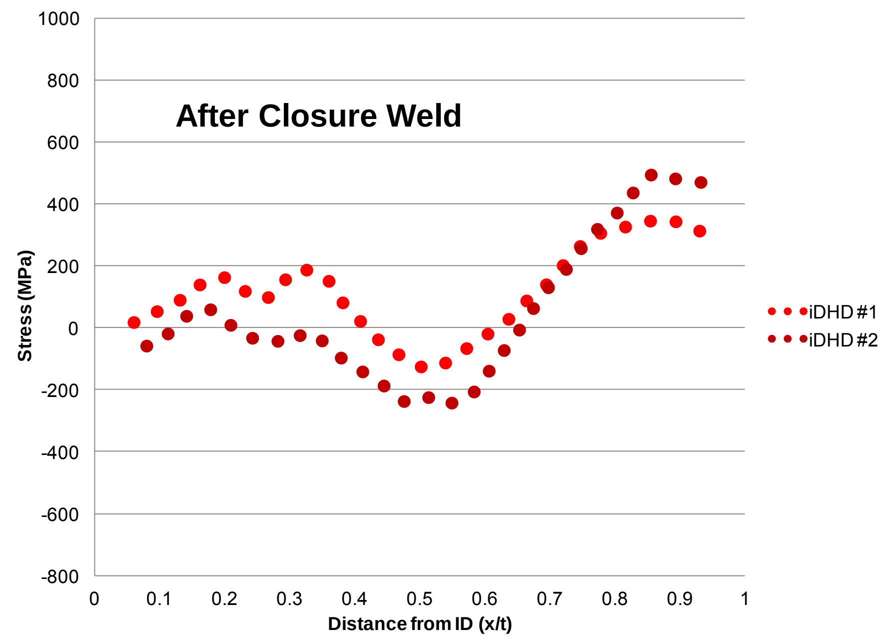
- Incremental deep hole and deep hole drilling - bulk
- Measurements taken before and after safe end to pipe weld was complete
  - Safe end to pipe weld can affect the stress field at the dissimilar metal weld



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)
- EMC[2] (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

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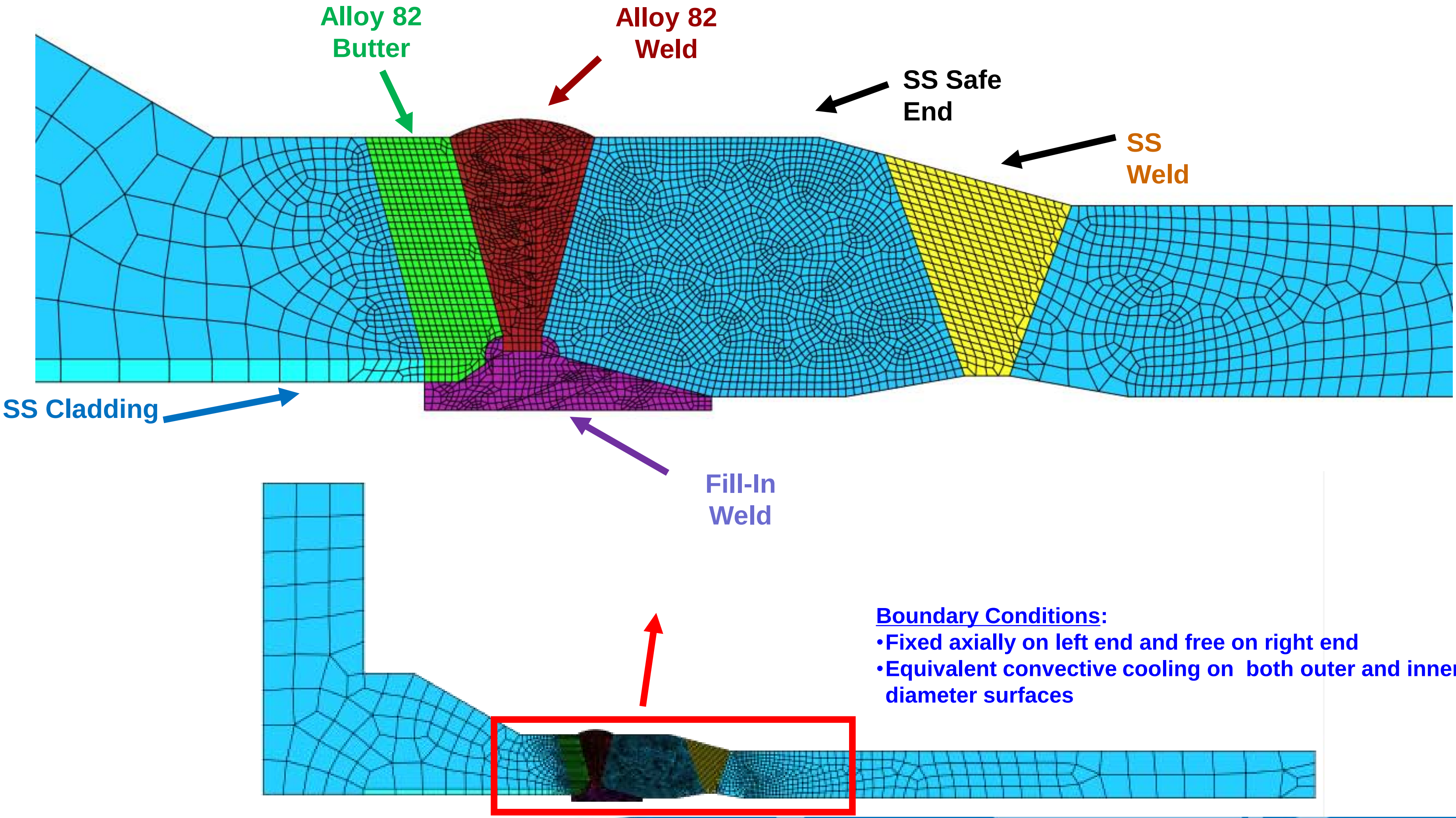
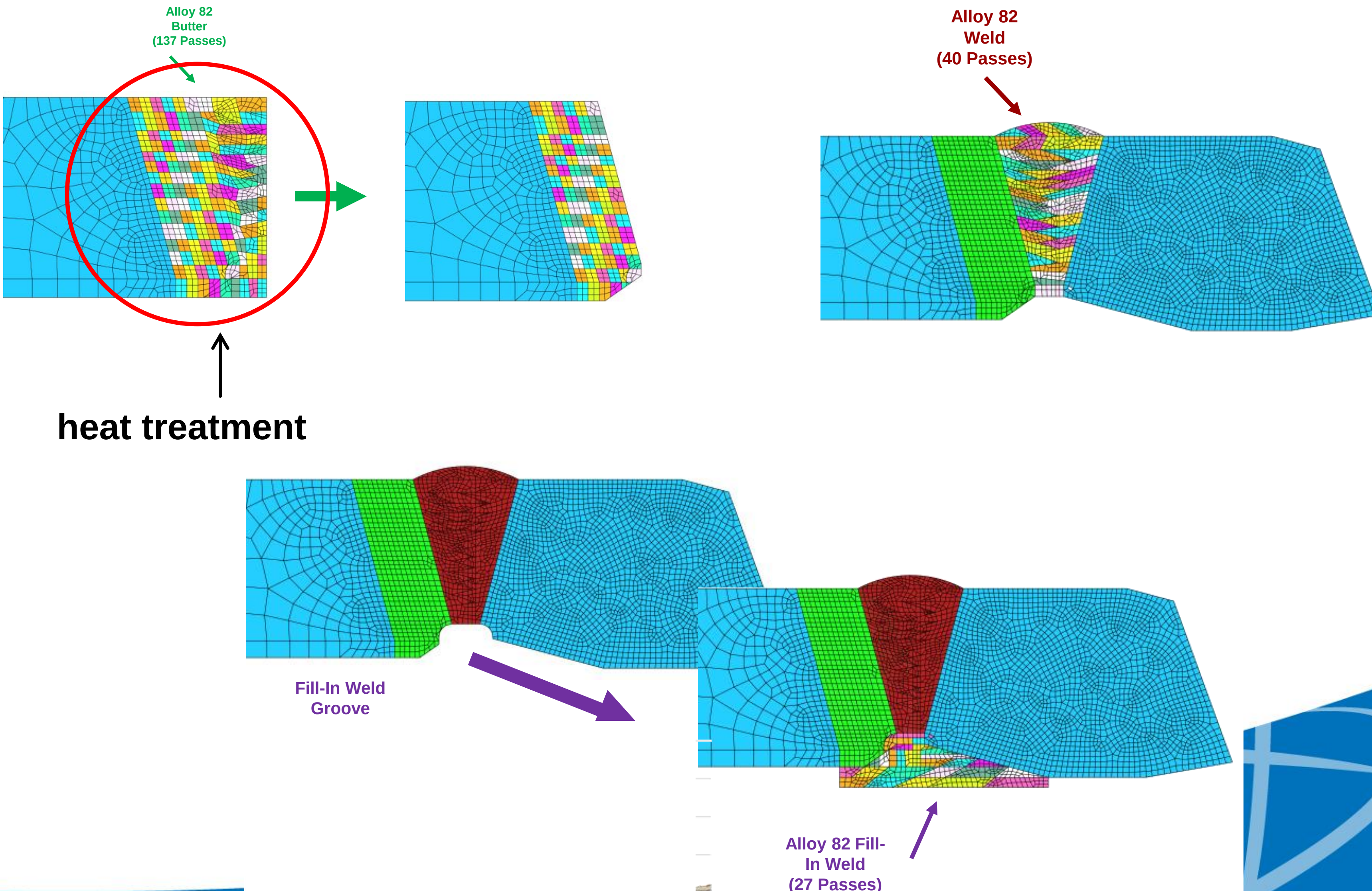
Example Model Geometry



Boundary Conditions:
- Fixed axially on left end and free on right end
- Equivalent convective cooling on both outer and inner diameter surfaces

Phase II: Fabricated Prototype Nozzles

Example Model Geometry



Phase II: Fabricated Prototype Nozzles

Analysis Stages: Can We Reduce Uncertainty?

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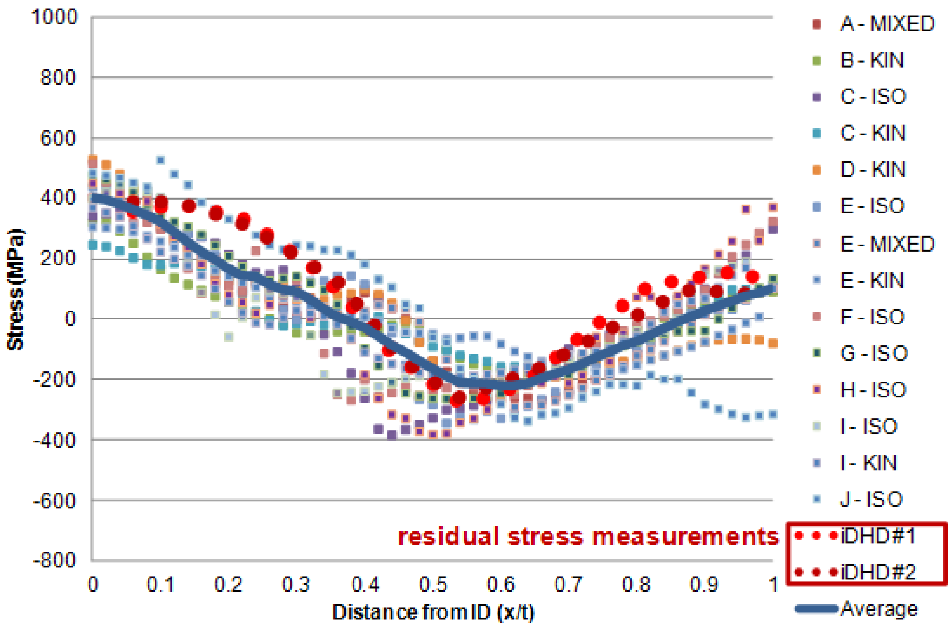
- Postulated sources of uncertainty: welding heat input and material properties
- Three analysis stages
  - No thermocouple data or material property data supplied
  - Thermocouple data only supplied
  - Thermocouple and material property data supplied
- Models completed before and after the stainless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

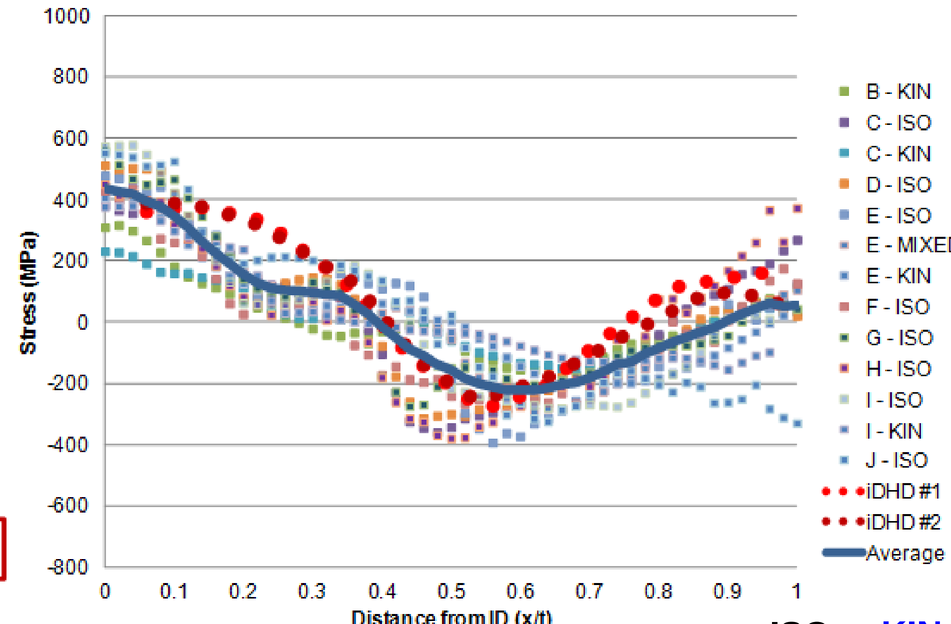
Phase II: Fabricated Prototype Nozzles

FEA Round Robin Results

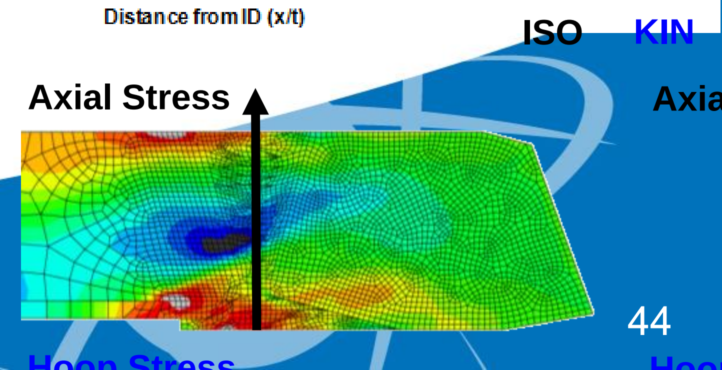
Pre-stainless steel weld
No material properties
No thermal couple data



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

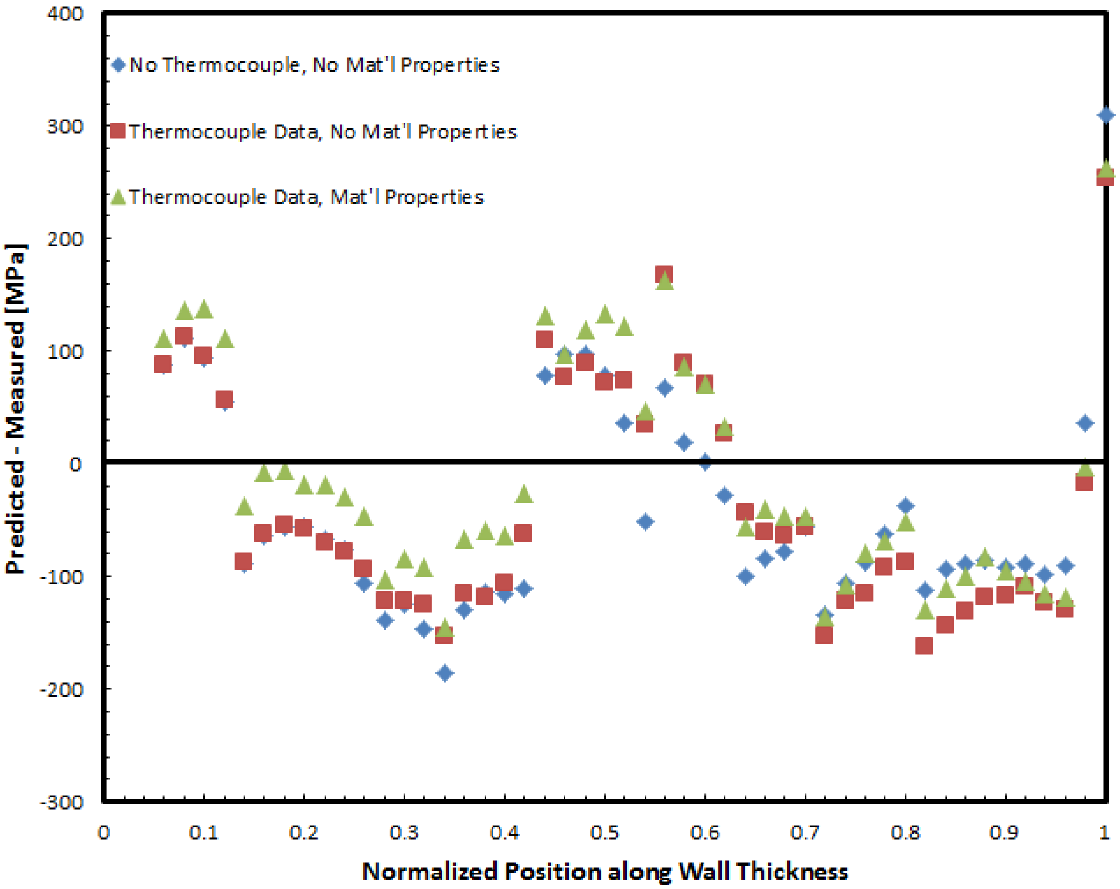


- Axial stresses shown here
- Variety of hardening laws employed
- Modeling uncertainty is the same



Phase II: Fabricated Prototype Nozzles

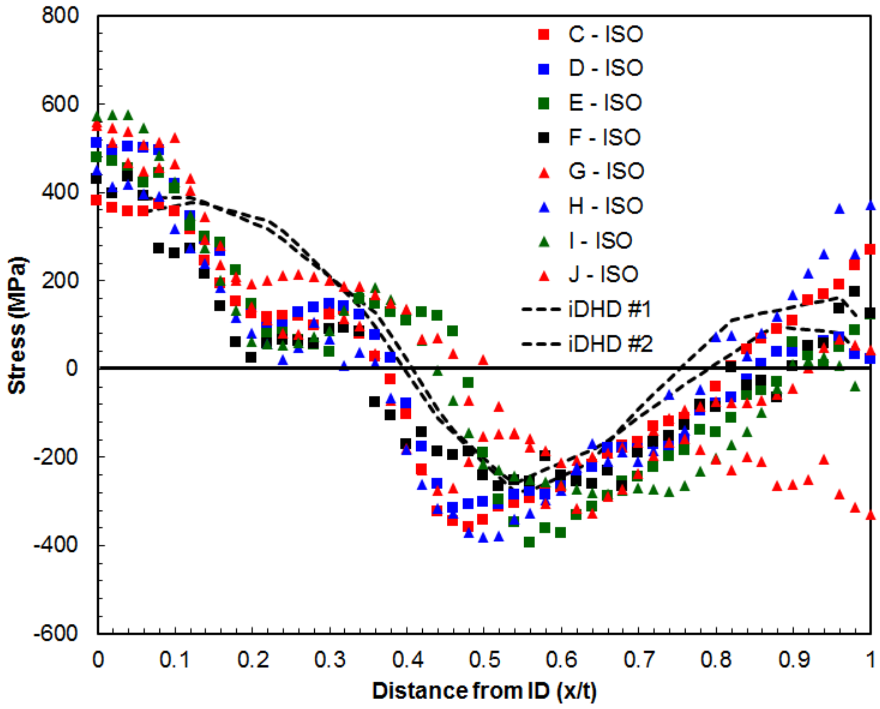
FEA Round Robin Results: Single Modeler

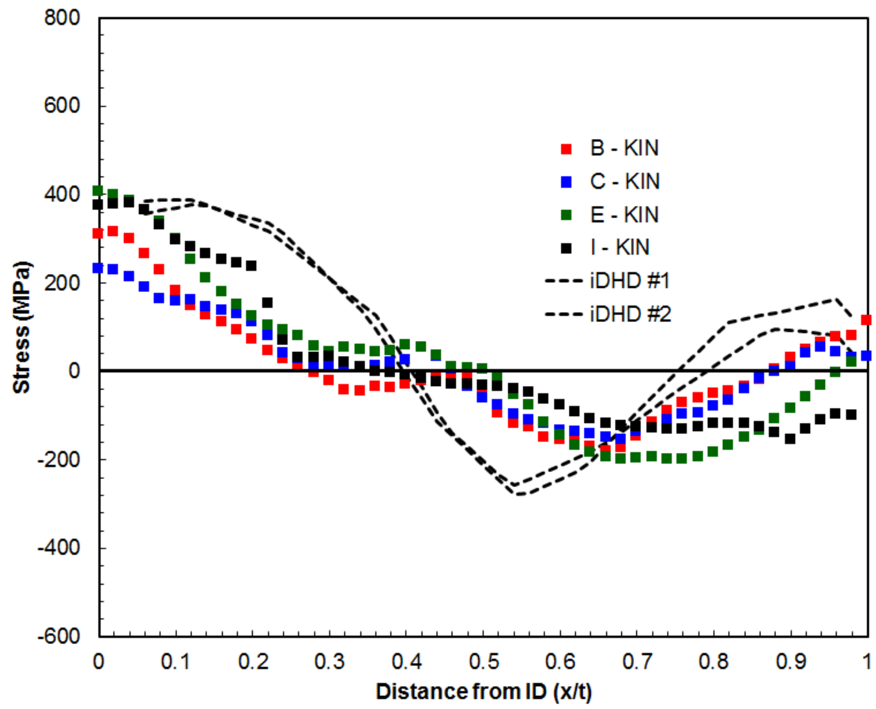


Hoop Stress
Pre-stainless steel weld
Supplied material properties
Supplied thermal couple data

Phase II: Fabricated Prototype Nozzles

FEA Round Robin Results: Separate Hardening Law

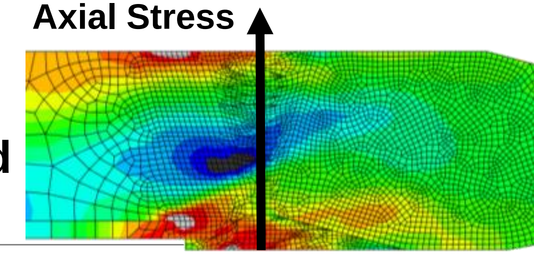




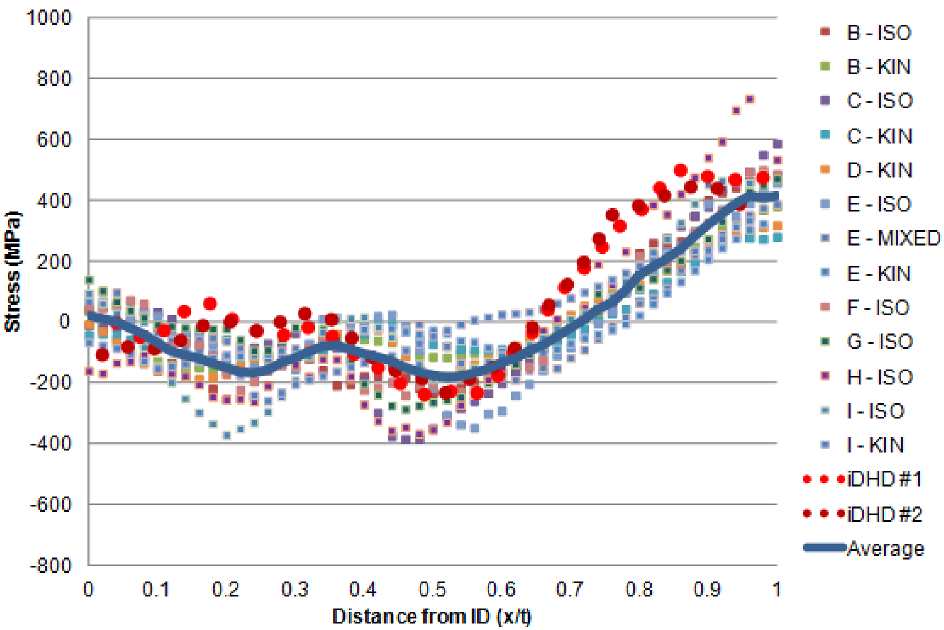
Axial Stress
Pre-stainless steel weld
Supplied material properties
Supplied thermal couple data

Phase II: Fabricated Prototype Nozzles

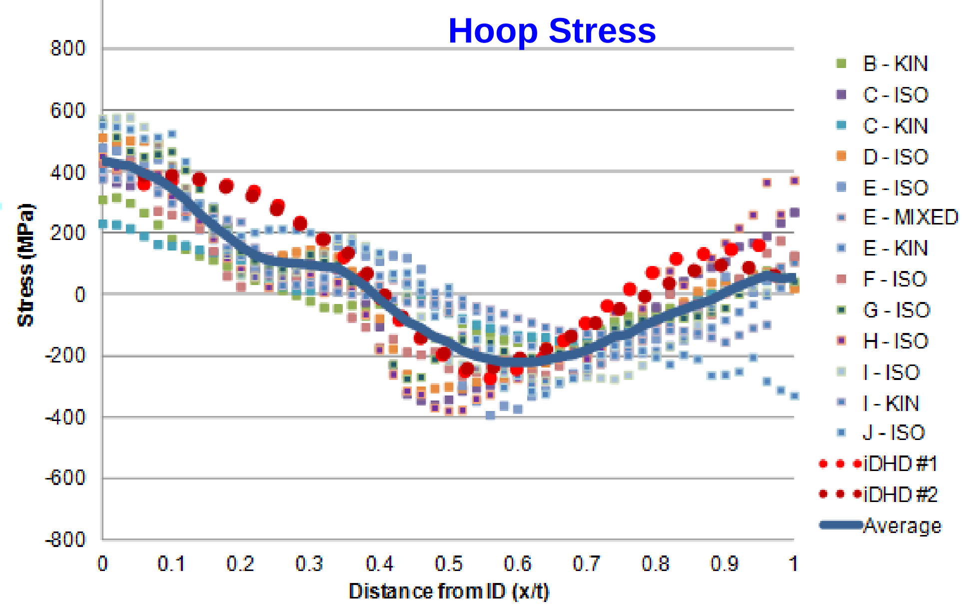
FEA Round Robin Results



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

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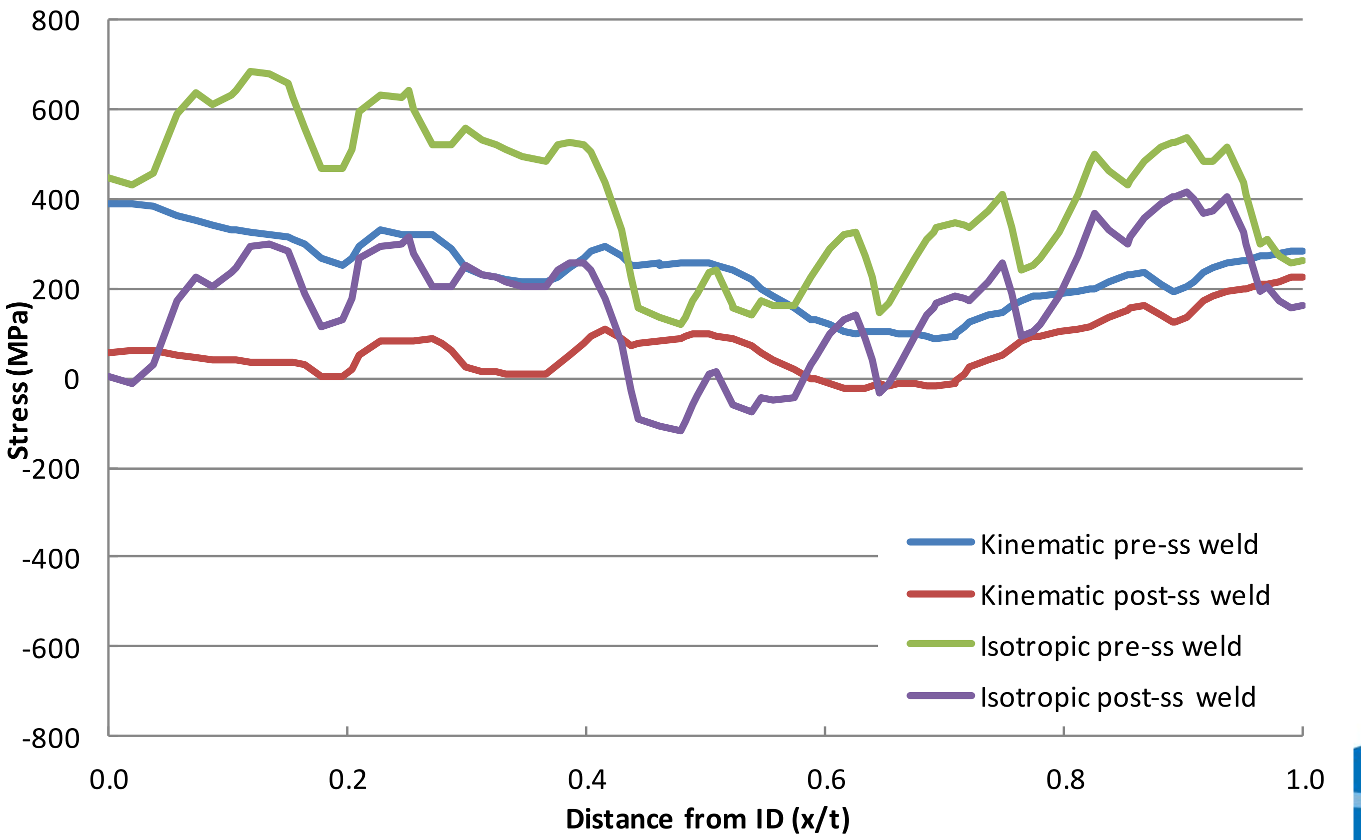
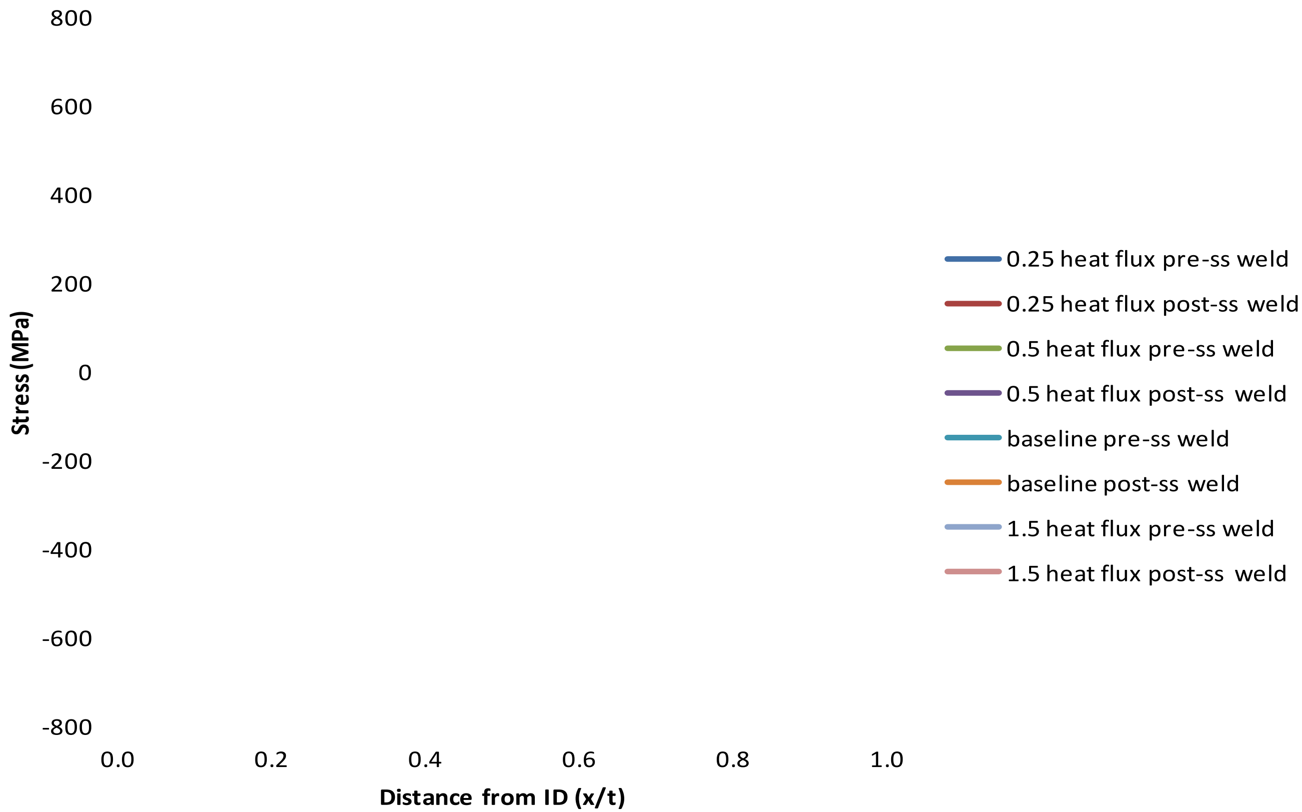
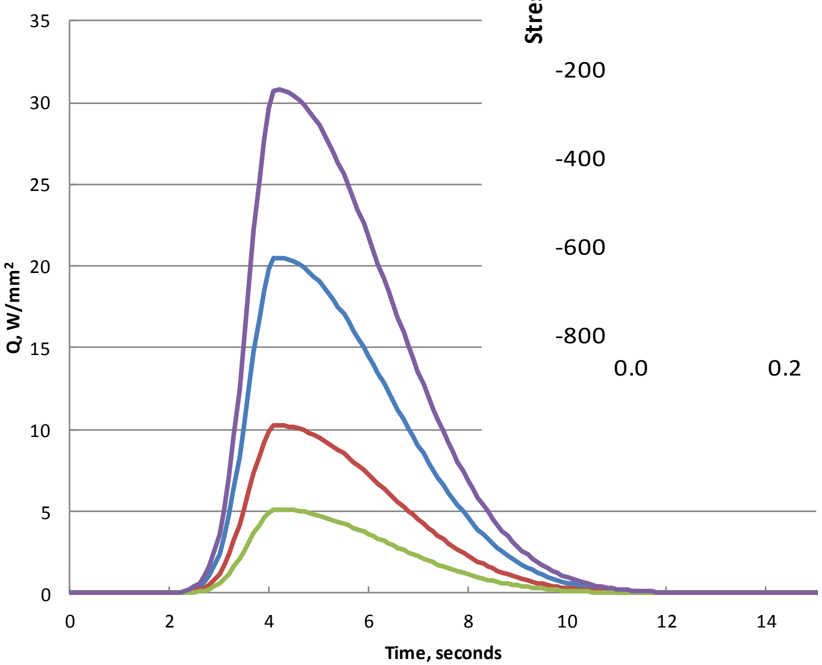
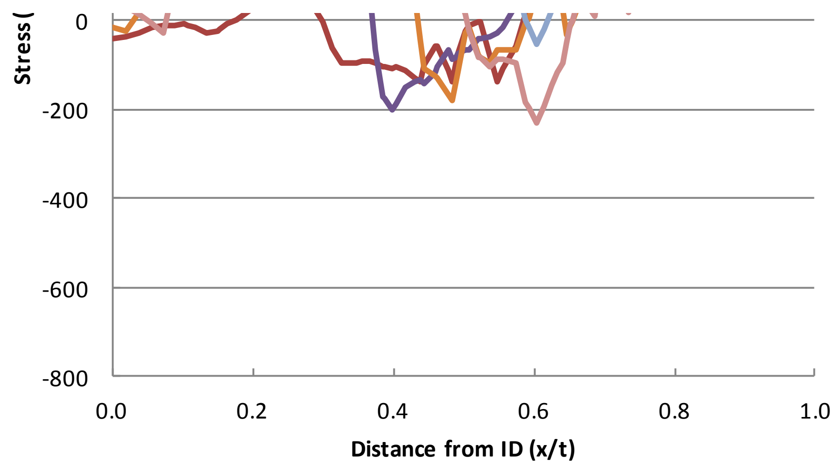


Phase II: Fabr

Sensitivity Studies: H







Phase II: Fabricated Prototype Nozzles

Observations from Phase II Work

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- 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

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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 N
•Type 8 Surge Nozzles (QTY
•Purpose: Prototypic scale un
conditions. Validate FE model

Phase 3 - EPRI

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

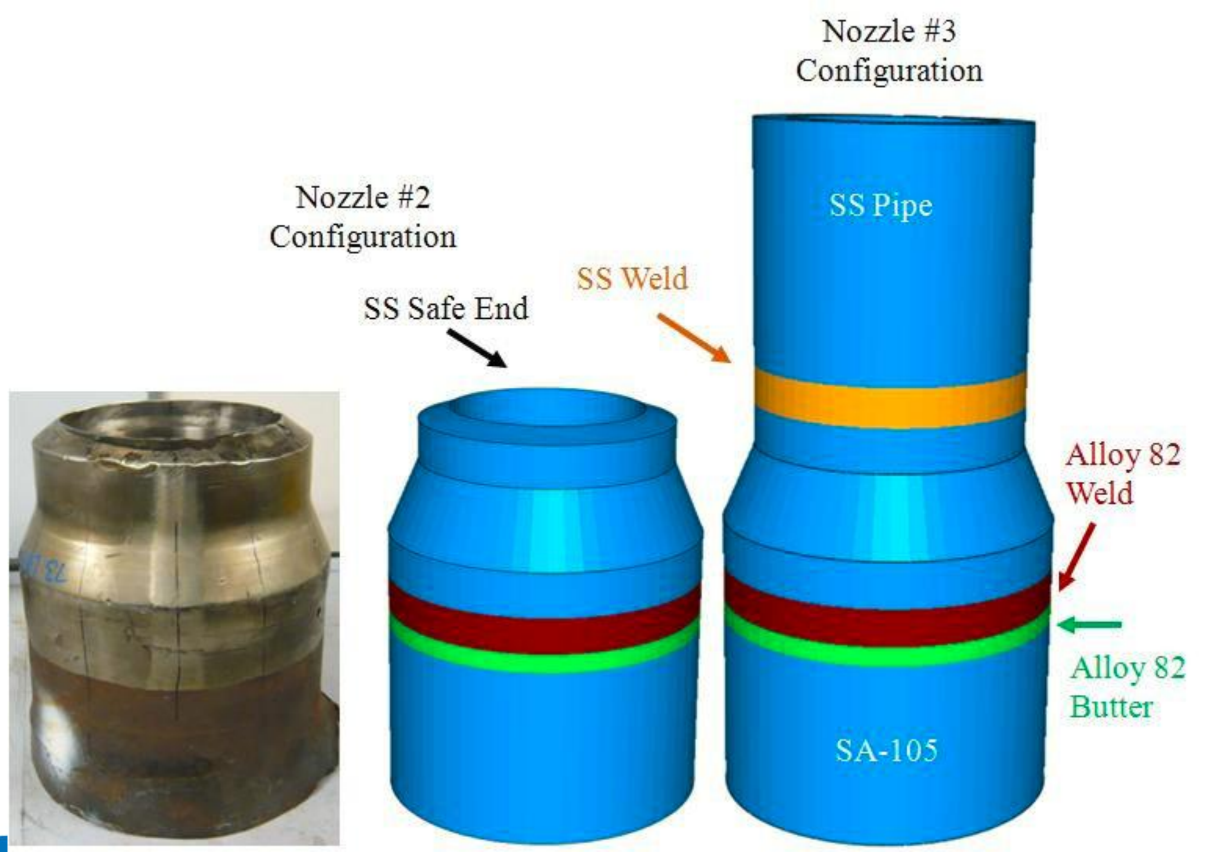

•Plant Components
•WNP-3 CL Nozzle (QTY 1)
•RS Measurements funded by
•Purpose: Effect of overlay on

Pha

Phase III: Cancelled Plant Nozzles

Overview

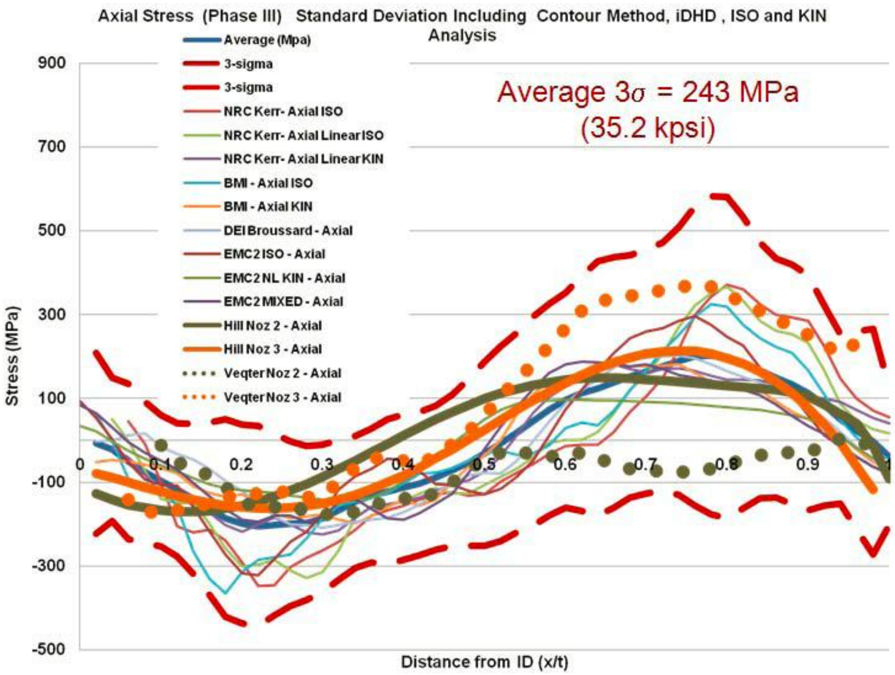
- Two nozzles required in order to apply the destructive contour method to both cases
- Outer diameter = 200 mm, Phase IIa was 350 mm



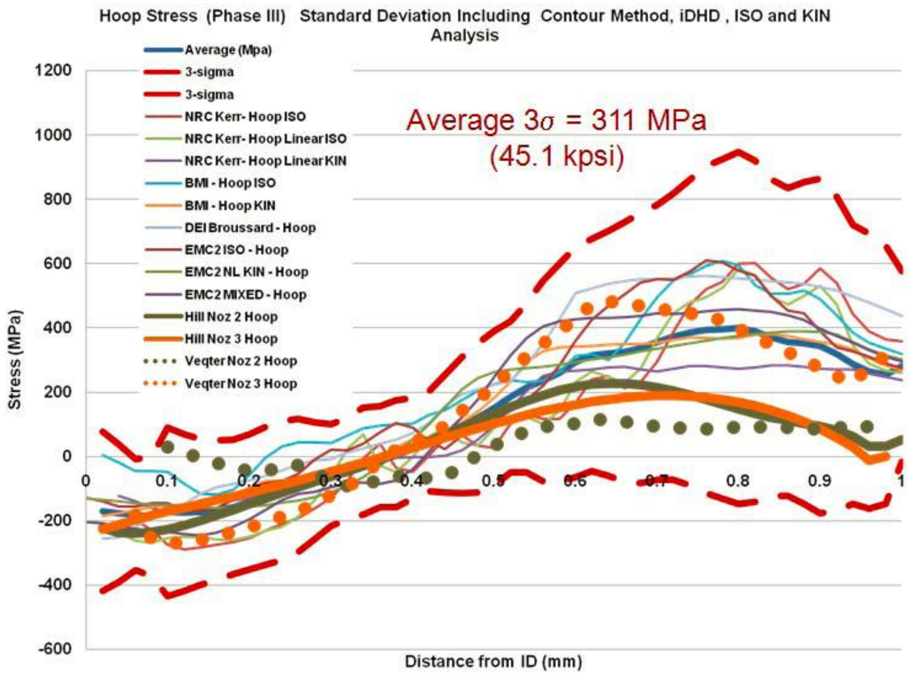
Phase III: Cancelled Plant Nozzles

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 3σ = 243 MPa, Phase 2a average 3σ = 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

U.S.NRC
United States Nuclear Regulatory Commission
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- 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

fic Weld Specimens
A: Restrained Plates (QTY 4)
B: Small Cylinders (QTY 4)
Develop FE models.

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

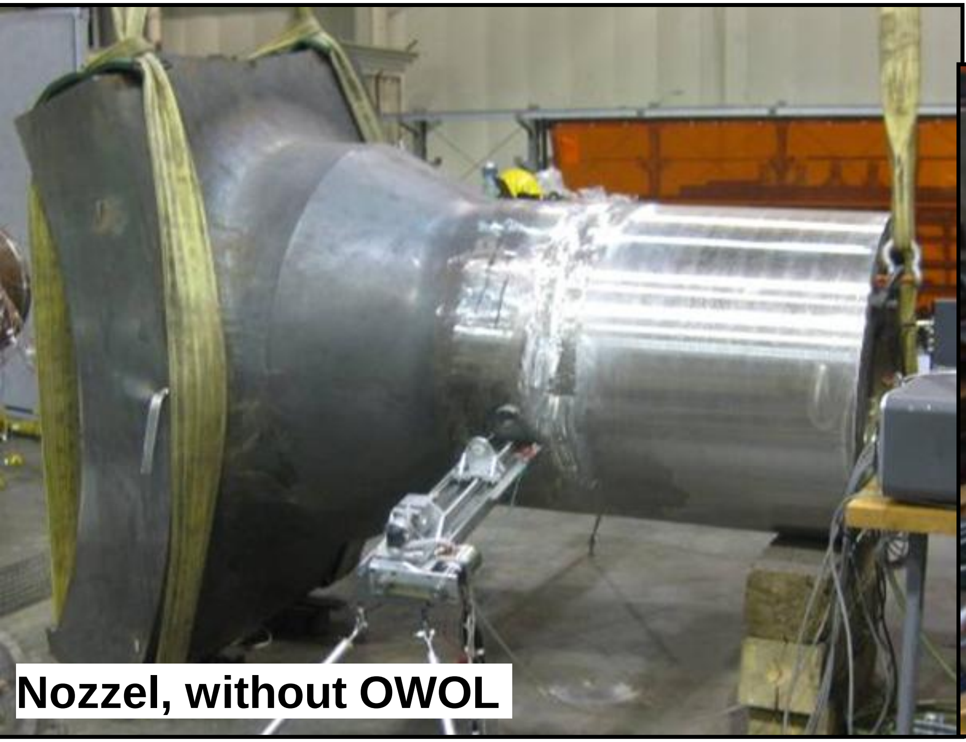
omponents
&R PZR Nozzles (QTY 3)
Validate FE models.

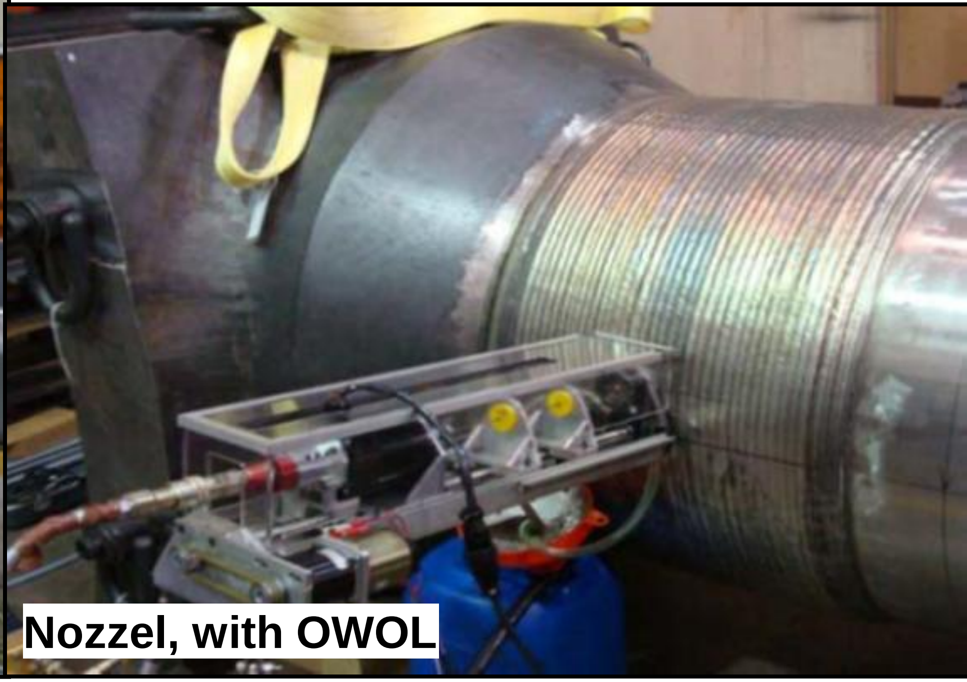
Phase 4 - EPRI

•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

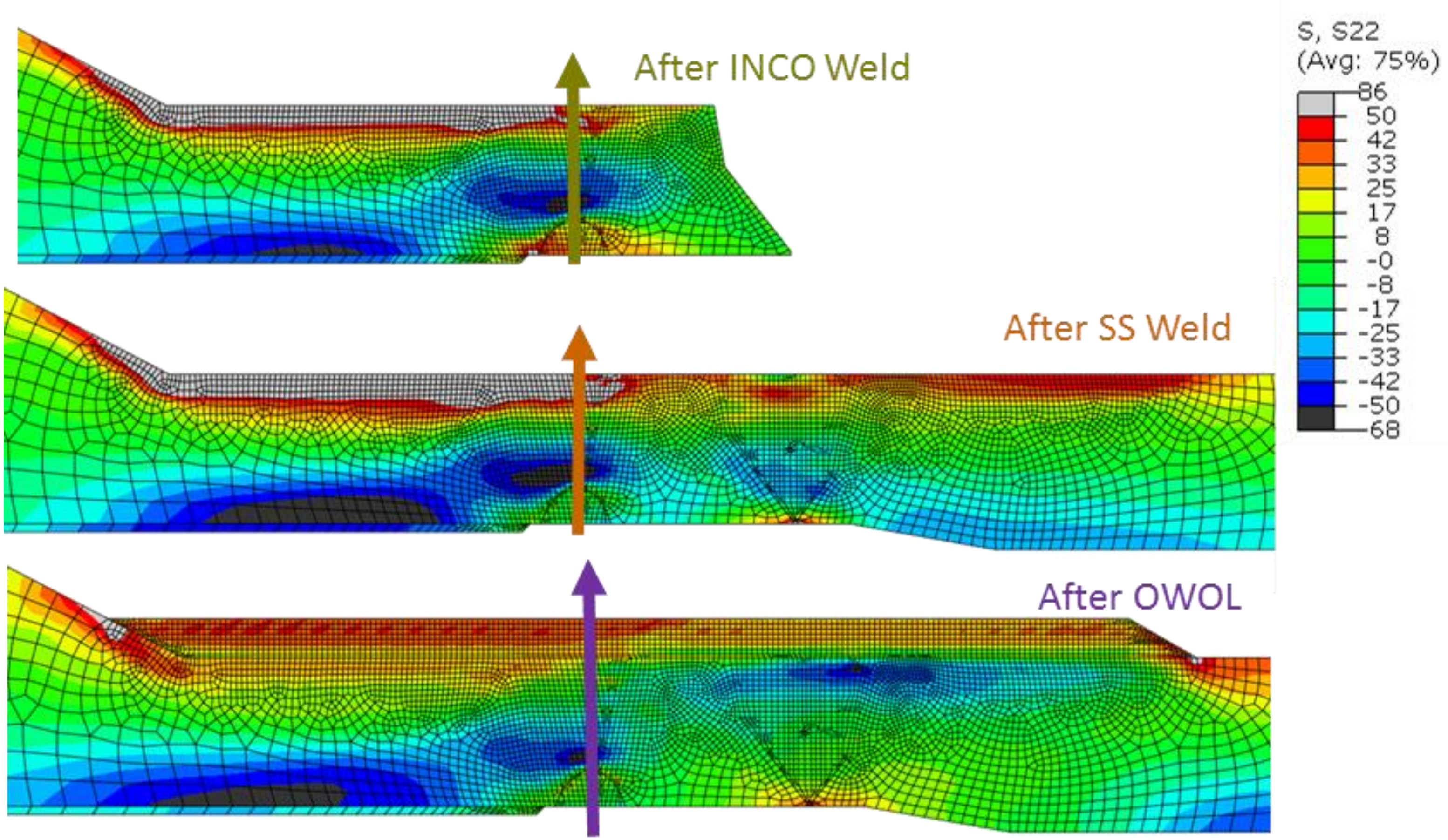




- Investigation of a mitigation technique: Optimized Weld Overlay (OWOL)

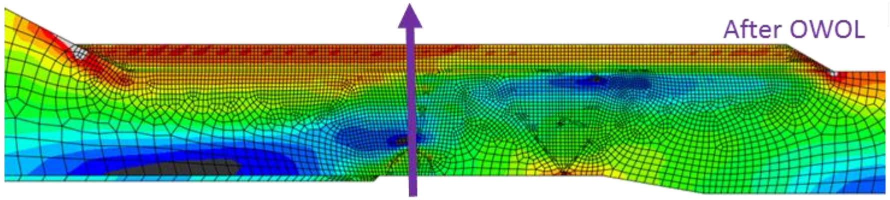
Phase IV: Cancelled Plant Nozzles

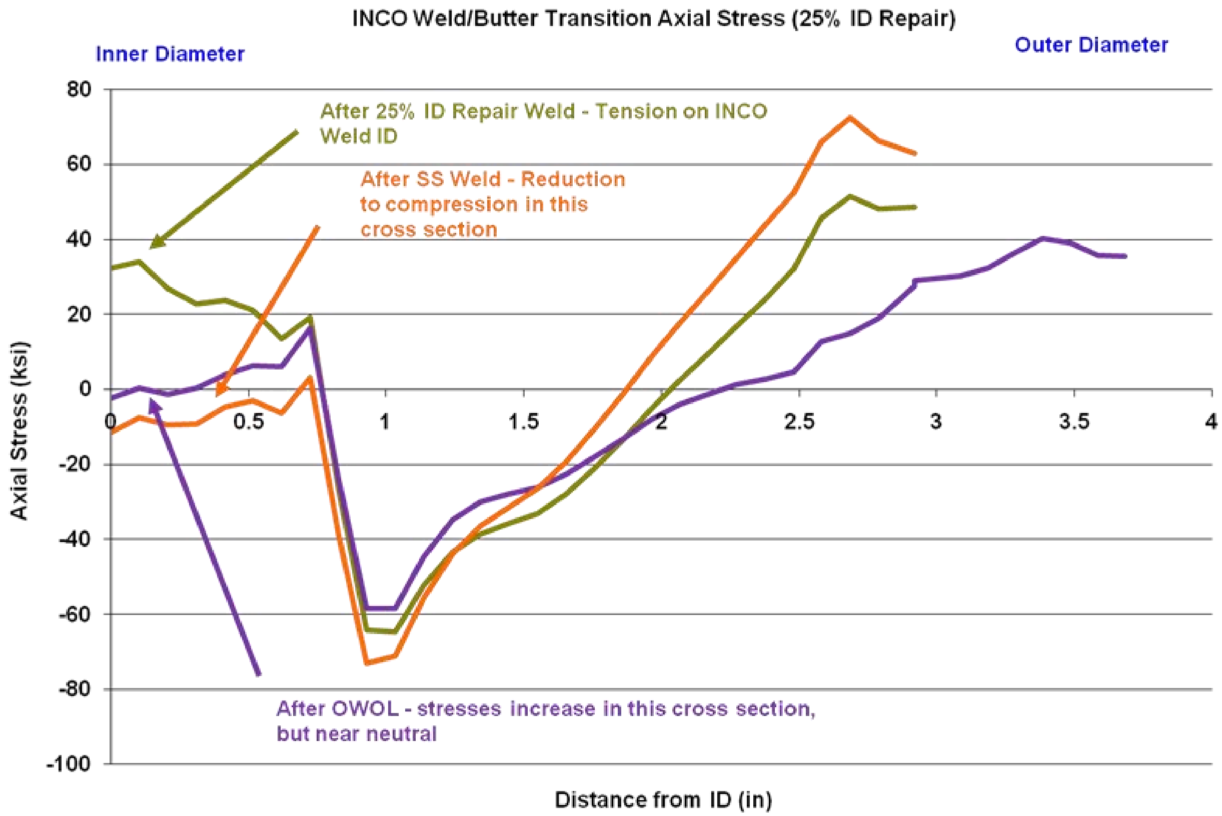
Results: Axial Stresses



Phase IV: Cancelled Plant Nozzles

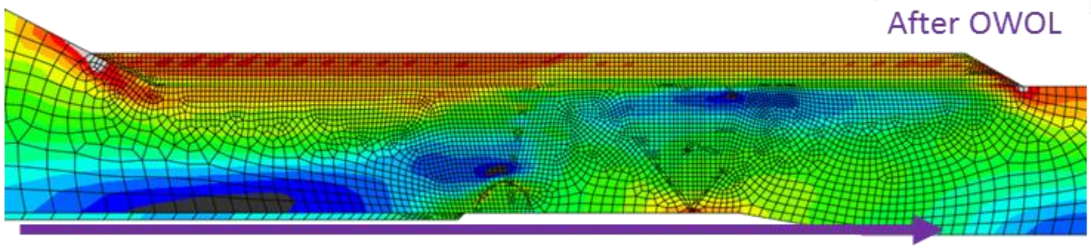
Results: Axial Stress, Midweld, Through Thickness

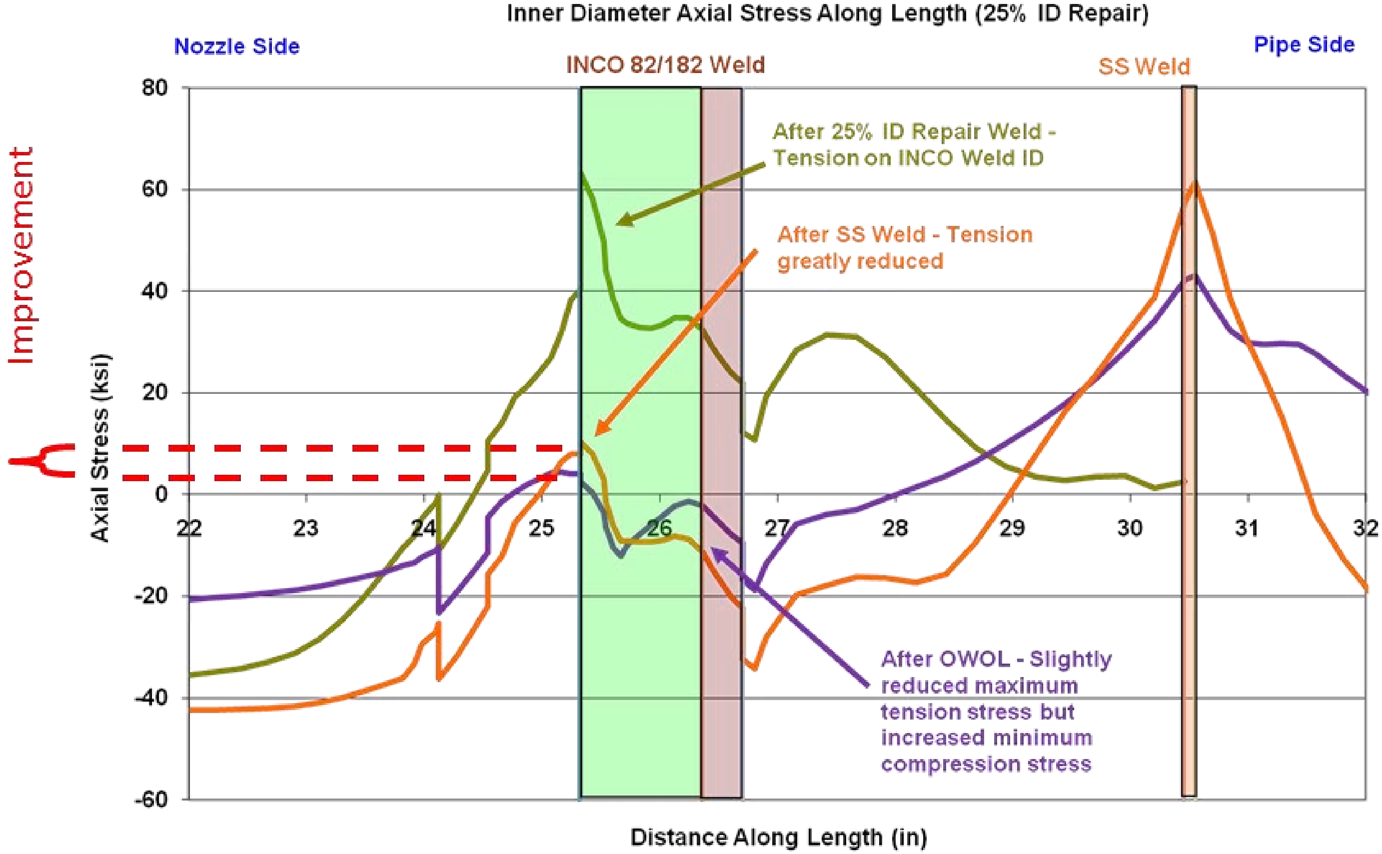




Phase IV: Cancelled Plant Nozzles

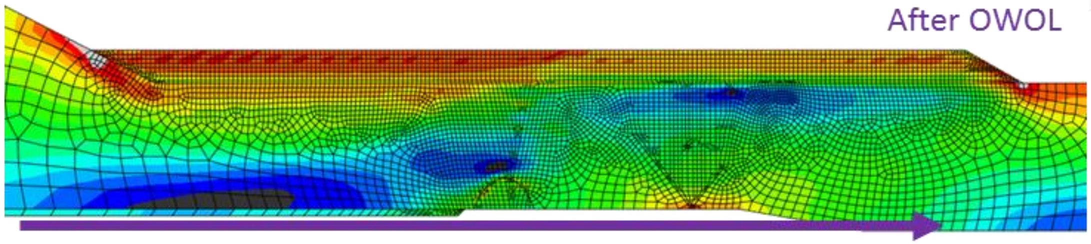
Results: Axial Stress, ID, Transverse to Weld

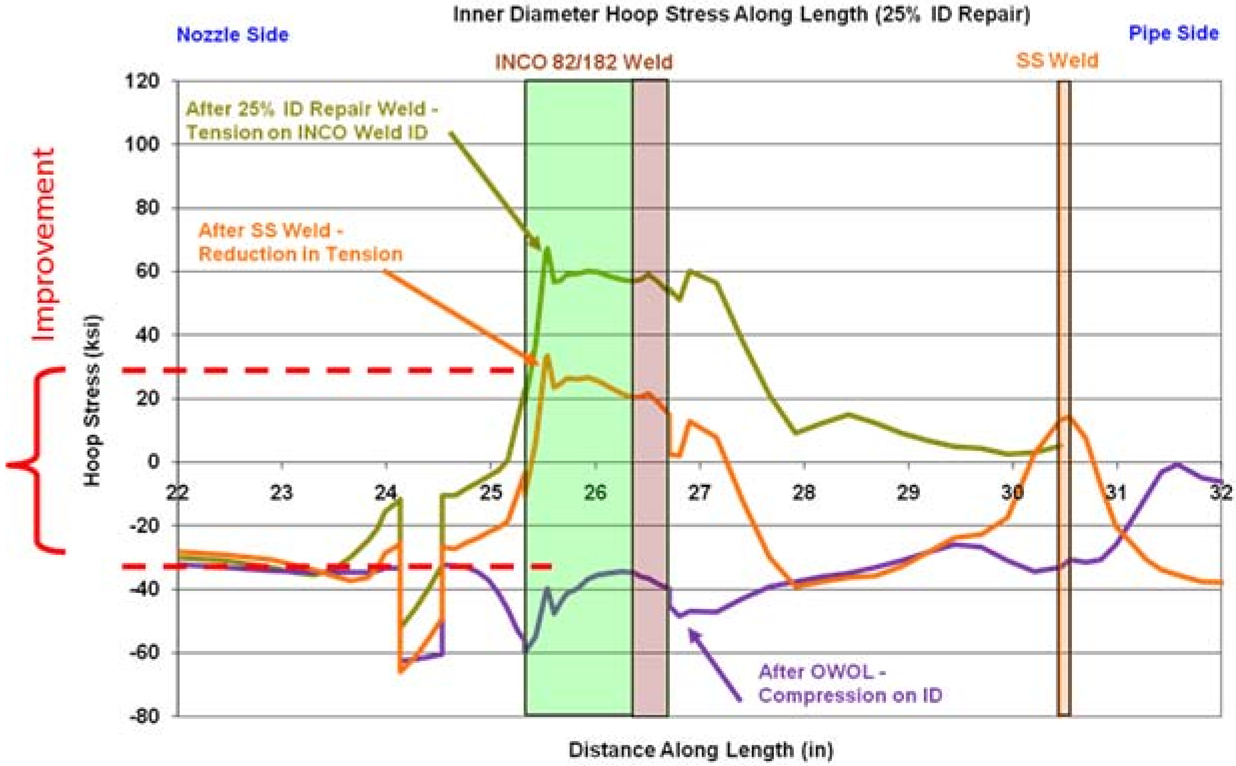




Phase IV: Cancelled Plant Nozzles

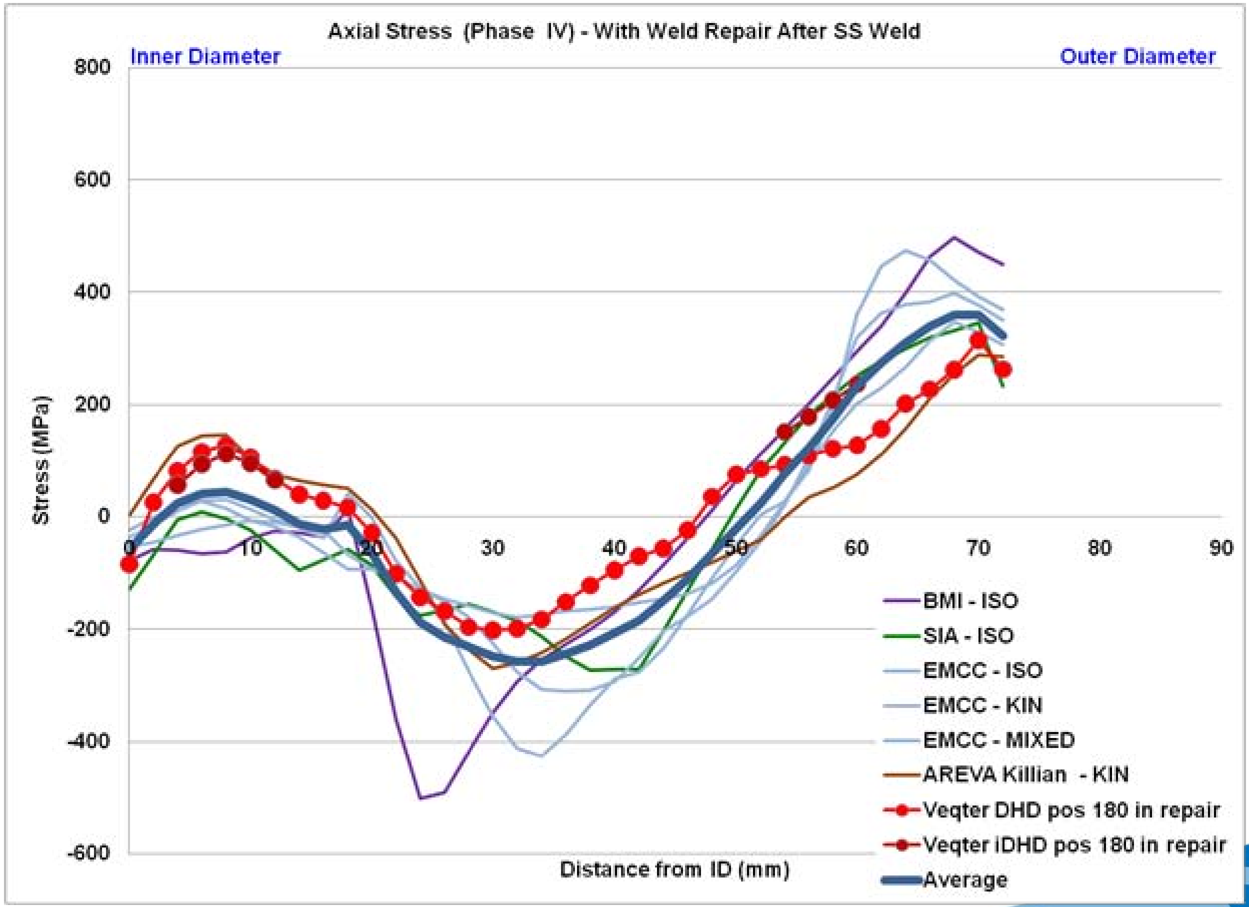
Results: Hoop Stress, ID, Transverse to Weld





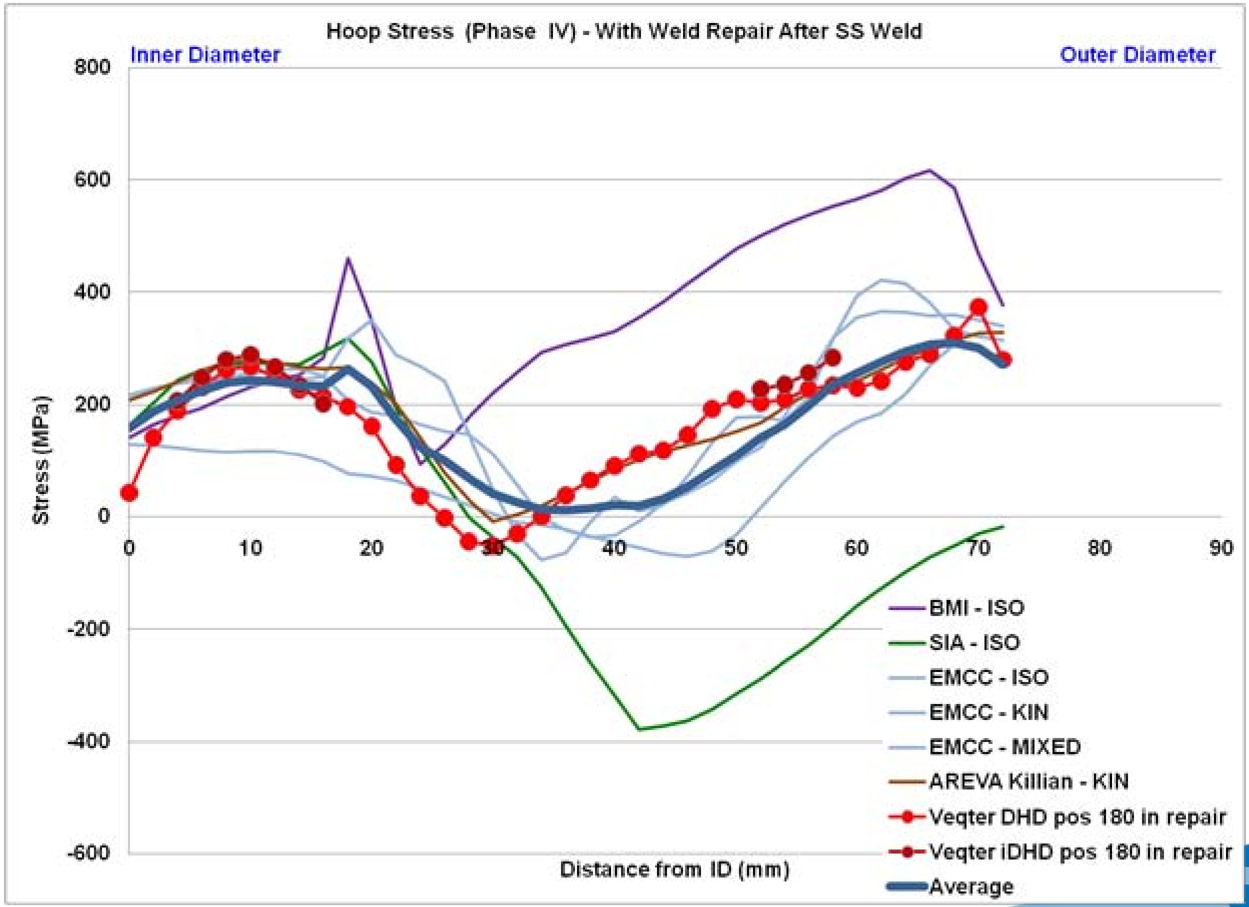
Phase IV: Cancelled Plant Nozzles

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

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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

U.S.NRC
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- Three presentations
  - Background and Regulatory Impact
  - Accomplishments
  - Future

WRS Validation Program
Background and Regulatory Impact

David Rudland

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Background

United States Nuclear Regulatory Commission
Protecting People and the Environment

- 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

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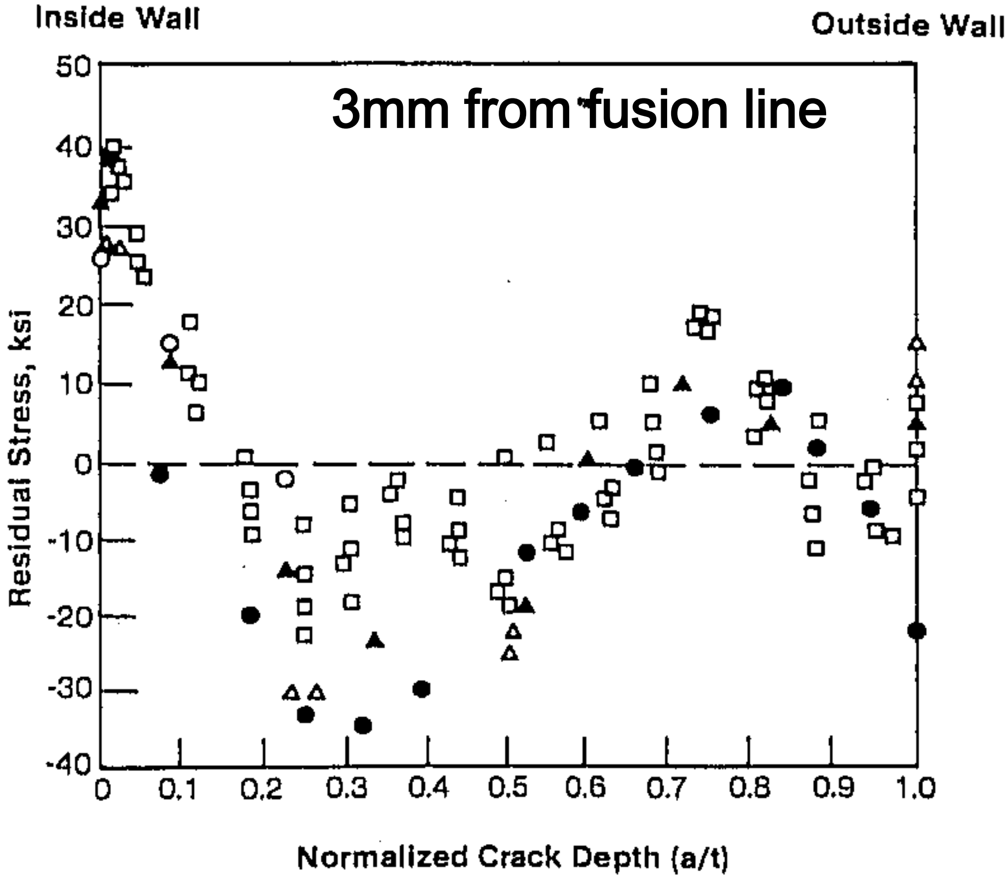

Open symbols – EPRI
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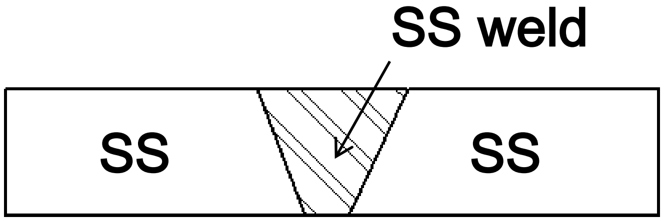
Results suggest that within the HAZ and into the base metal, the WRS are consistent from weld to weld



Pipe Flaw Evaluation Recommendation

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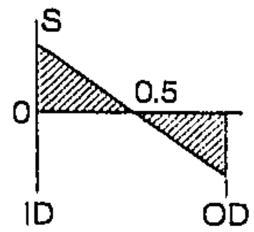
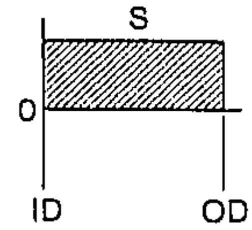
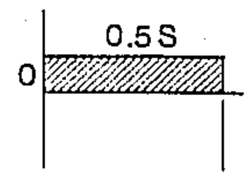
<1 inch		
≥1 inch	See Note 3	

[1] S = 30 ksi

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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

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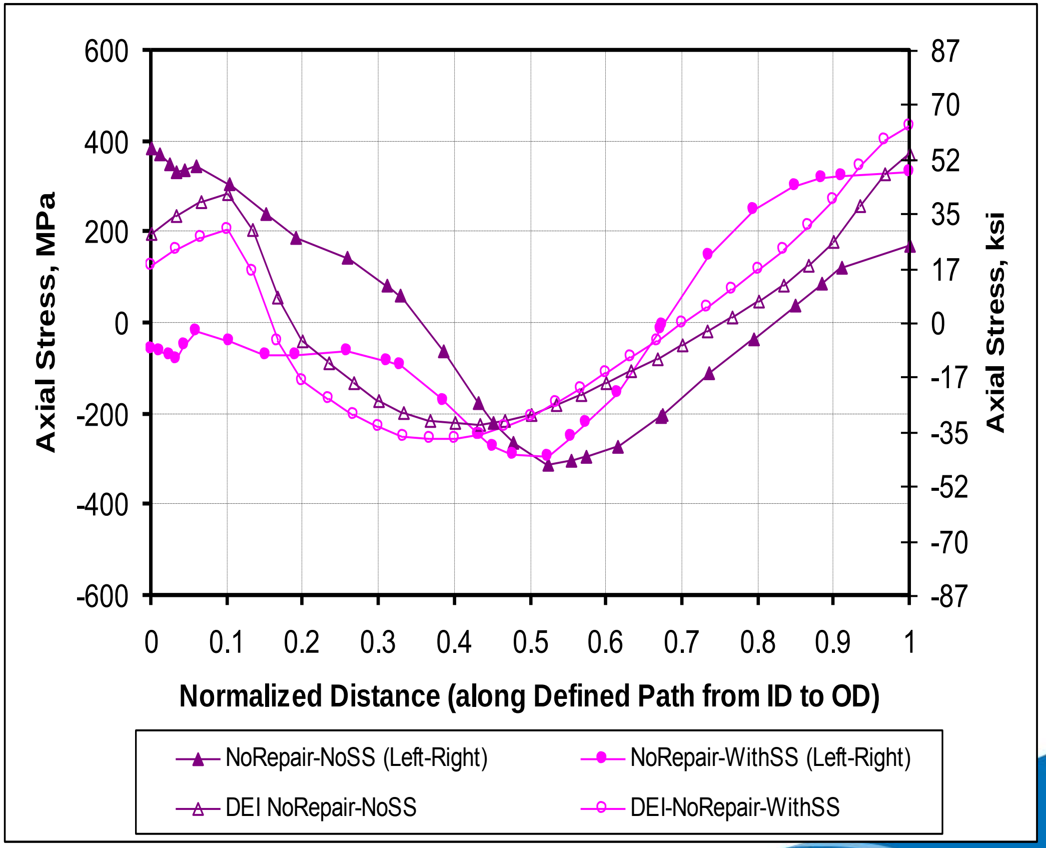
- Ultrasonic examinations at Wolf Creek in Fall 2006 found indications in pressurizer Alloy 600 dissimilar metal butt welds
- Staff and industry conducted analyses that demonstrated WRS has large impact on flaw evaluation



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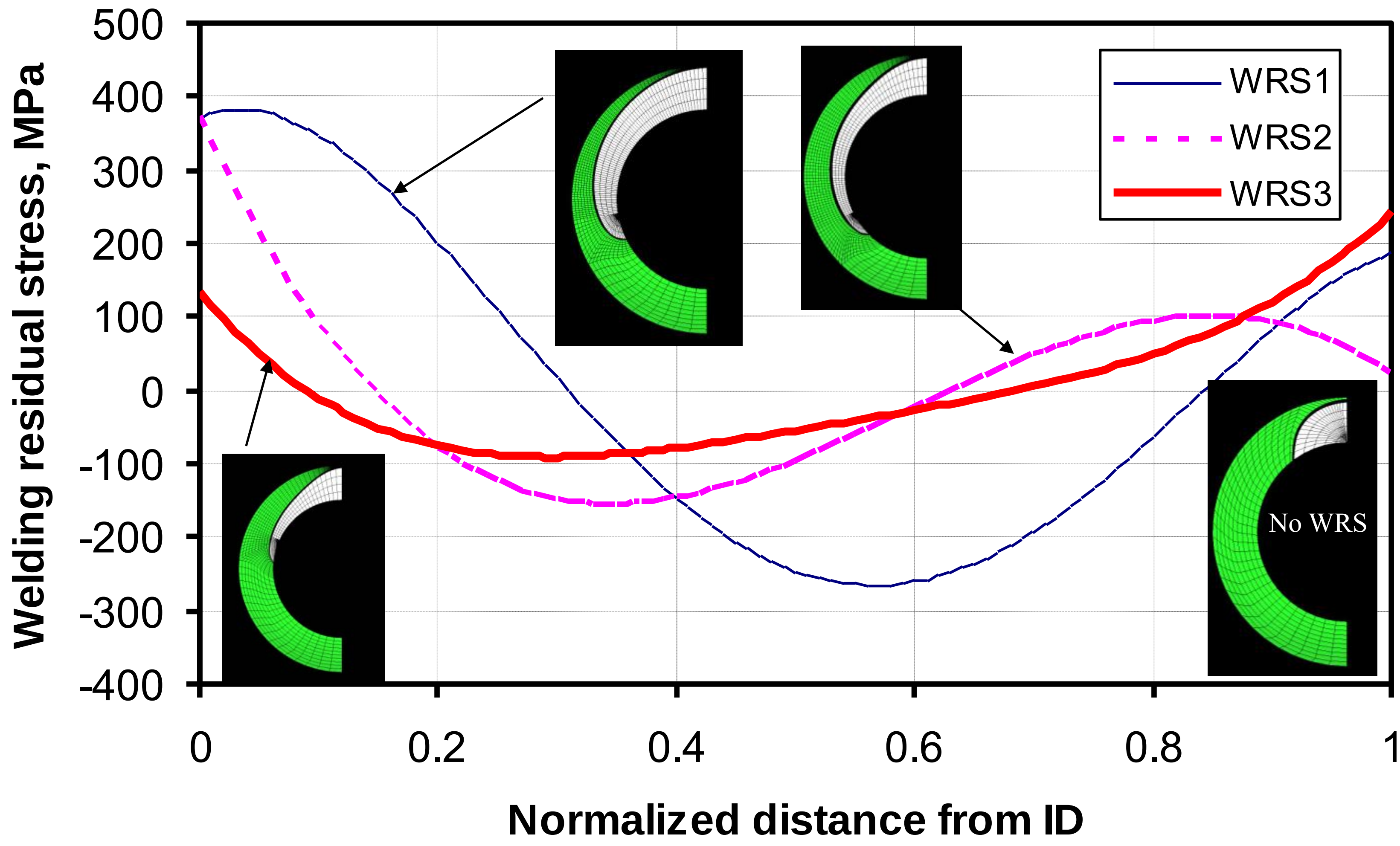

Advanced FEA Project: WRS Validation

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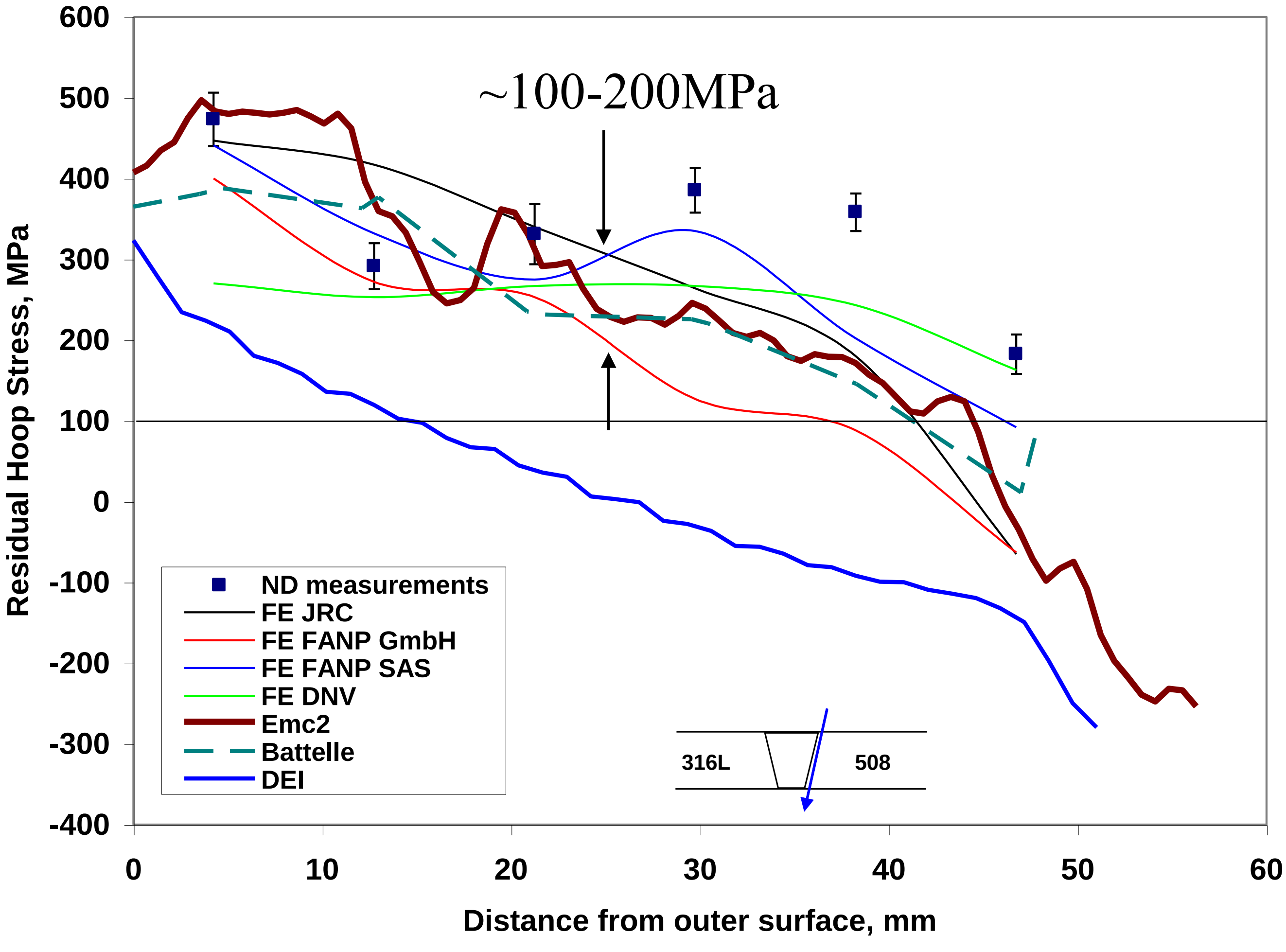

- Open WRS validation conducted
- Used results from NESC III PROJECT
- Results suggested 100-200MPa scatter between analysts

What about measurement error and uncertainty??

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- NRC issued (2007) confirmatory action letters (CAL) to 40 plants
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  - 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

U.S.NRC
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- 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

U.S.NRC
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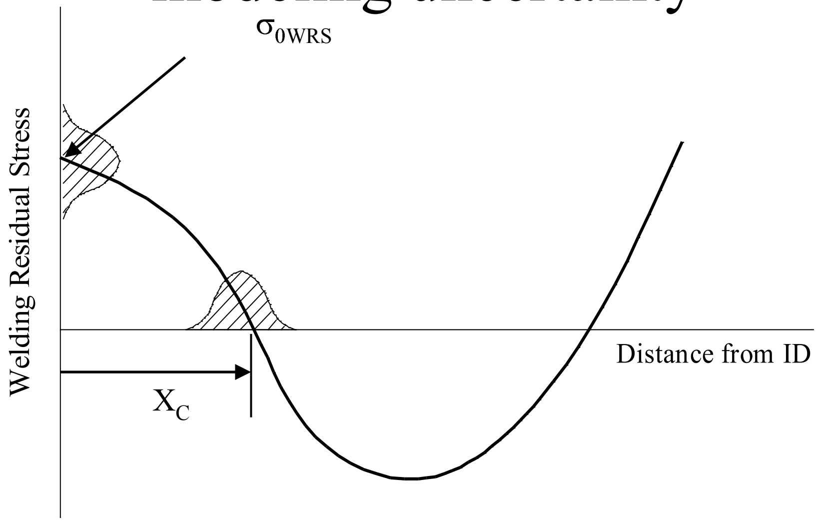
- Version 1
  - 3rd order curve fit with variability on WRS at ID and at X_c
  - Difficulty fitting WRS data and properly modeling uncertainty



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

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- 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

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- 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

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- 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

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U.S.NRC

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Introduction

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- 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

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

- 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

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

- 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

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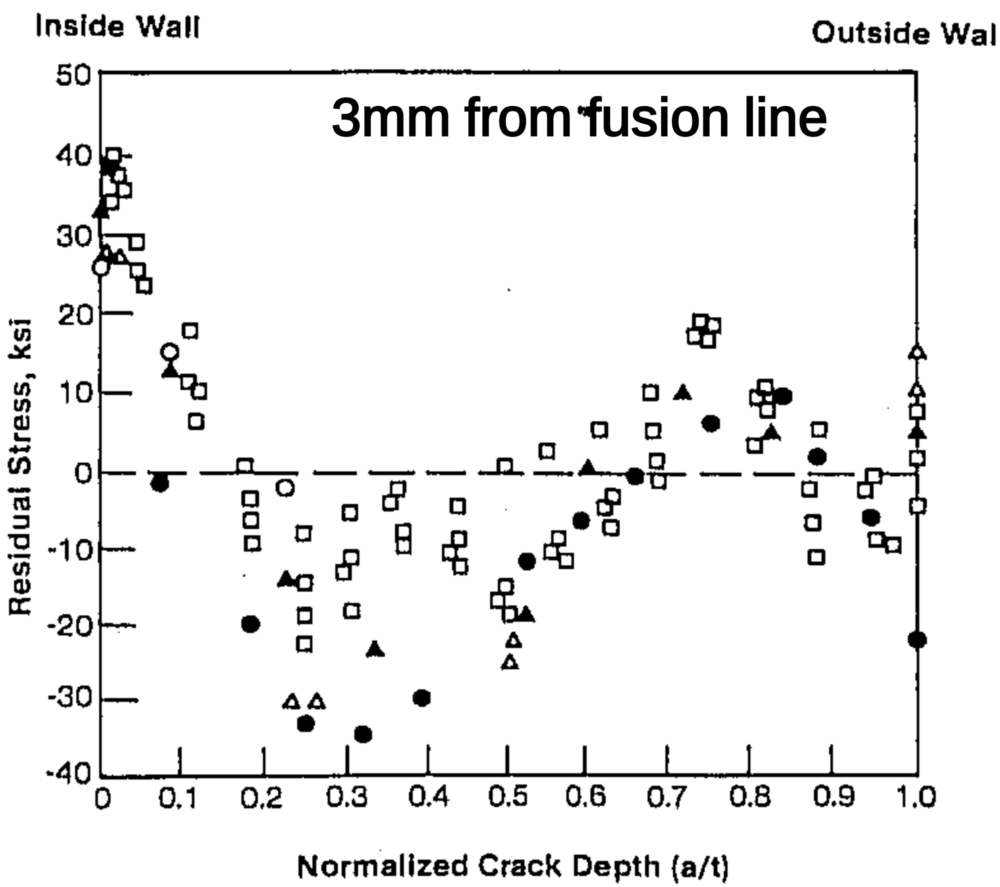

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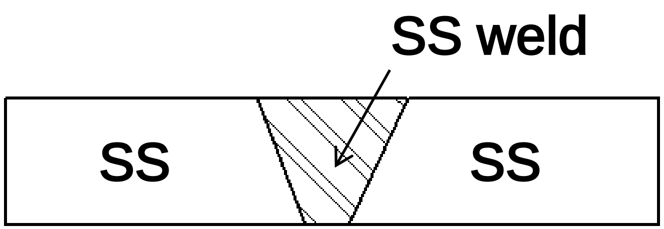

Pipe Flaw Evaluation Recommendation

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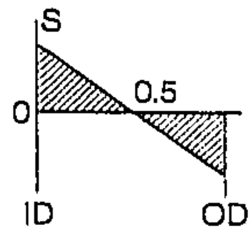
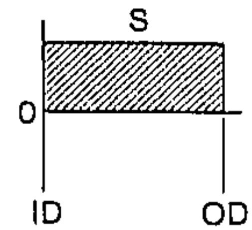
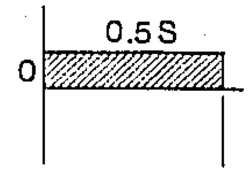
<1 inch		
≥1 inch	See Note 3	

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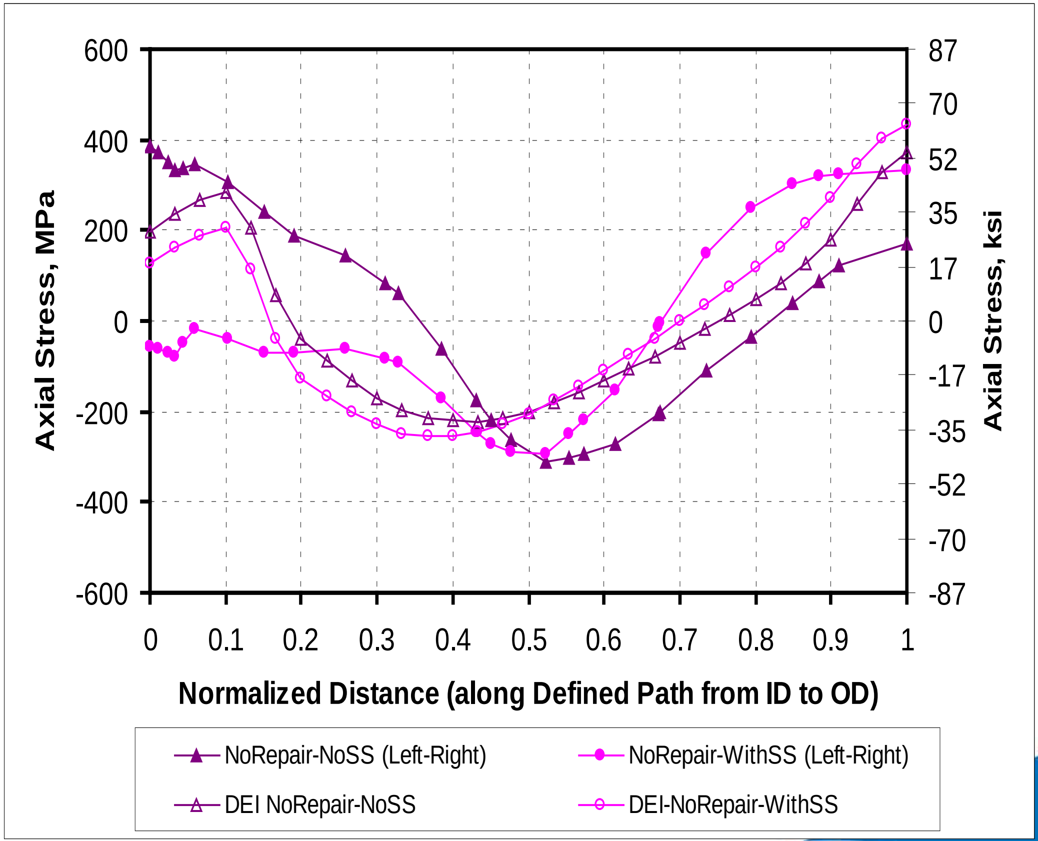

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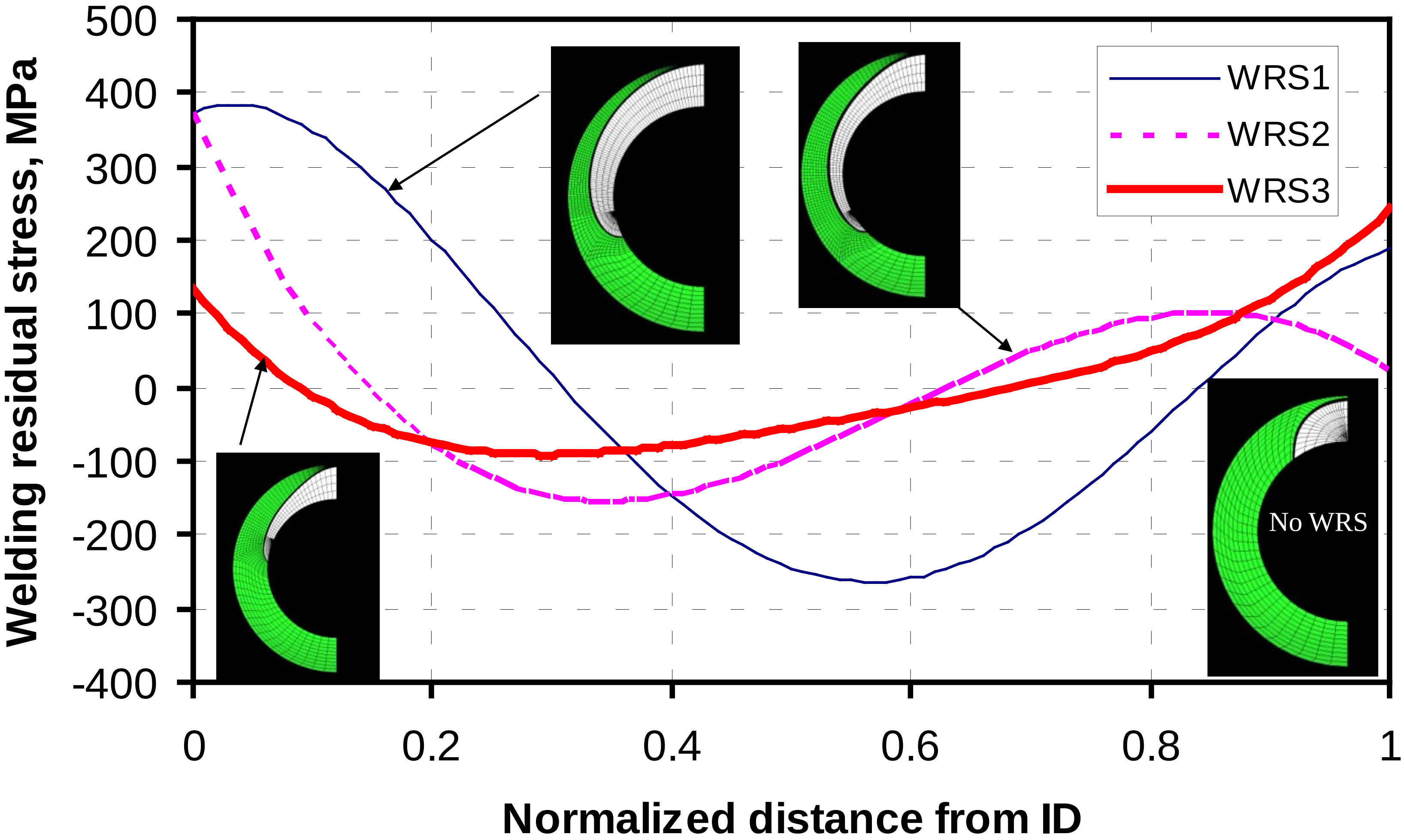

Advanced FEA Project: WRS Validation

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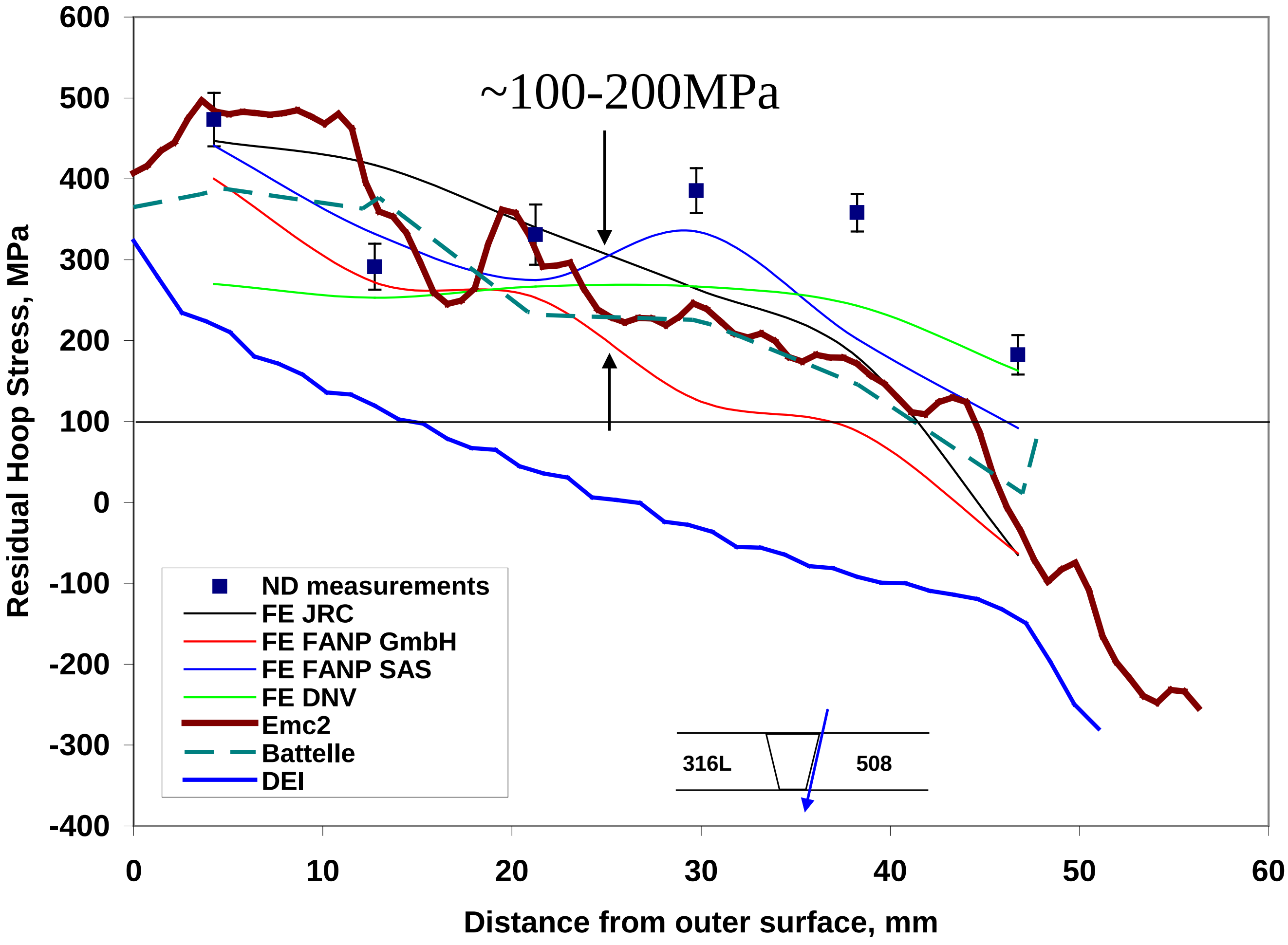

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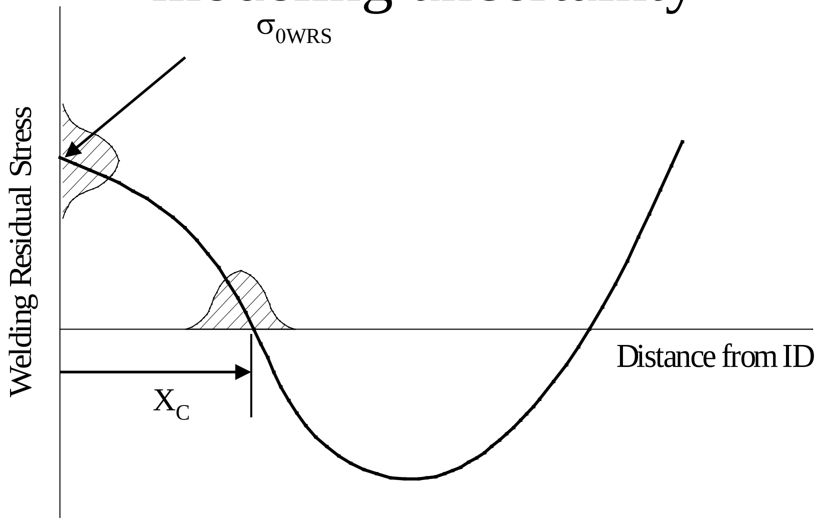

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Mean Stress (Mpa)	Plus 2σ Stress (Mpa)	Minus 2σ Stress (Mpa)	x/t
σ_1	σ^+_1	σ^-_1	0
σ_2	σ^+_2	σ^-_2	0.05
σ_3	σ^+_3	σ^-_3	0.1
σ_4	σ^+_4	σ^-_4	0.15
...	...	...	...
...	...	...	...
σ_{20}	σ^+_{20}	σ^-_{20}	0.95
σ_{21}	σ^+_{21}	σ^-_{21}	1

Data developed from WRS Validation effort will be used as input to xLPR

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

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- 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

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- 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

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- 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

ACRS Meeting of the Subcommittee on Materials, Metallurgy, & Reactor Fuels

February 6, 2013

Rockville, MD

U.S.NRC
United States Nuclear Regulatory Commission
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Outline

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

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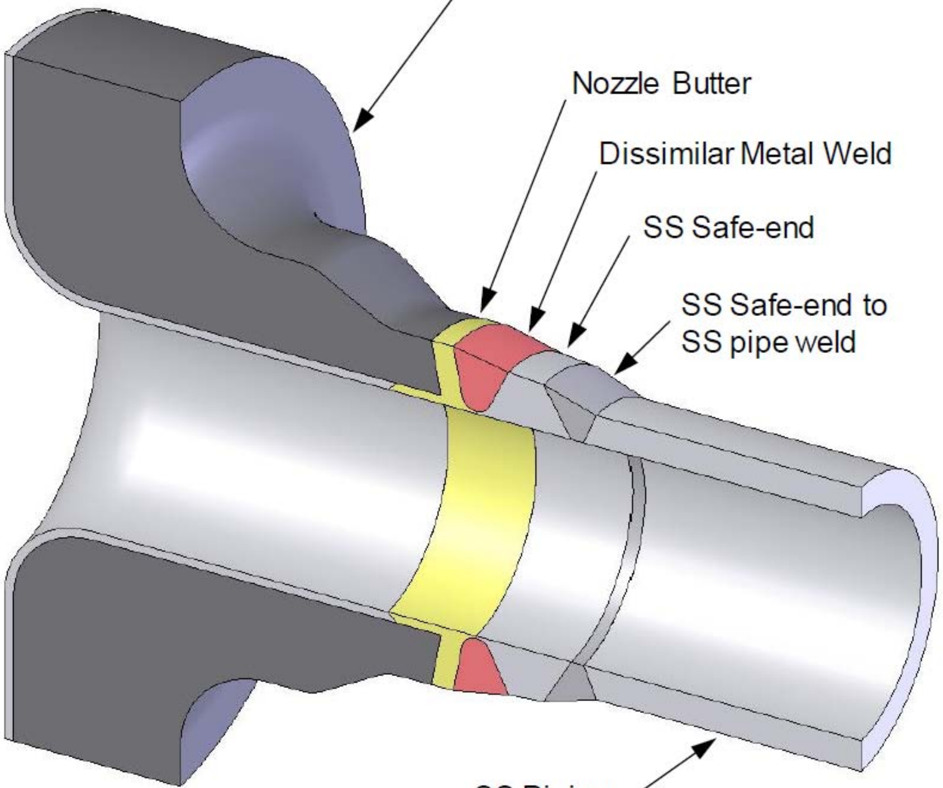
WRS Validation Program Overview

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)

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- 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

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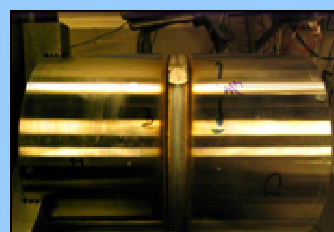
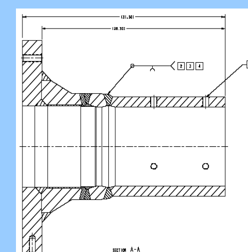
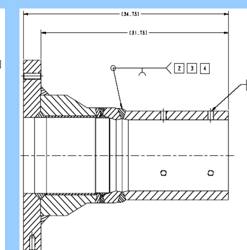
Phase 1 - EPRI

- 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

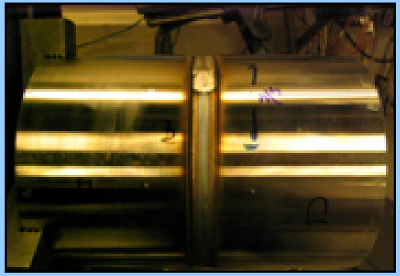
Phase I: Scientific Weld Specimens

Overview

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

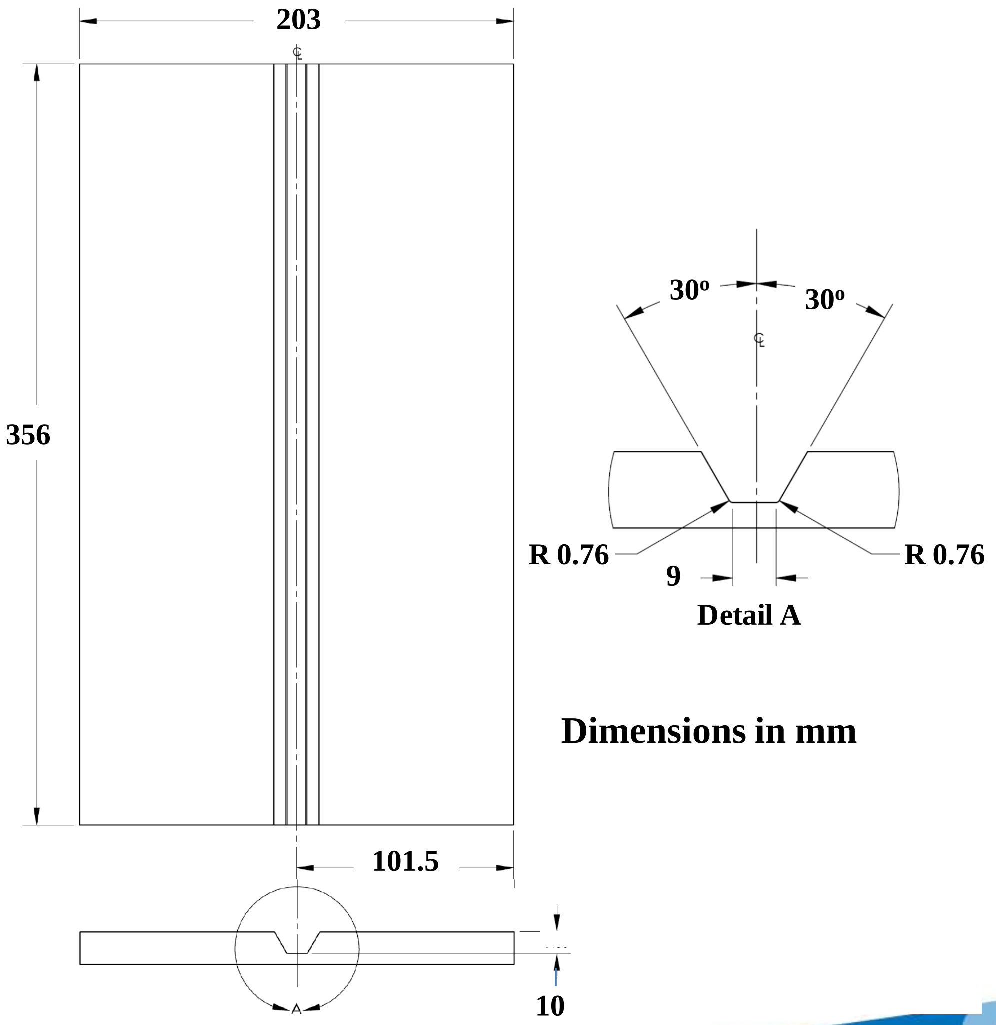
Phase 1 - EPRI

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

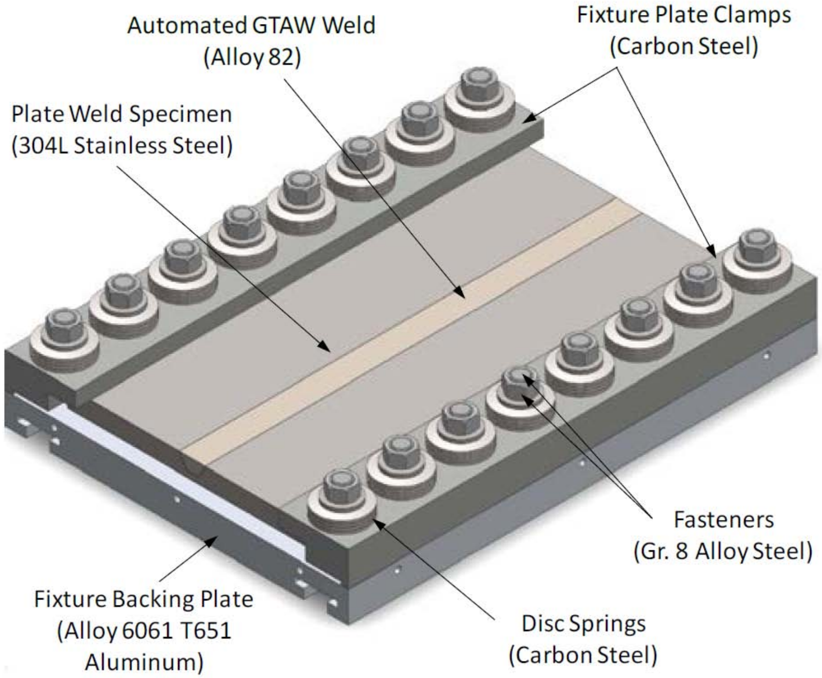


Phase I: Scientific Weld Specimens

Plate Specimens



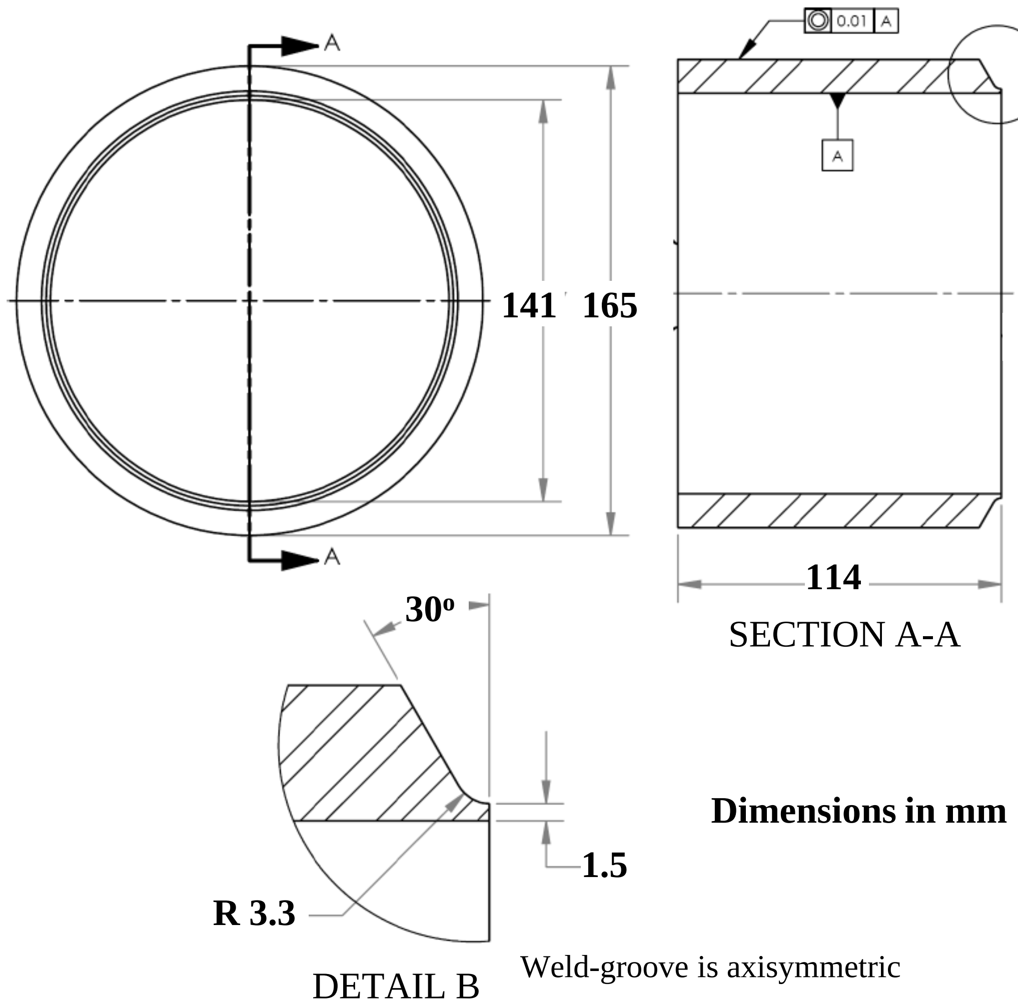
Dimensions in mm

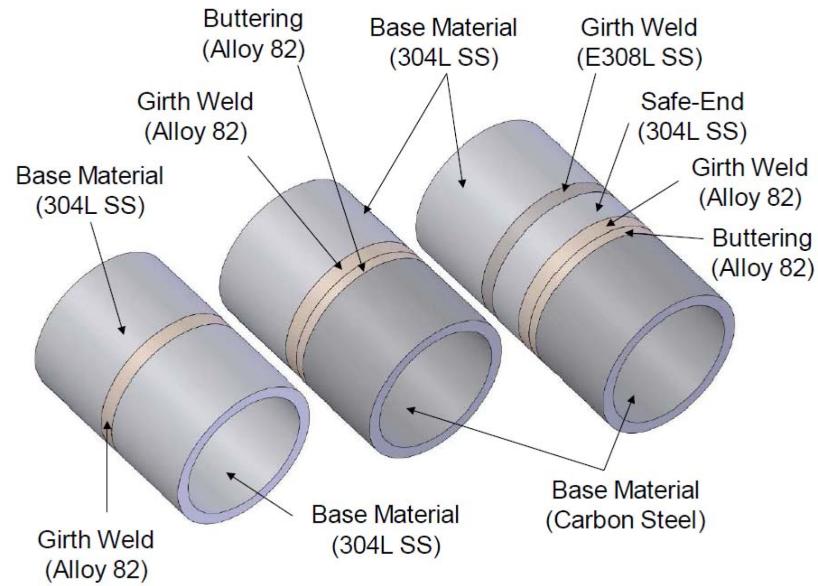


Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

Cylindrical Specimens





Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

Weld Repair

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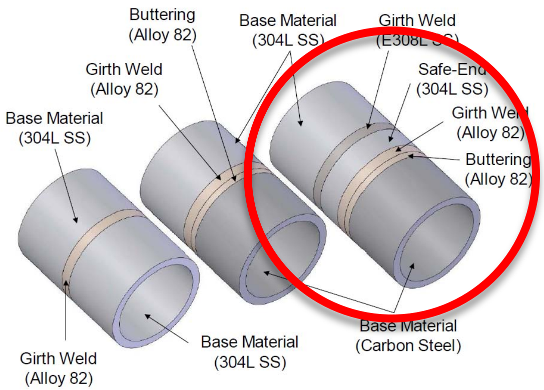
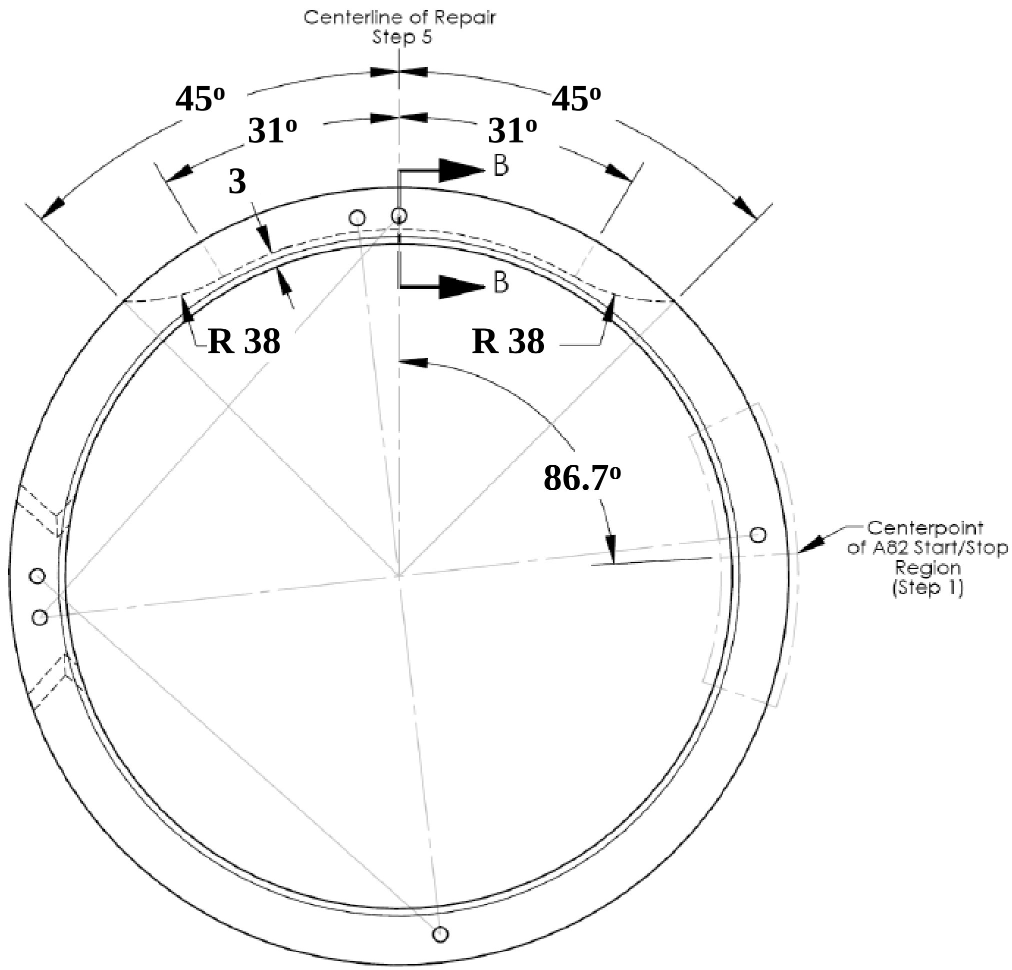


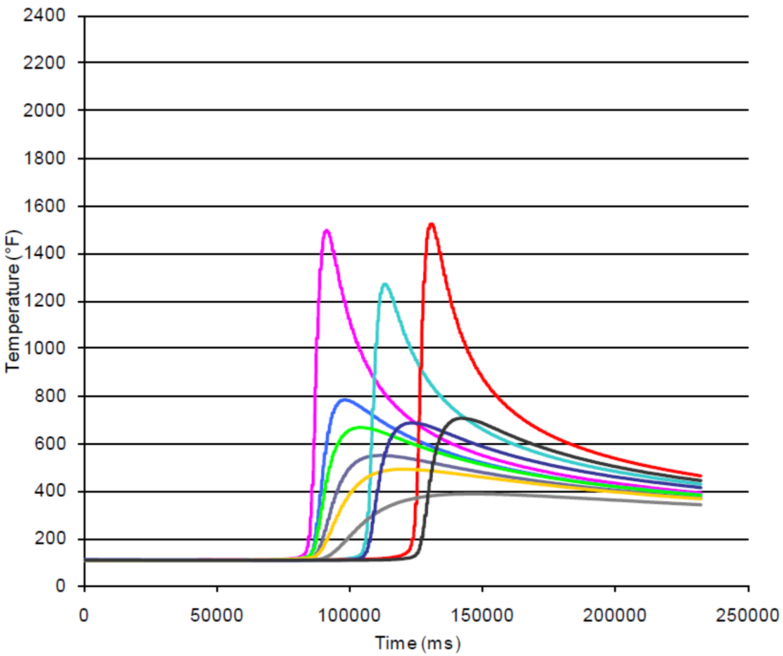


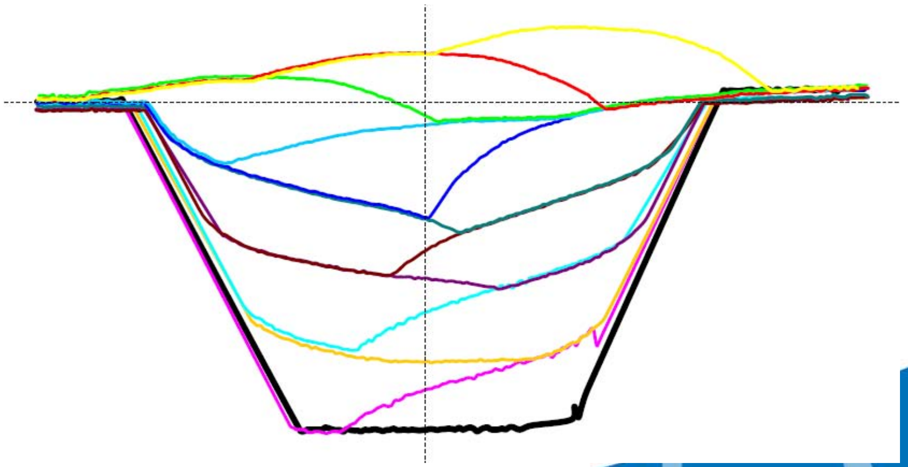
Source: MRP-316, EPRI, 2011

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



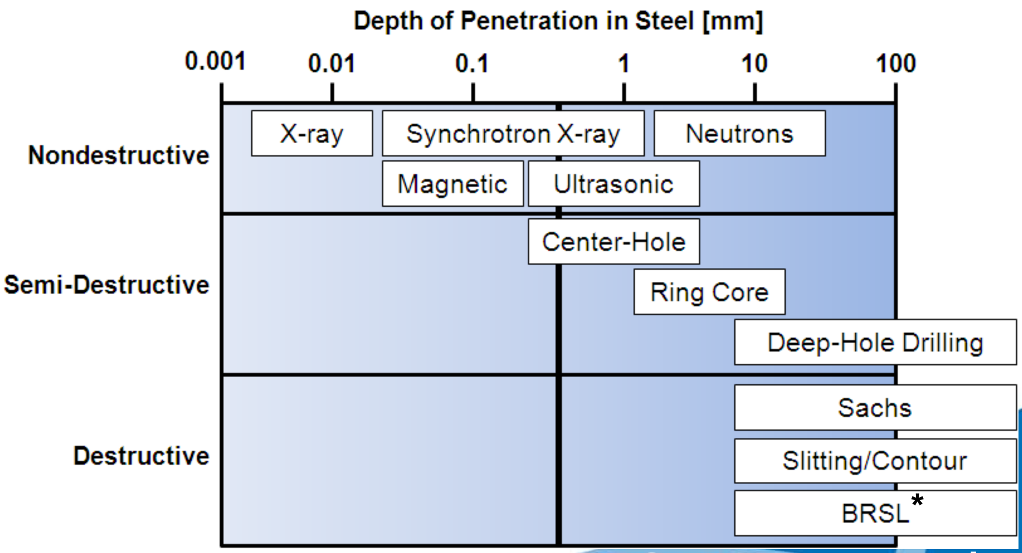


Source: MRP-316, EPRI, 2011

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



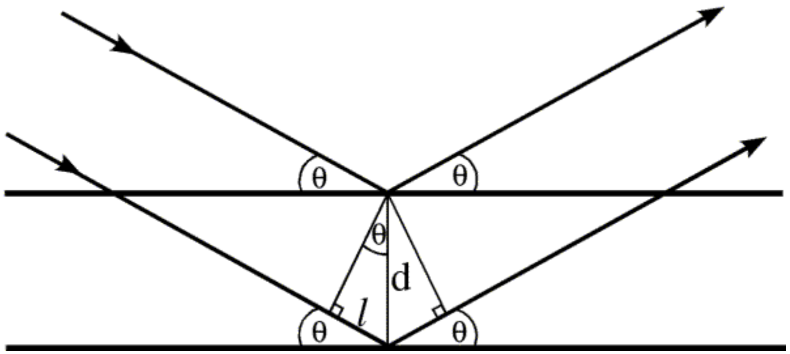
Source: Veqter, Ltd.

* 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



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

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

Phase I: Scientific Weld Specimens

Strain-Relief Techniques

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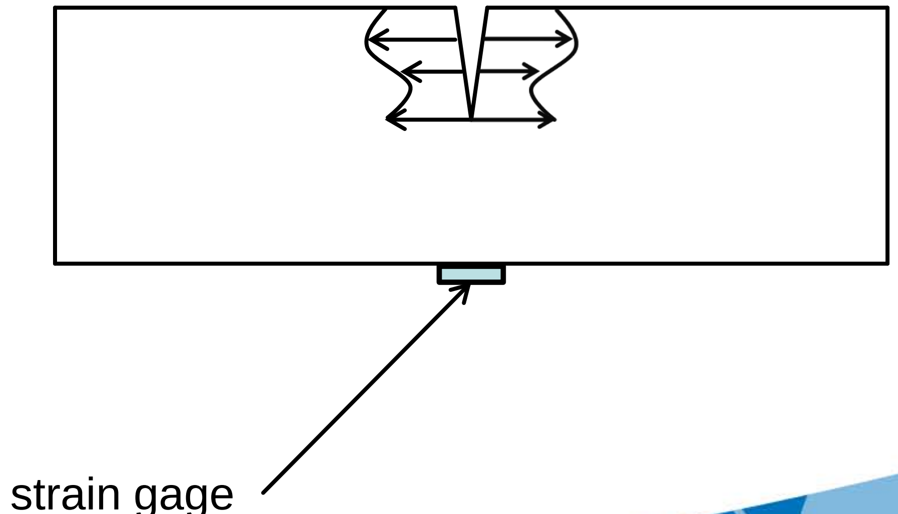
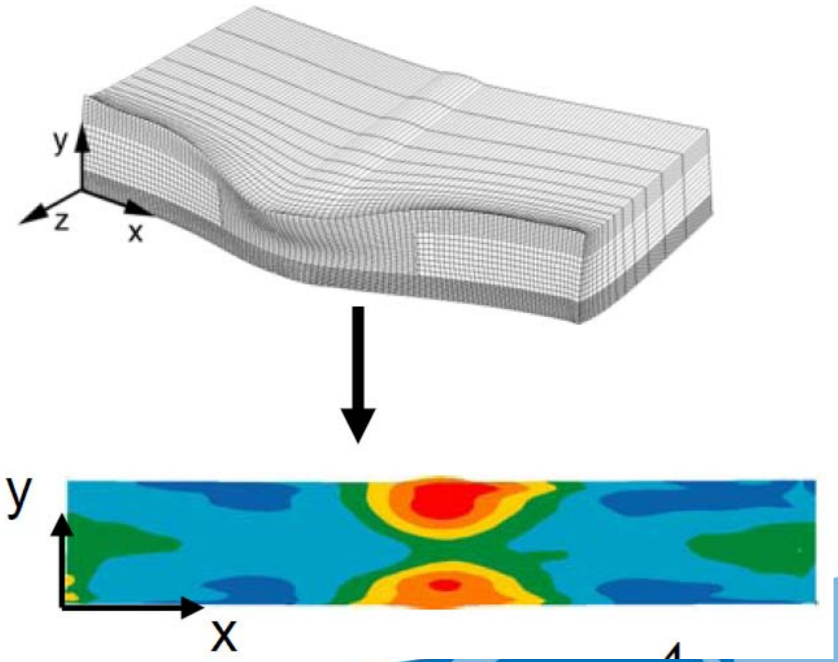
- Incremental slitting: near surface



Phase I: Scientific Weld Specimens

Strain-Relief Techniques

- Contour method: bulk

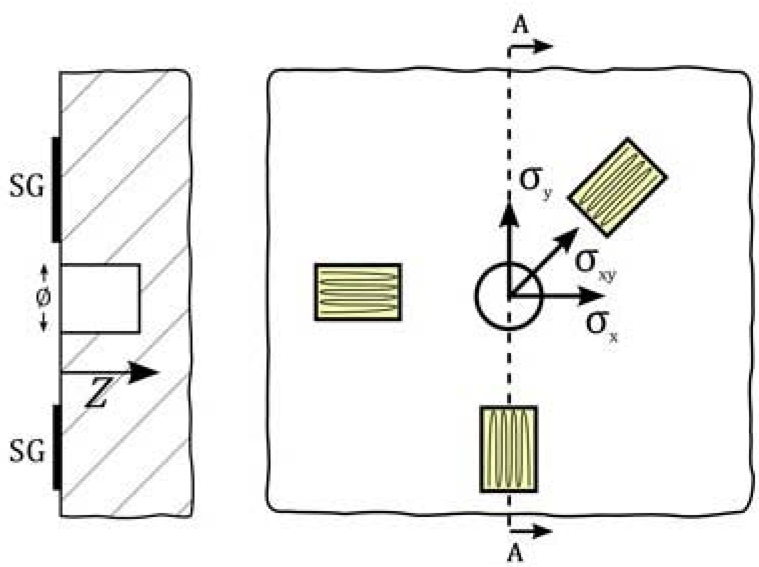


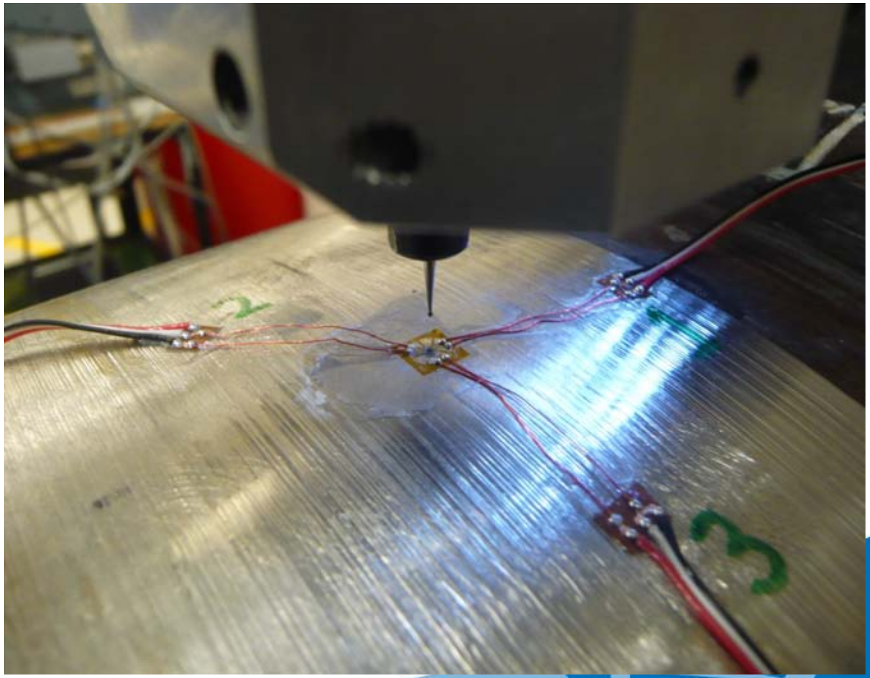
Source: Hill Engineering

Phase I: Scientific Weld Specimens

Strain-Relief Techniques

- Incremental center hole drilling: can be near-surface



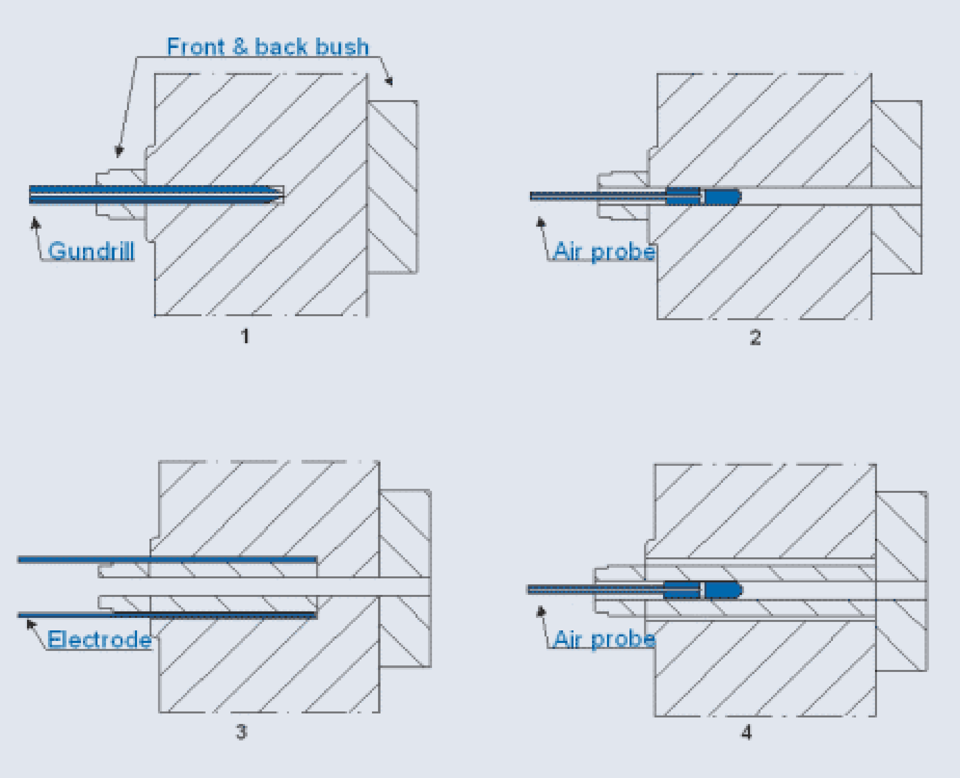


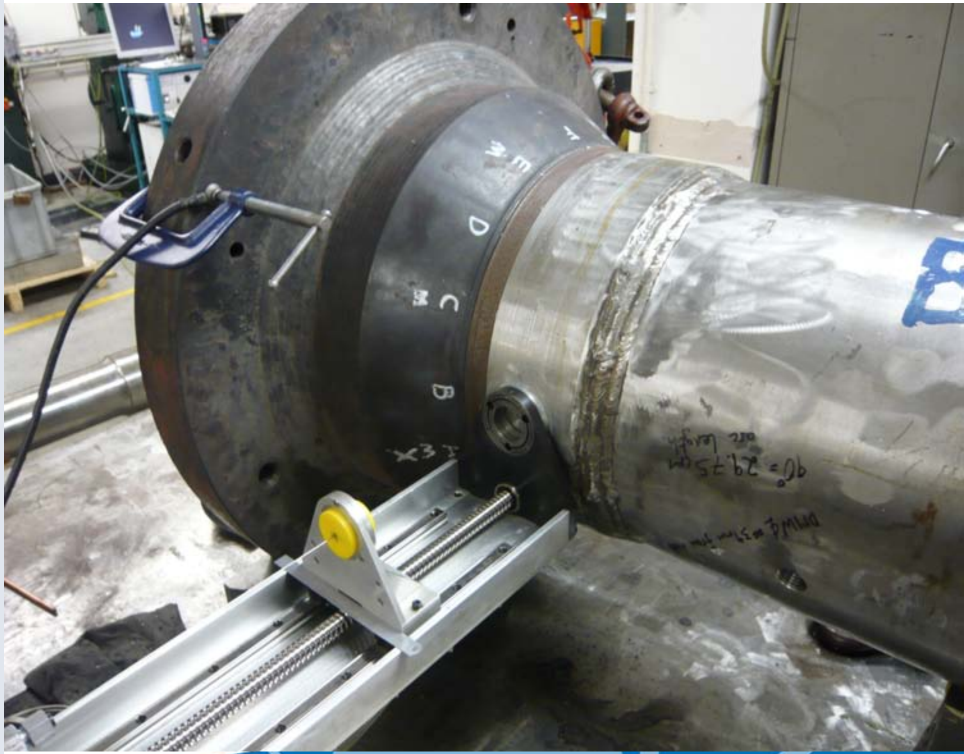
Source: VEQTER, Ltd.

Phase I: Scientific Weld Specimens

Strain-Relief Techniques

- Deep hole drilling: bulk





Source: VEQTER, Ltd.

Phase I: Scientific Weld Specimens

Measurement Summary: Plate Specimens

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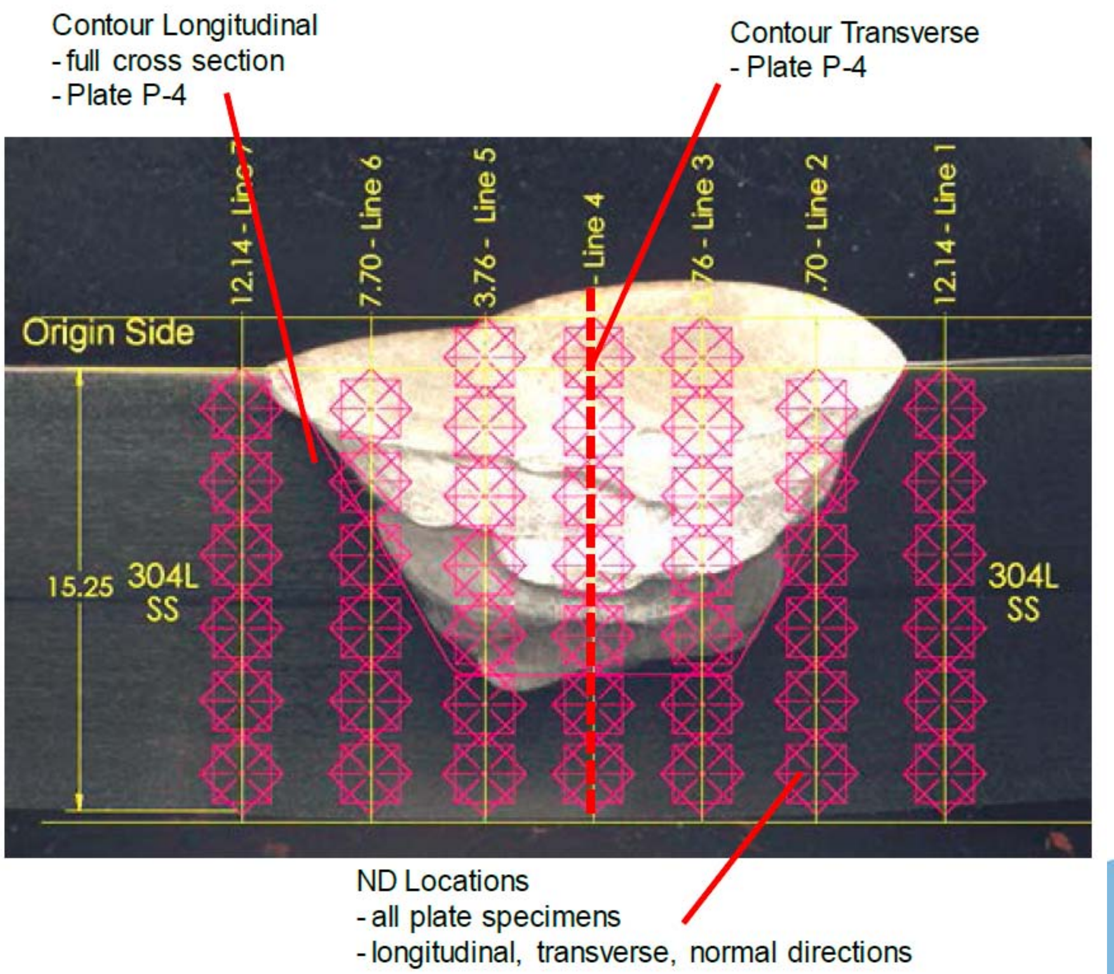
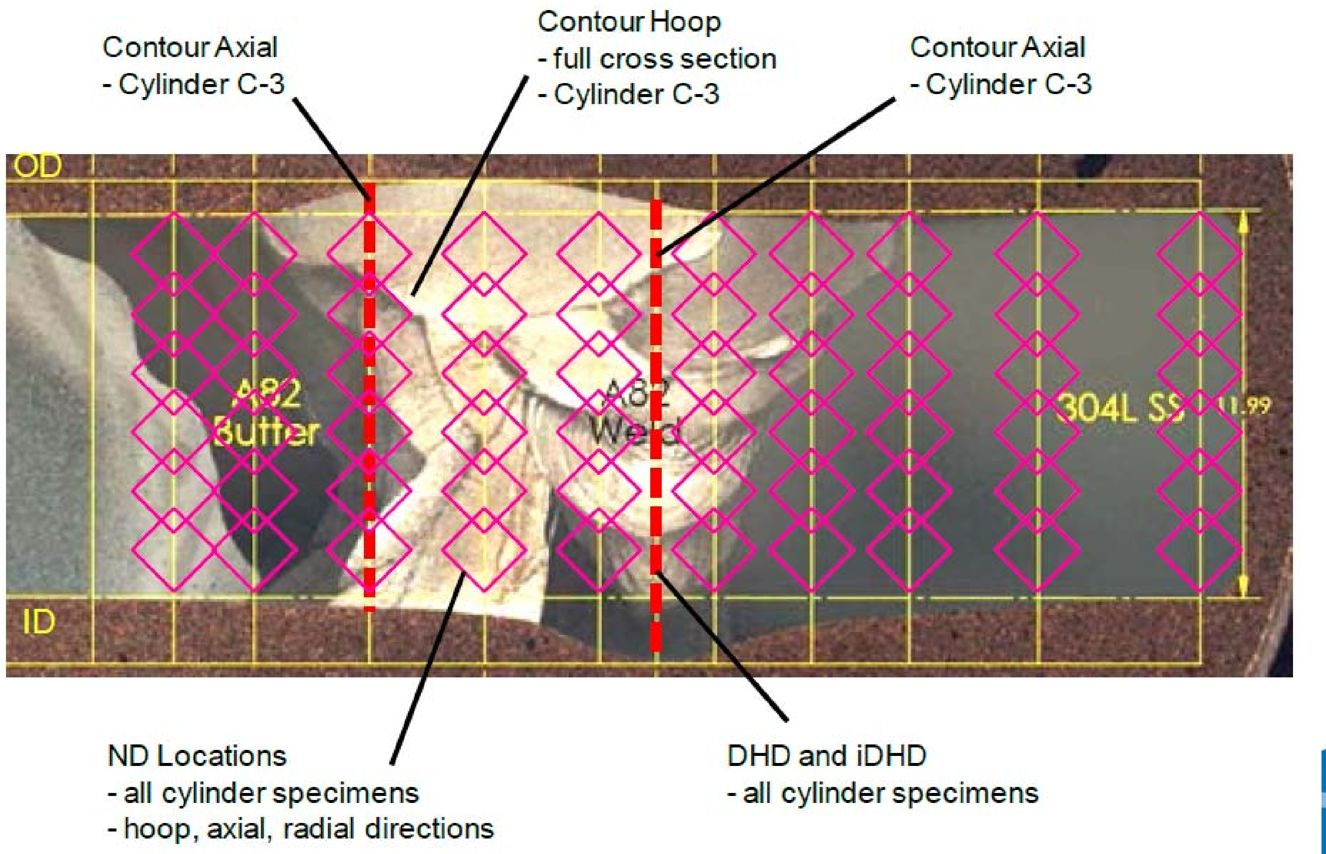


Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

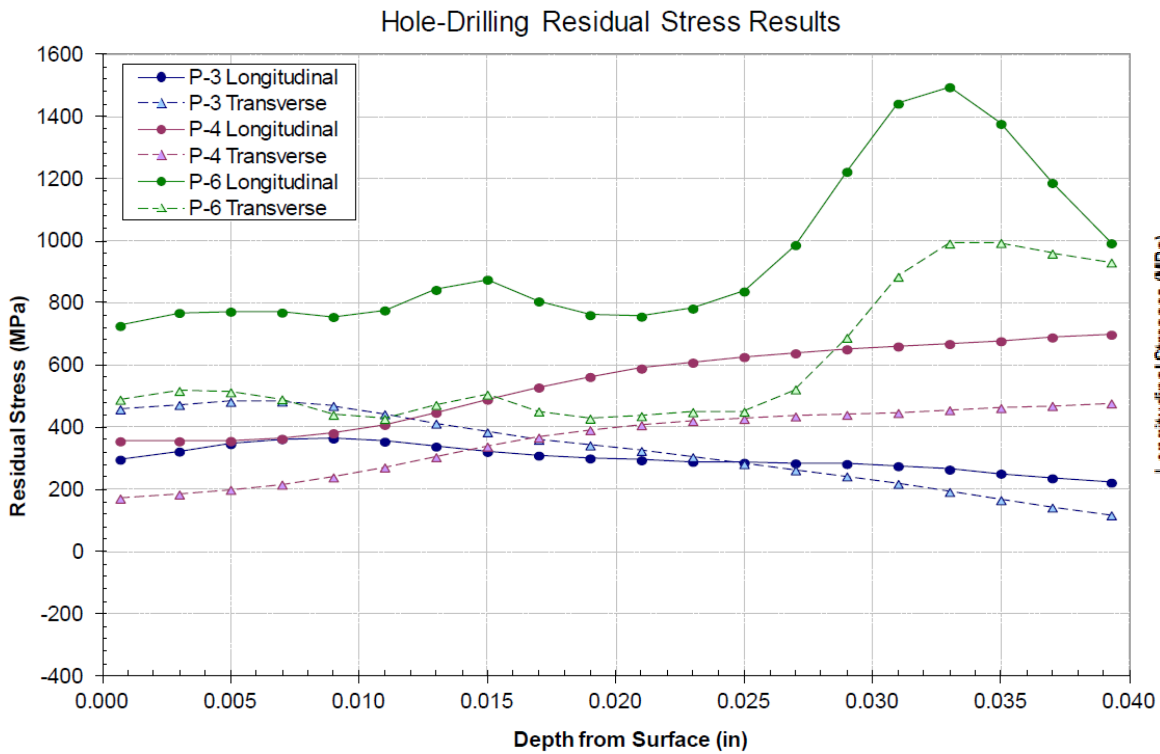
Measurement Summary: Cylinder Specimens

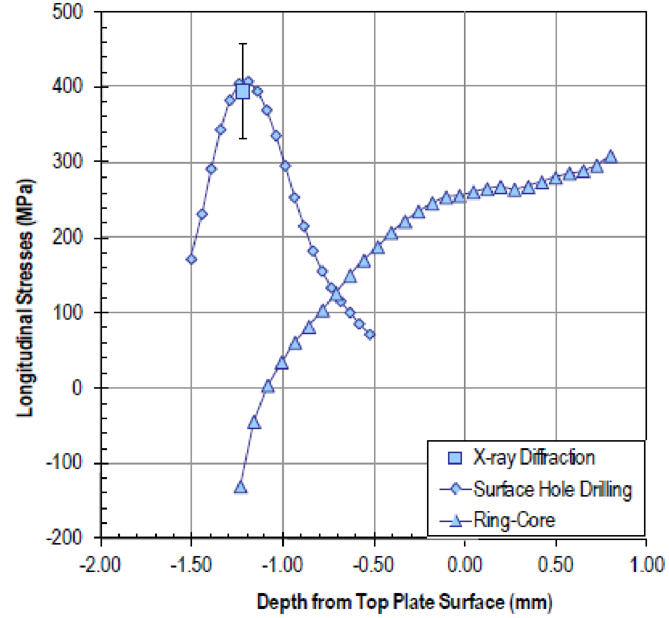


Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

Surface Stress Measurement Results





- 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

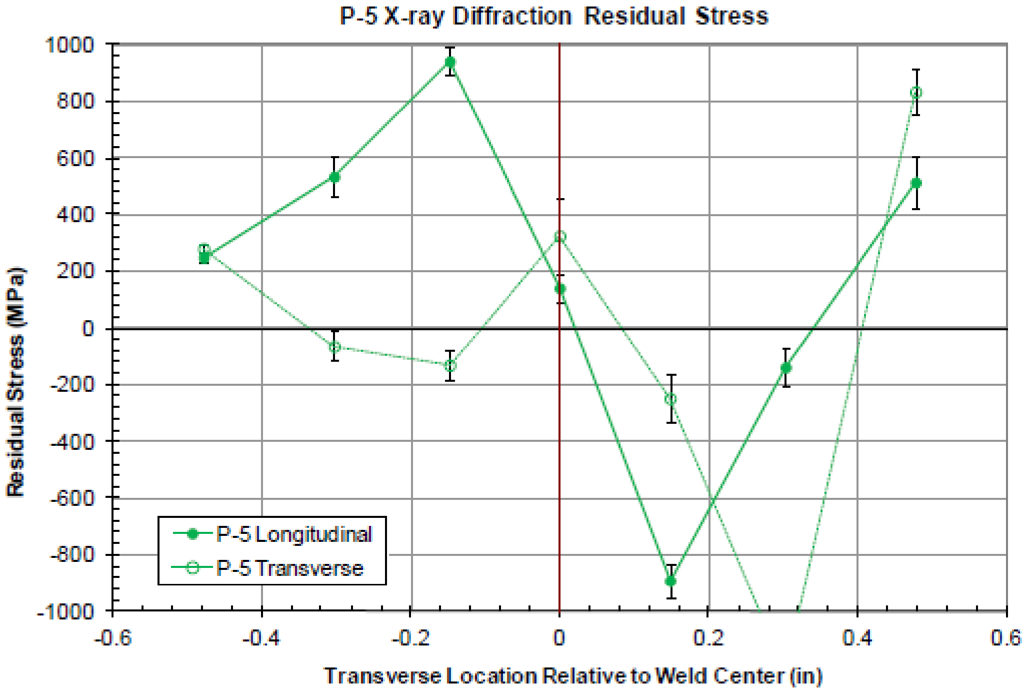


Plate Specimen

- 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

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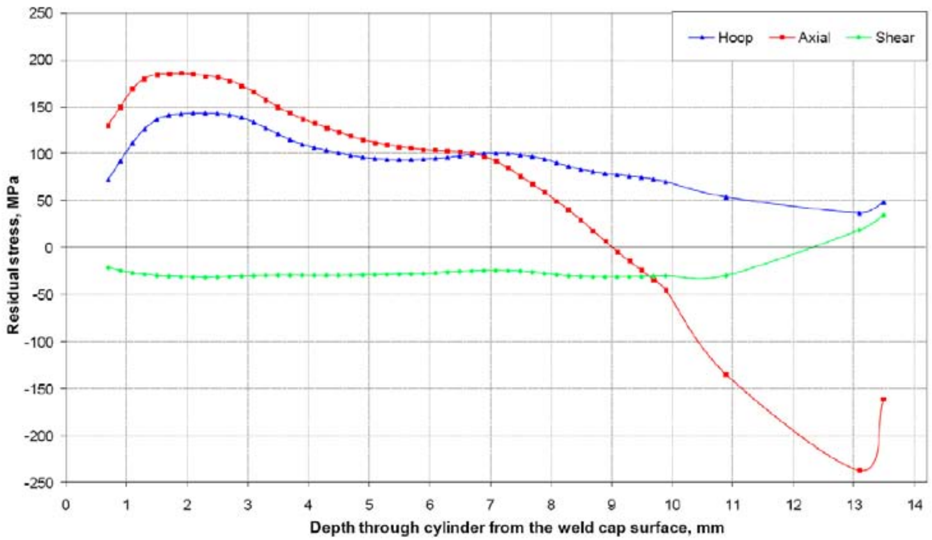
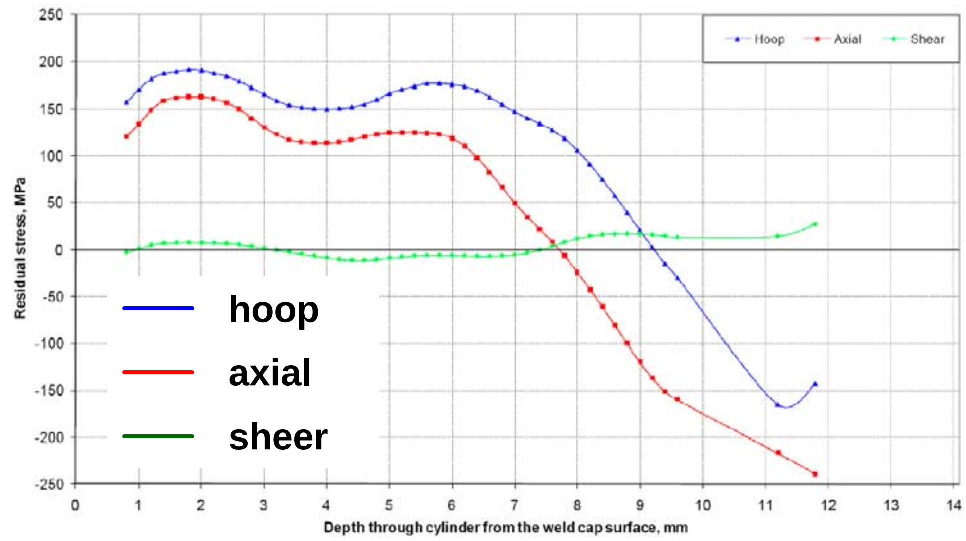
Weld Centerline



Repair Weld Centerline



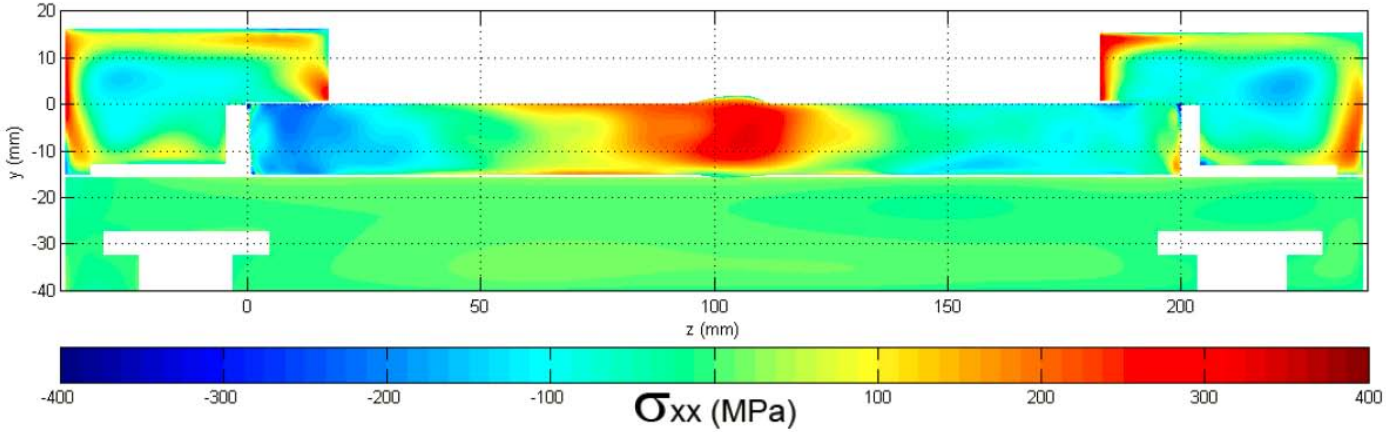
Cylinder Specimen

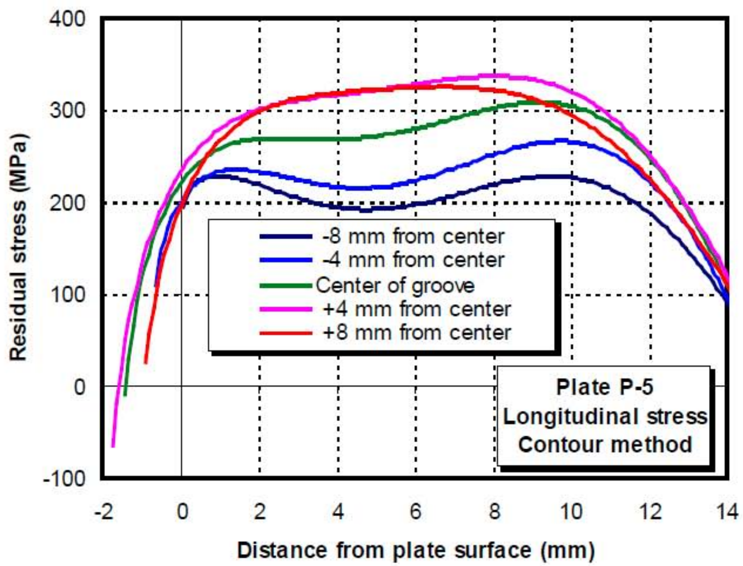
- Smooth trends and reasonable magnitudes: e.g., -200 to 200 MPa
- Repair weld significantly affected the hoop stress

Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

Bulk Stress Measurement Results: Contour





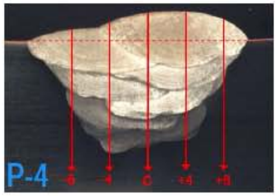


Plate Specimen

Phase I: Scientific Weld Specimens

Bulk Stress Measurement Results: Contour

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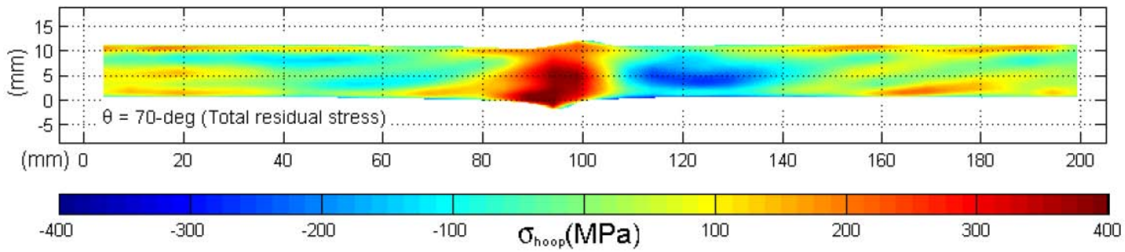
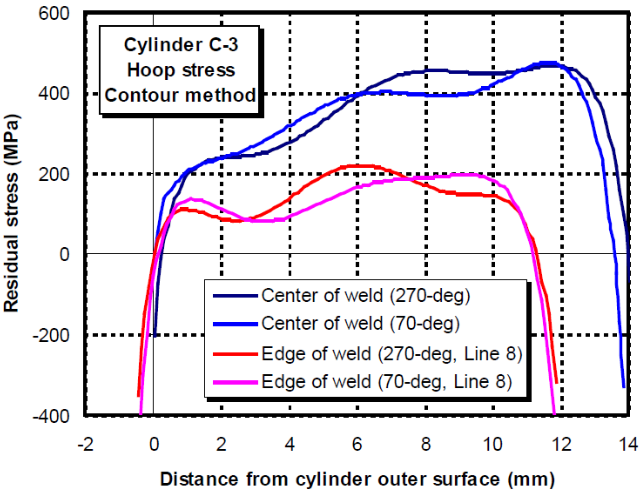
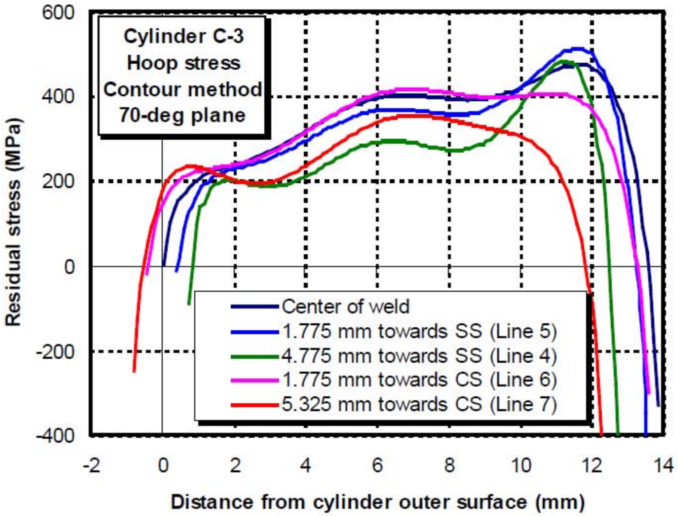
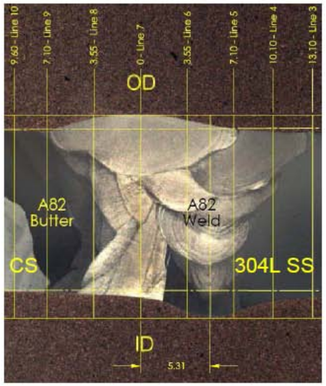






Ring Specimen



Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

Bulk Stress Measurement Results: Neutron Diffraction

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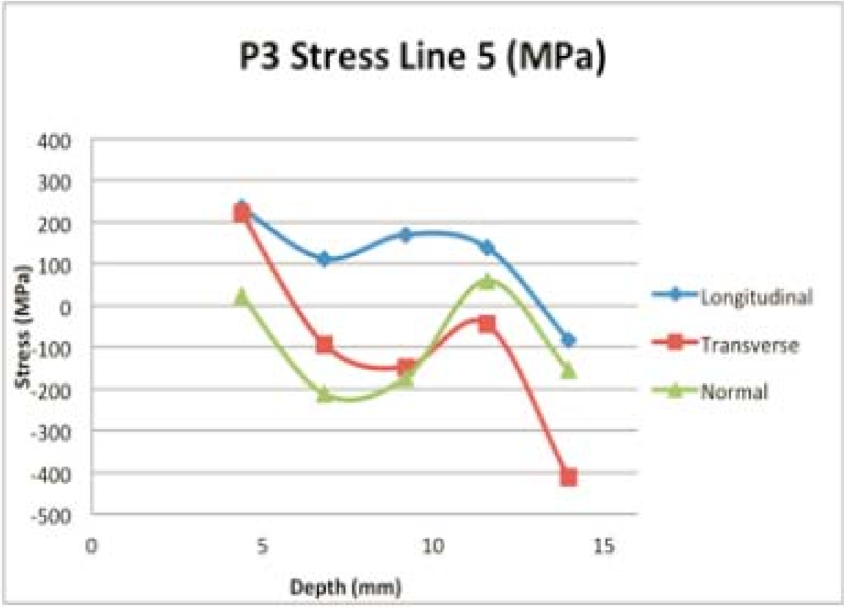


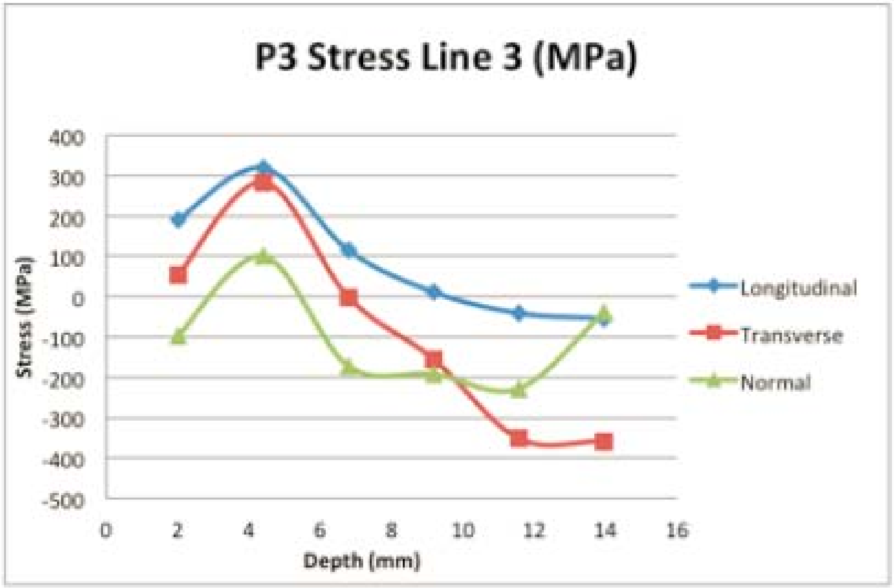
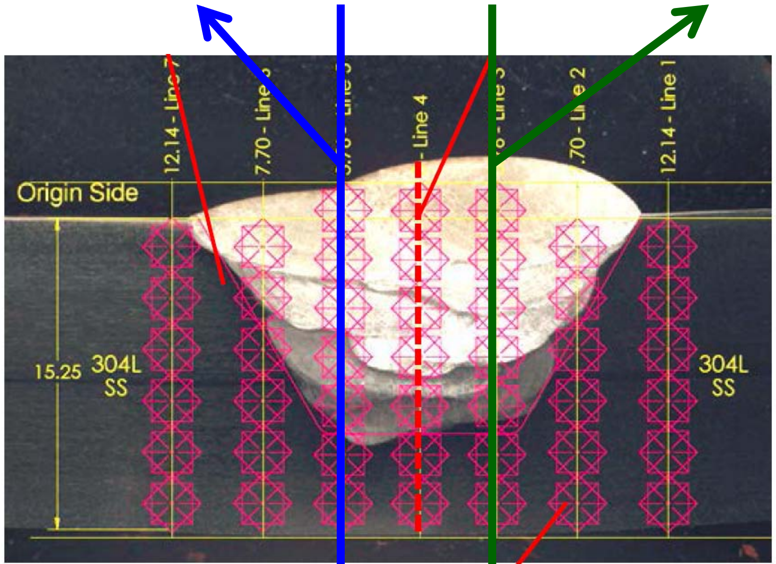


Plate Specimen



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

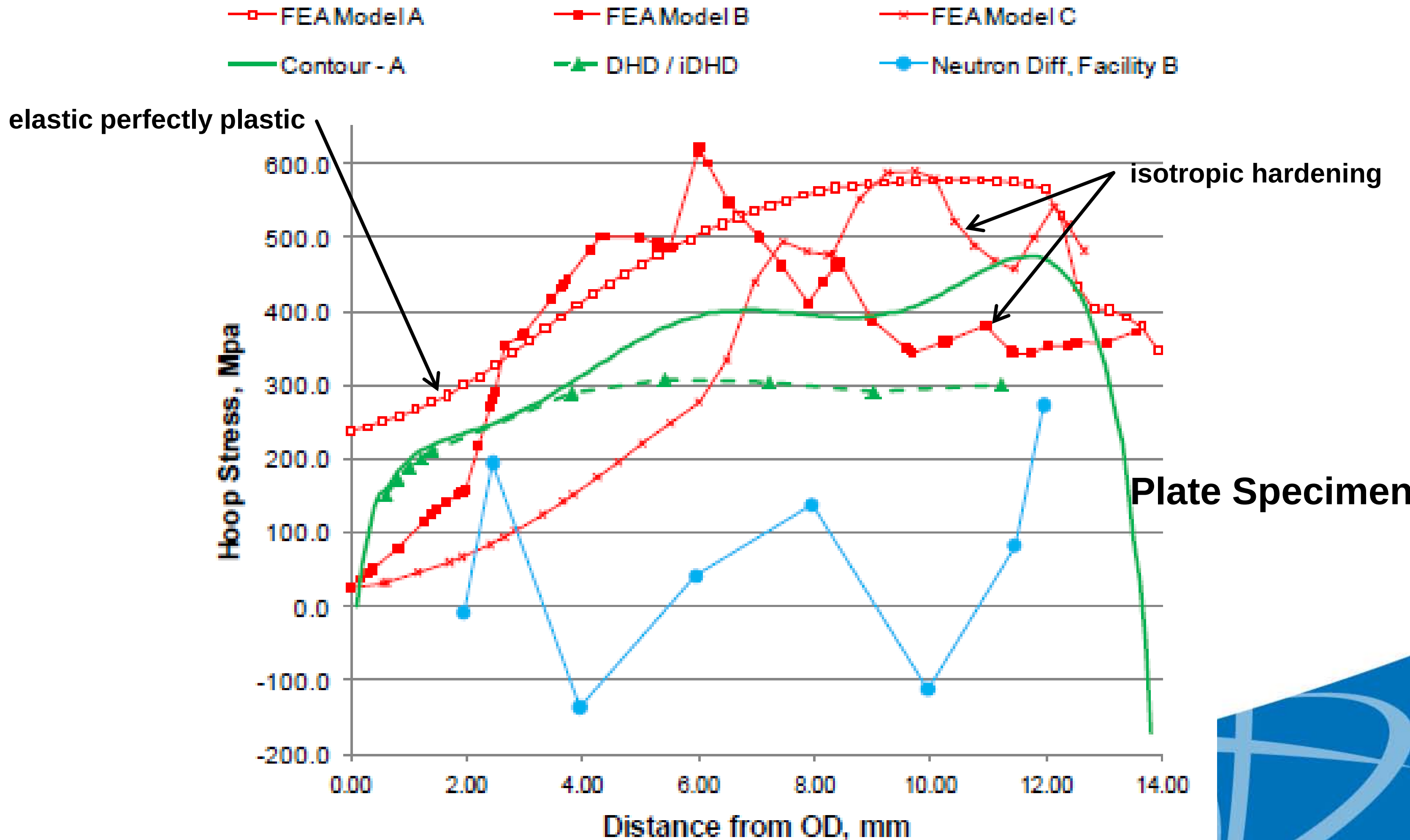
Phase I: Scientific Weld Specimens

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



Source: MRP-316, EPRI, 2011

Phase I: Scientific Weld Specimens

Data from a Pulsed Neutron Source

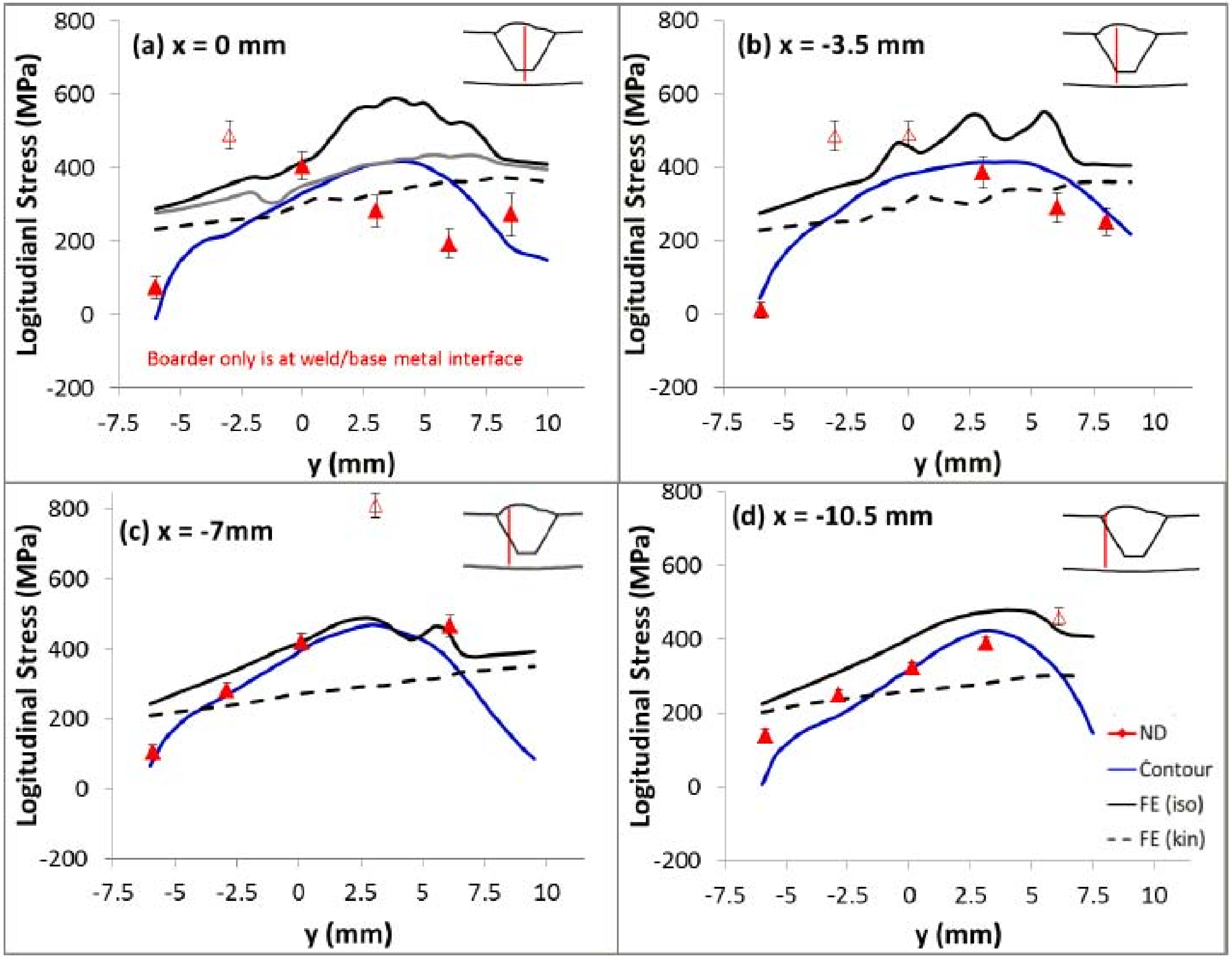


Plate Specimen

Source: MRP-316, EPRI, 2011

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

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- 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
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Phase II: Fabricated Prototype Nozzles

Overview

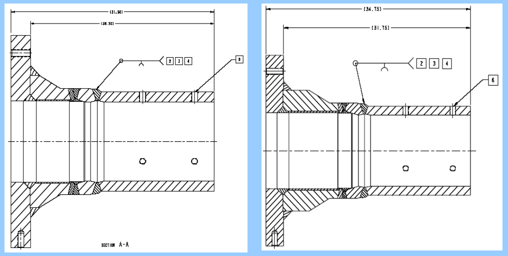
- Full-scale mockups
  - Two mockups: Only Phase IIa discussed here
  - Fabricated under controlled conditions
- Finite Element Round Robin
  - Double-blind: i.e., modelers did not have access to the measurement data
  - Obtain modeling results from a community of independent modelers
- Objectives
 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

Phase 2 - NRC

•Fabricated Prototypic Nozzles

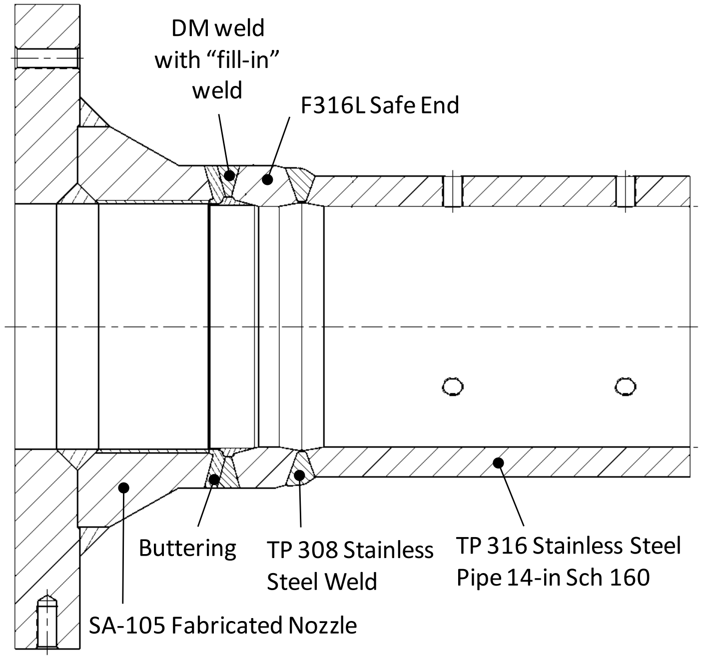
•Type 8 Surge Nozzles (QTY 2)

•Purpose: Prototypic scale under controlled conditions. Validate FE models.



Phase II: Fabricated Prototype Nozzles

Mockup Fabrication

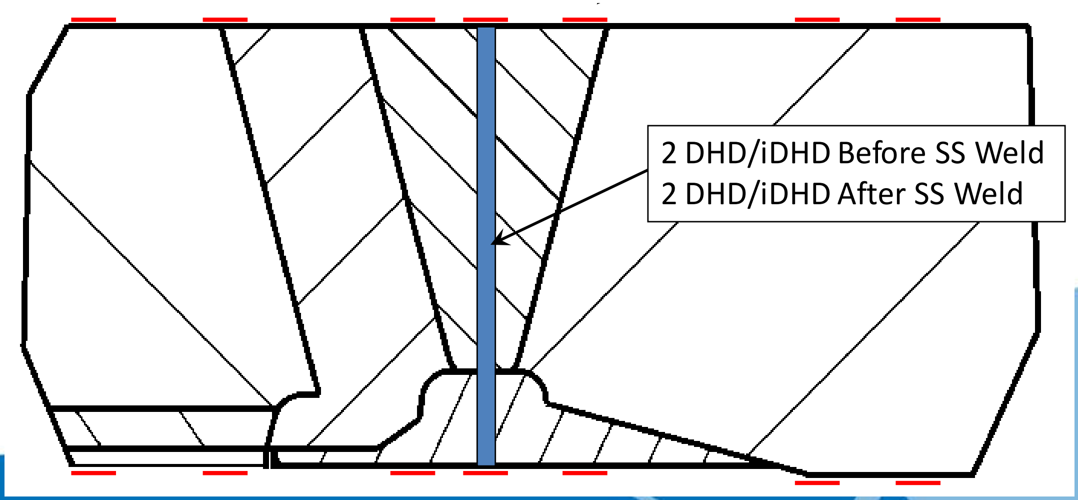


- Pressurizer surge nozzle
- Welding performed by automated gas tungsten arc welding
- Thermocouple and laser profilometry readings
- Rough dimensions: 31" overall length, 11" inner diameter

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

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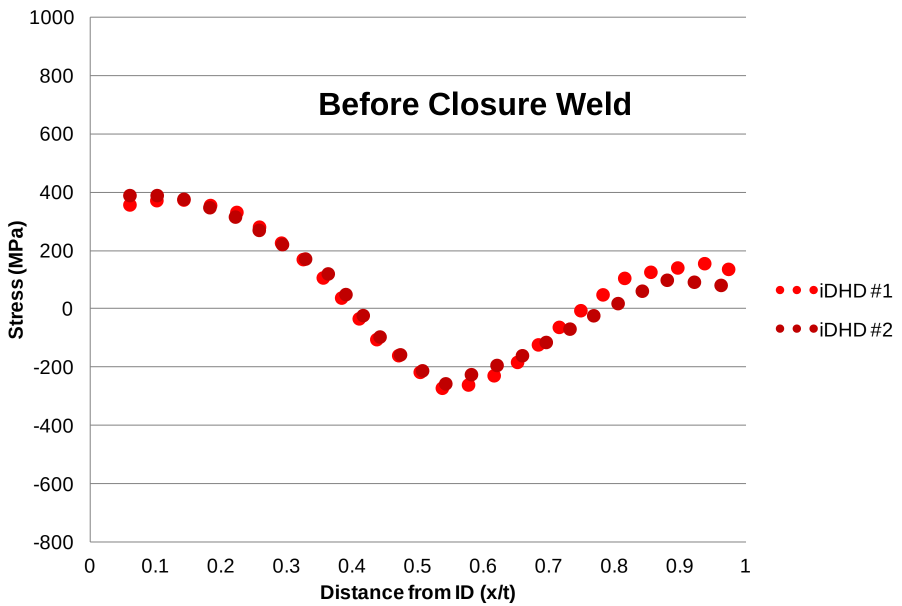

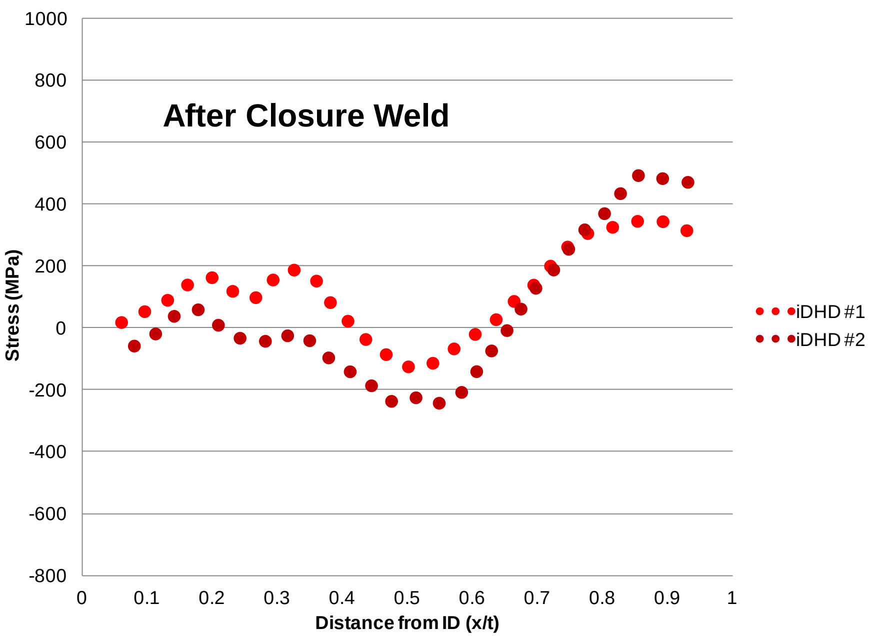

- Axial stresses shown here
- Safe end to pipe weld can potentially have a beneficial affect on inner diameter stress
- Safe end length can be an important parameter

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)
- EMC^2 (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

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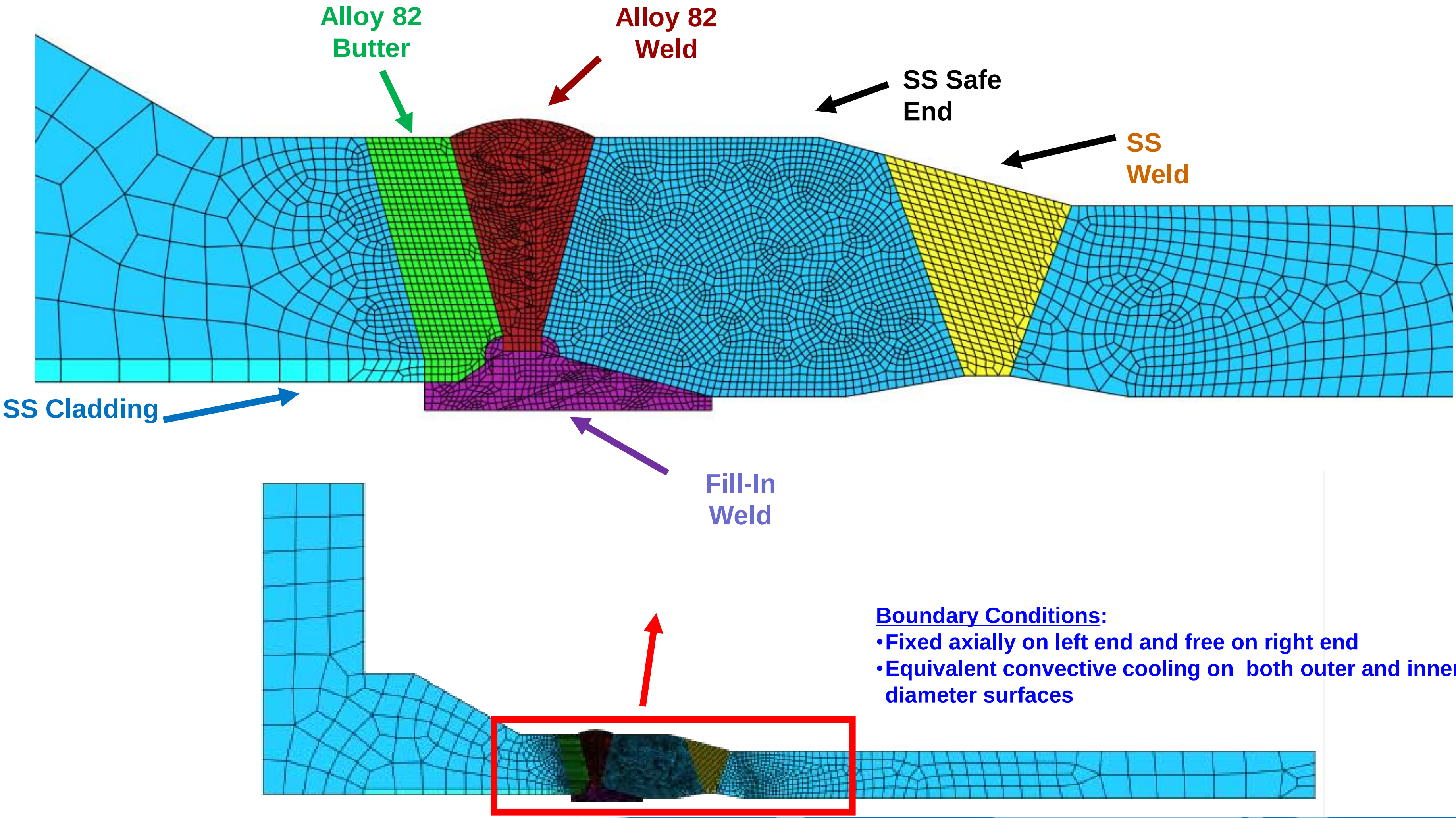
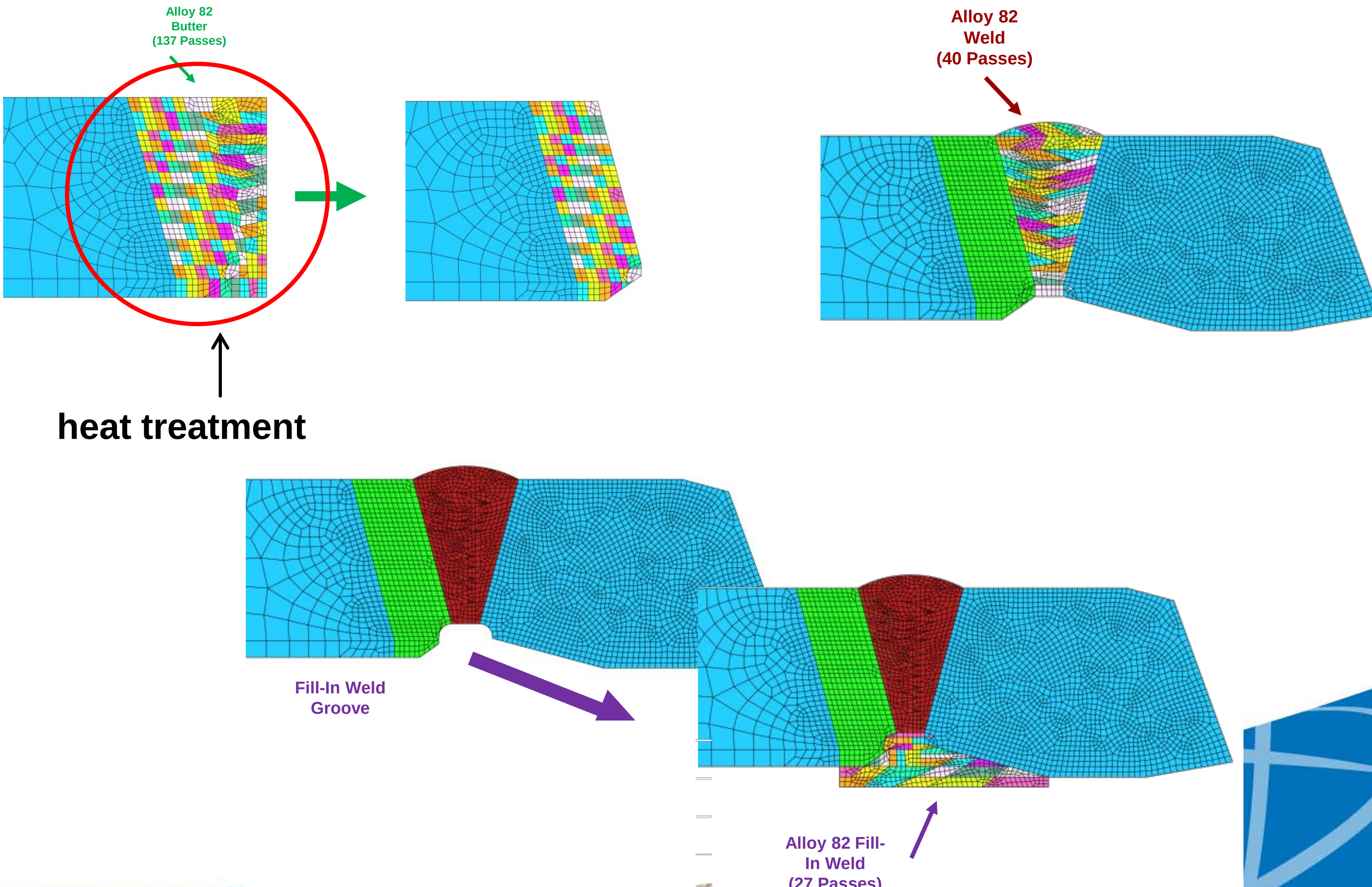
Example Model Geometry



Boundary Conditions:
- **Fixed axially on left end and free on right end**
- **Equivalent convective cooling on both outer and inner diameter surfaces**

Phase II: Fabricated Prototype Nozzles

Example Model Geometry



Phase II: Fabricated Prototype Nozzles

Analysis Stages: Can We Reduce Uncertainty?

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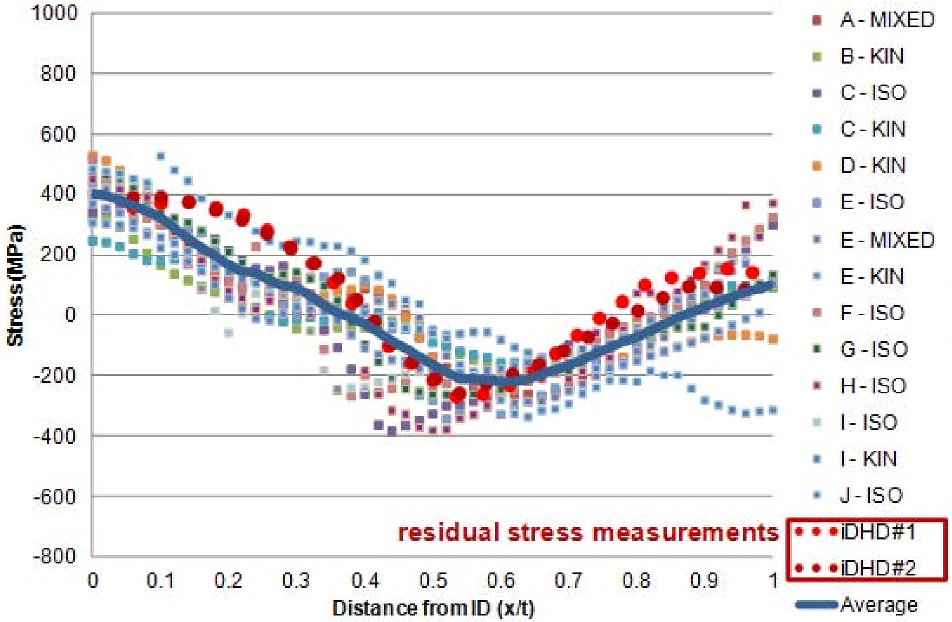
- Postulated sources of uncertainty: welding heat input and material properties
- Three analysis stages
  - No thermocouple data or material property data supplied
  - Thermocouple data only supplied
  - Thermocouple and material property data supplied
- Models completed before and after the stainless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

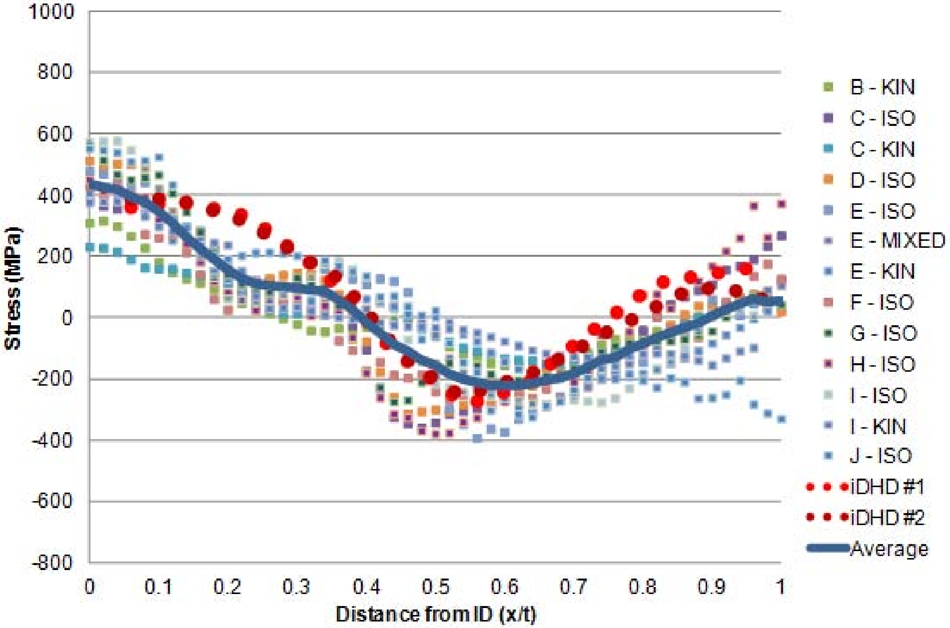
Phase II: Fabricated Prototype Nozzles

FEA Round Robin Results

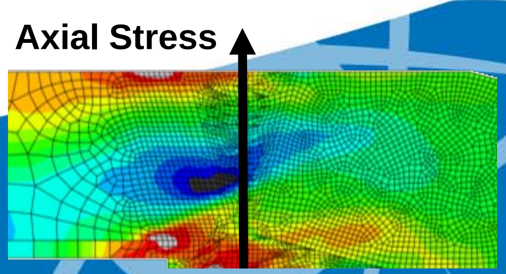
Pre-stainless steel weld
No material properties
No thermal couple data



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

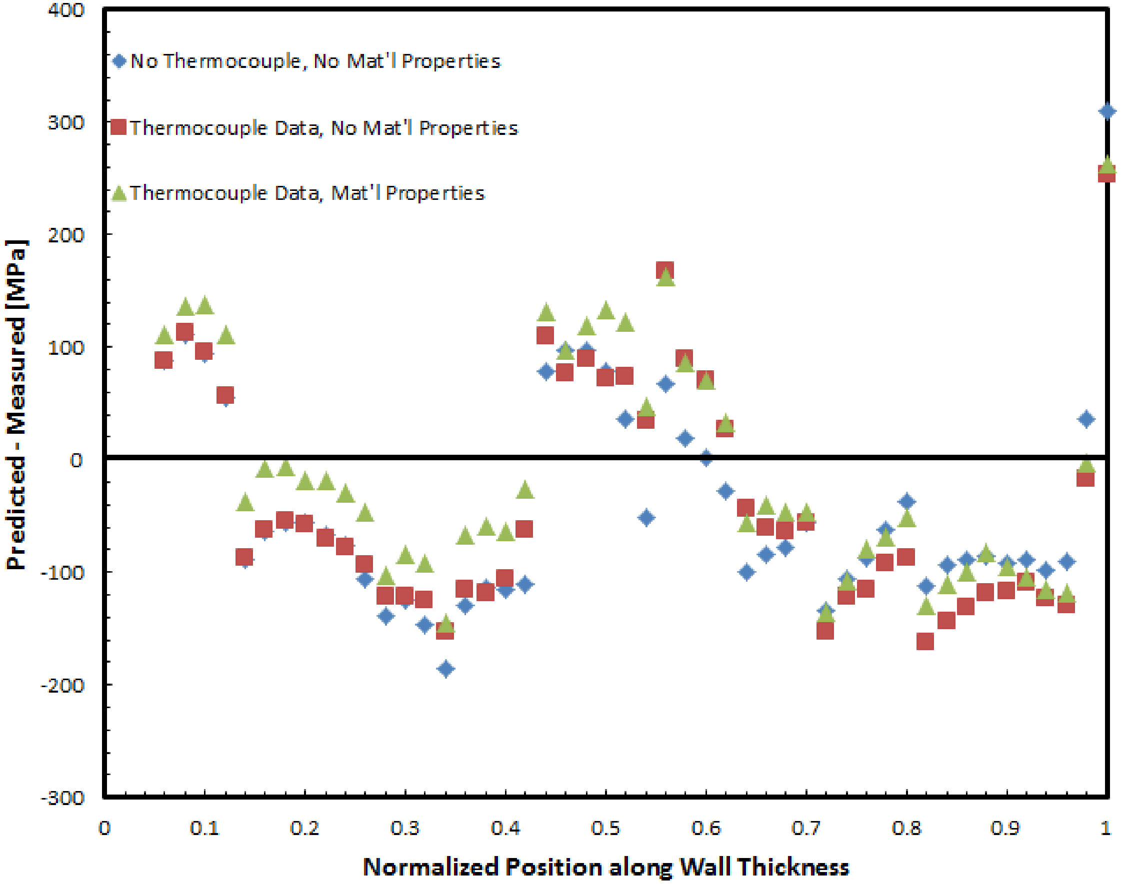


- Axial stresses shown here
- Variety of hardening laws employed
- Modeling uncertainty is the same



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

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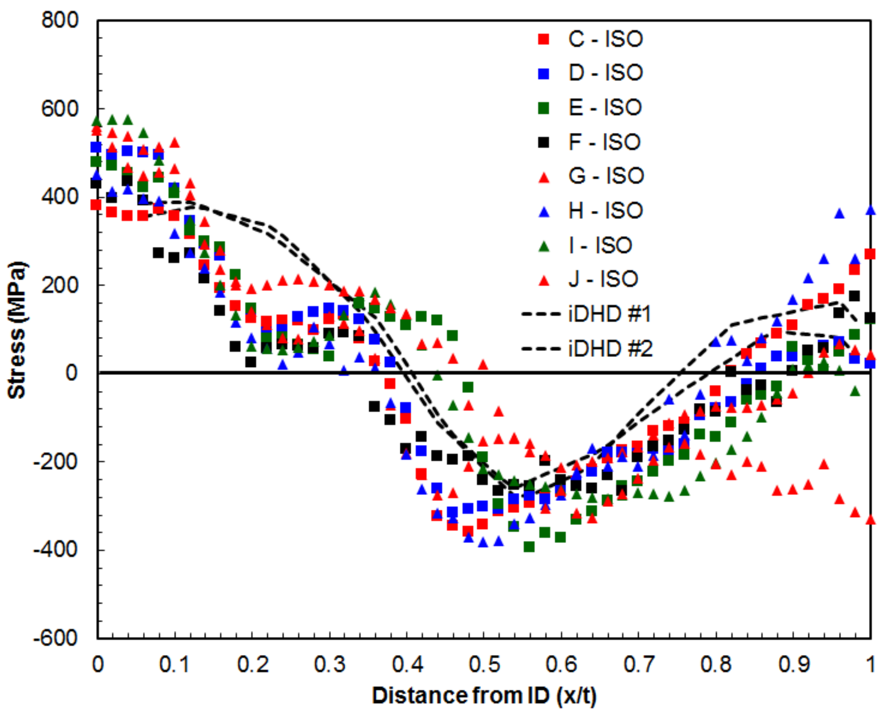
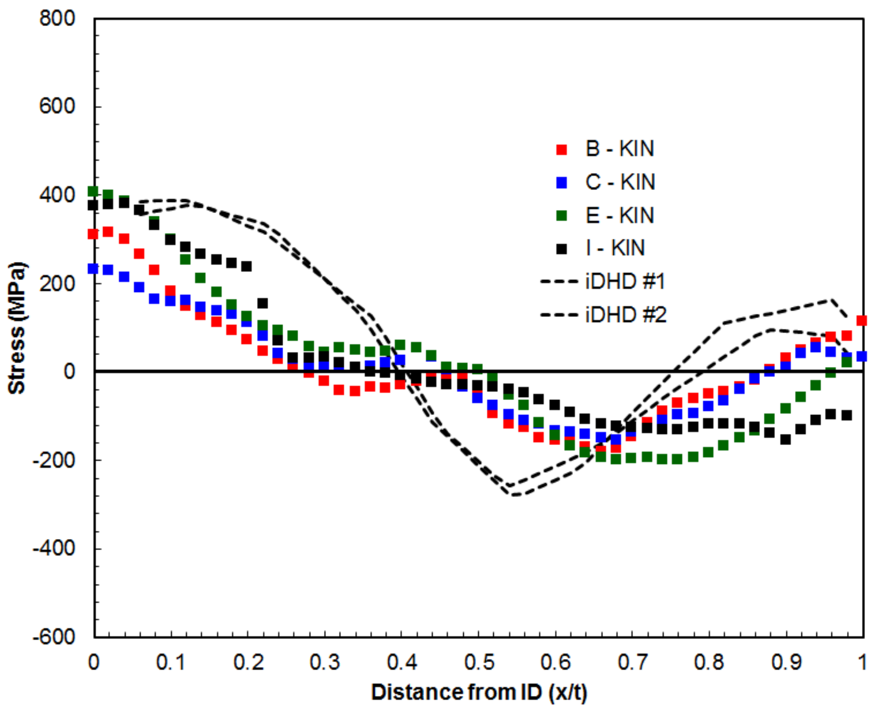
FEA Round Robin Results: Separate Hardening Law





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

Phase II: Fabricated Prototype Nozzles

FEA Round Robin Results

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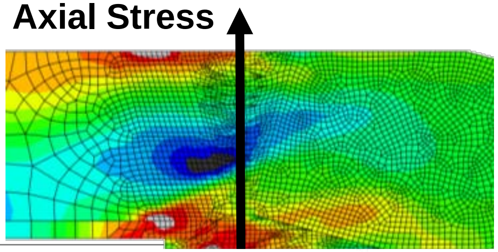
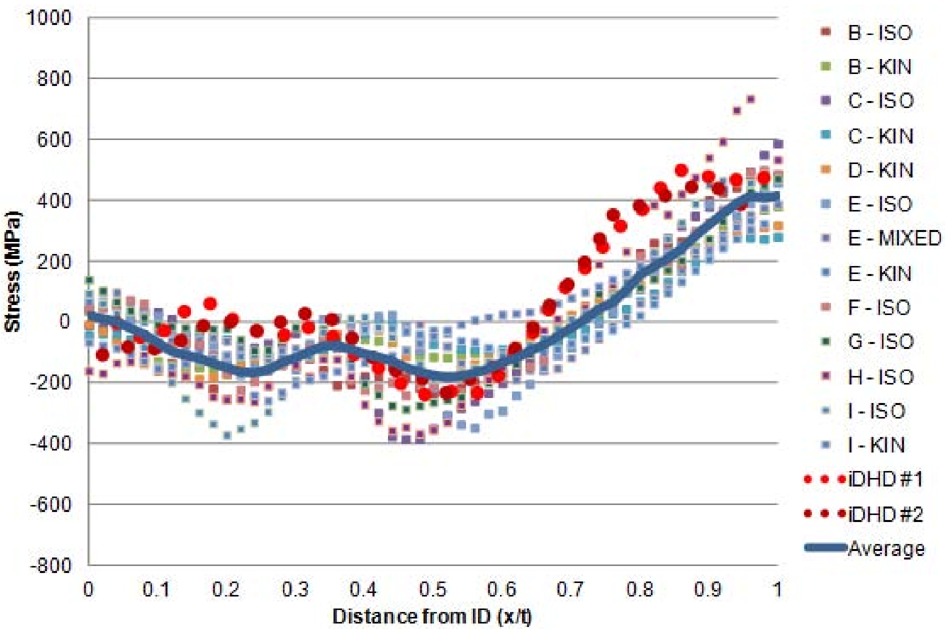
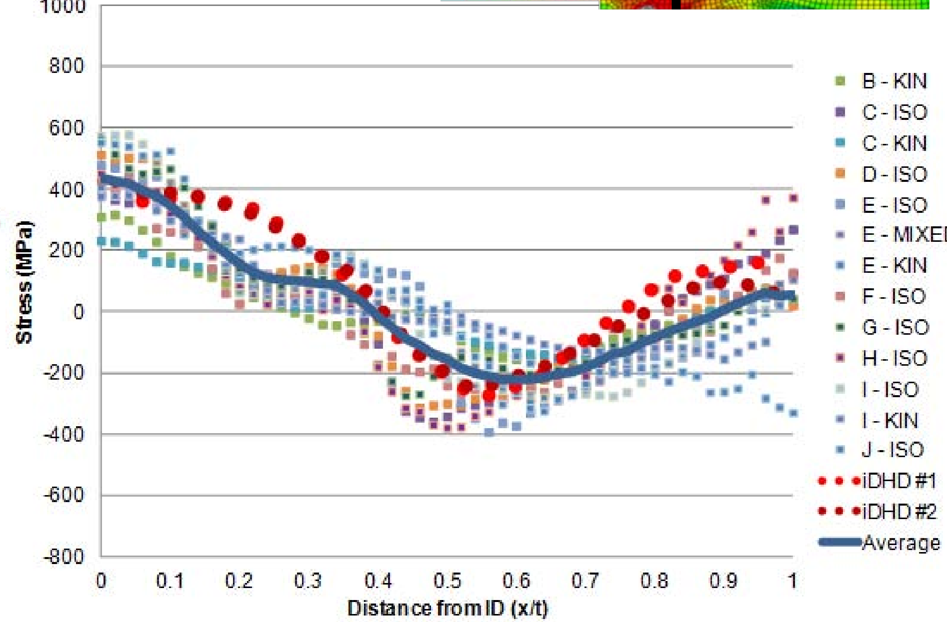


Including stainless steel weld



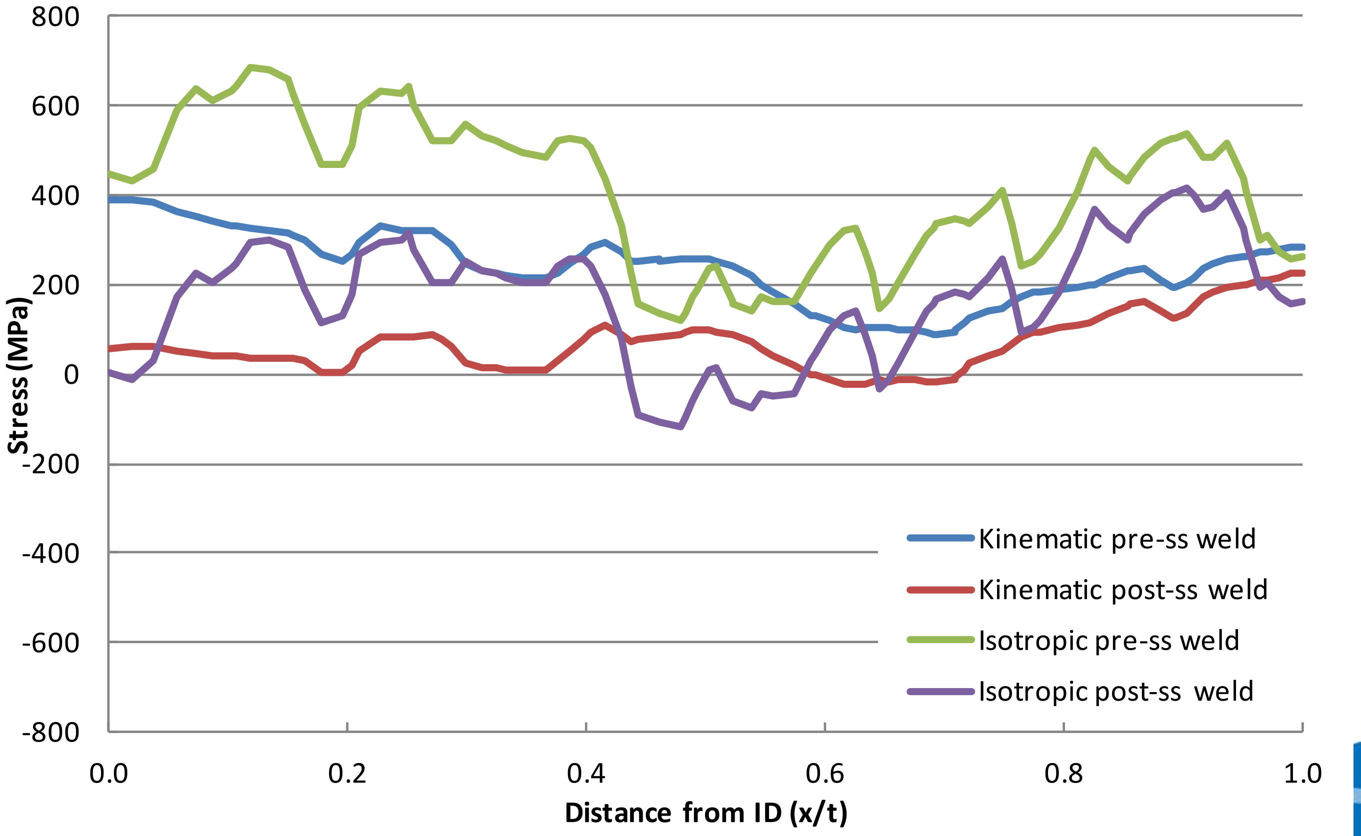
Pre-stainless steel weld



- 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

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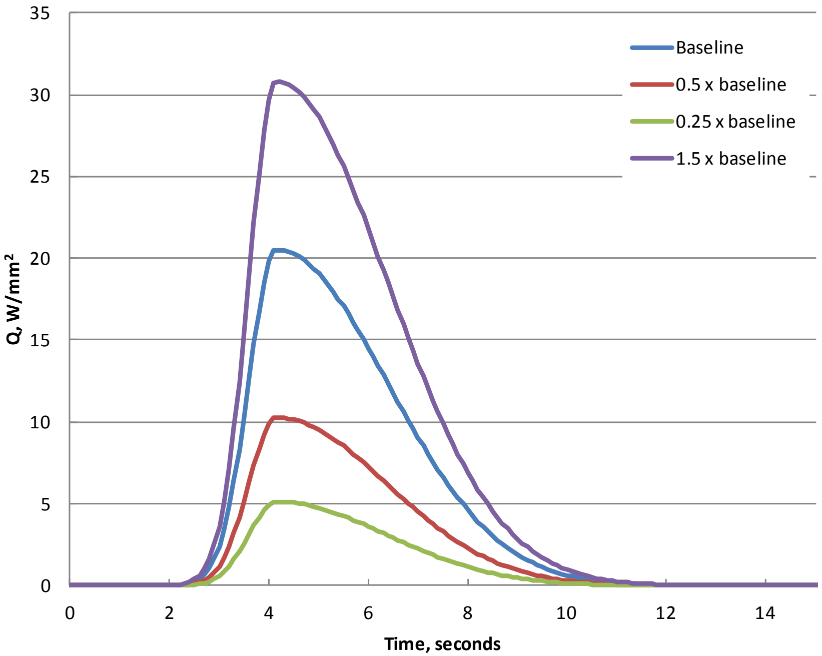
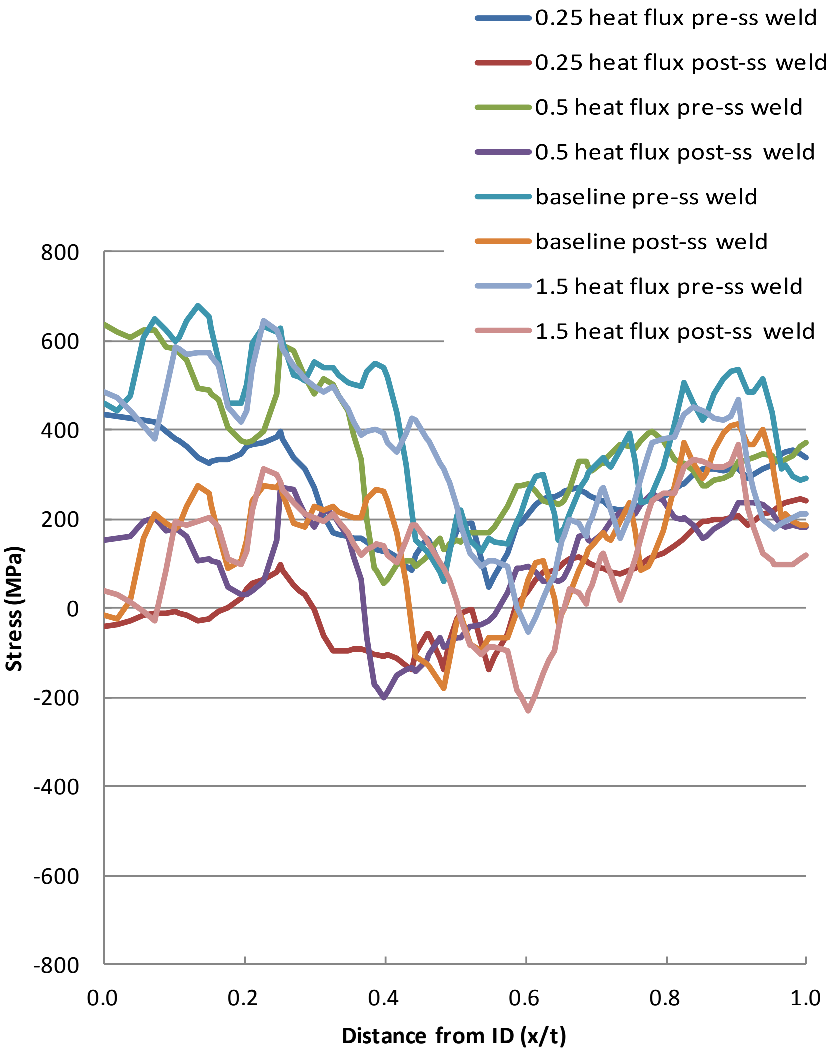
Sensitivity Studies: Heat Input





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

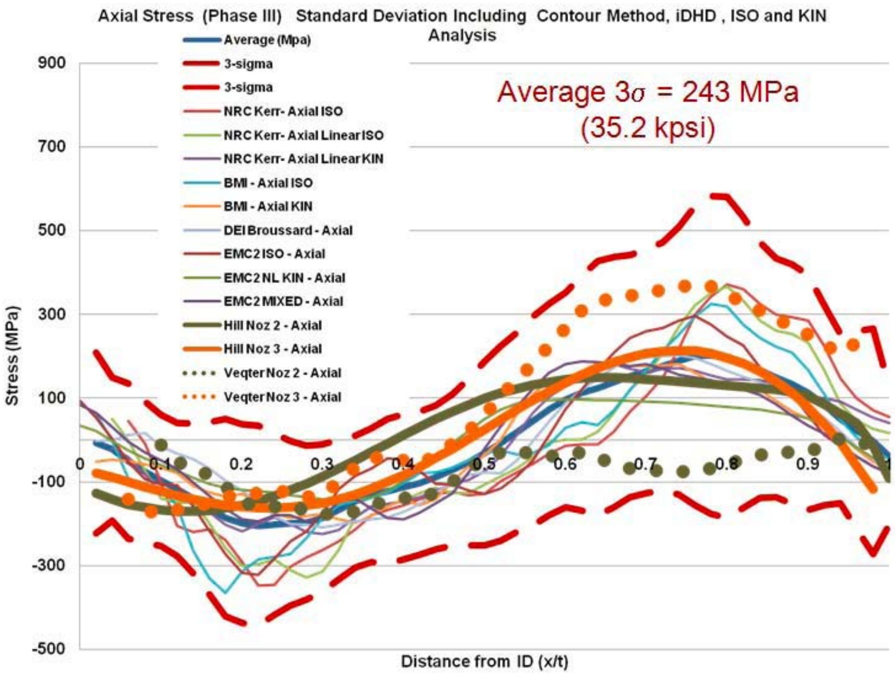
Overview

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

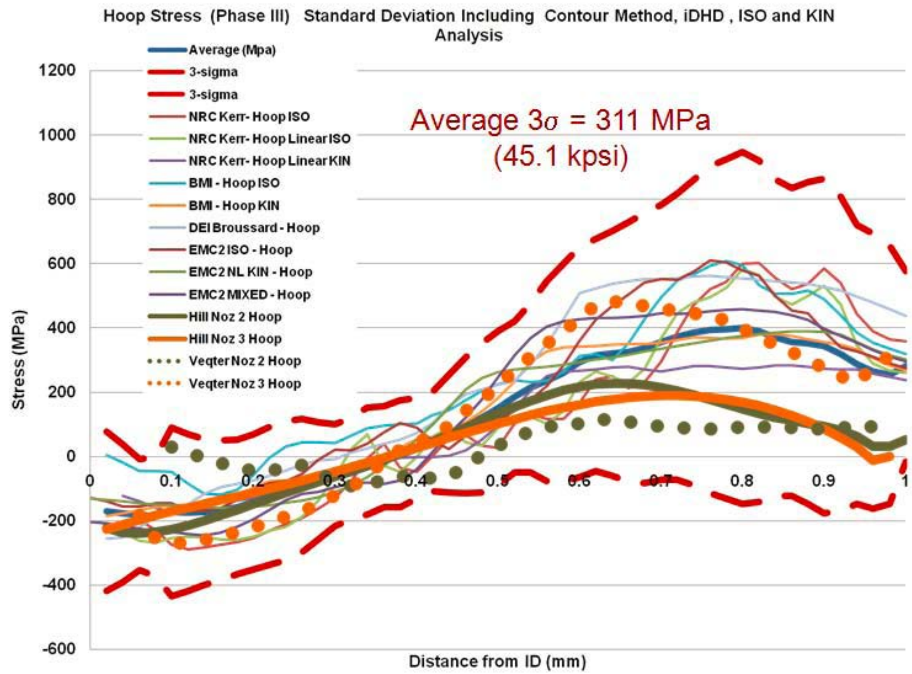
Phase III: Cancelled Plant Nozzles

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 3σ = 243 MPa, Phase 2a average 3σ = 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

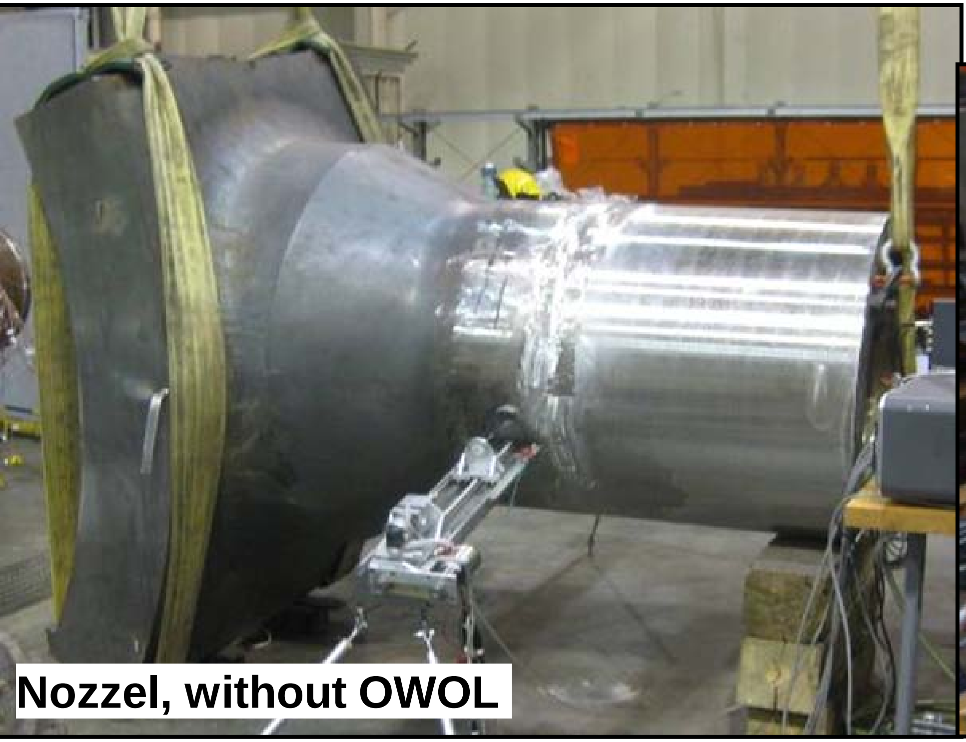
- Full-scale components
  - Actual cold leg nozzle fabricated for intended service
- Finite Element Round Robin
  - Double-blind: i.e., modelers did not have access to measurement data
  - Obtain modeling results from a community of independent modelers
- Objectives
  - To validate WRS modeling with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

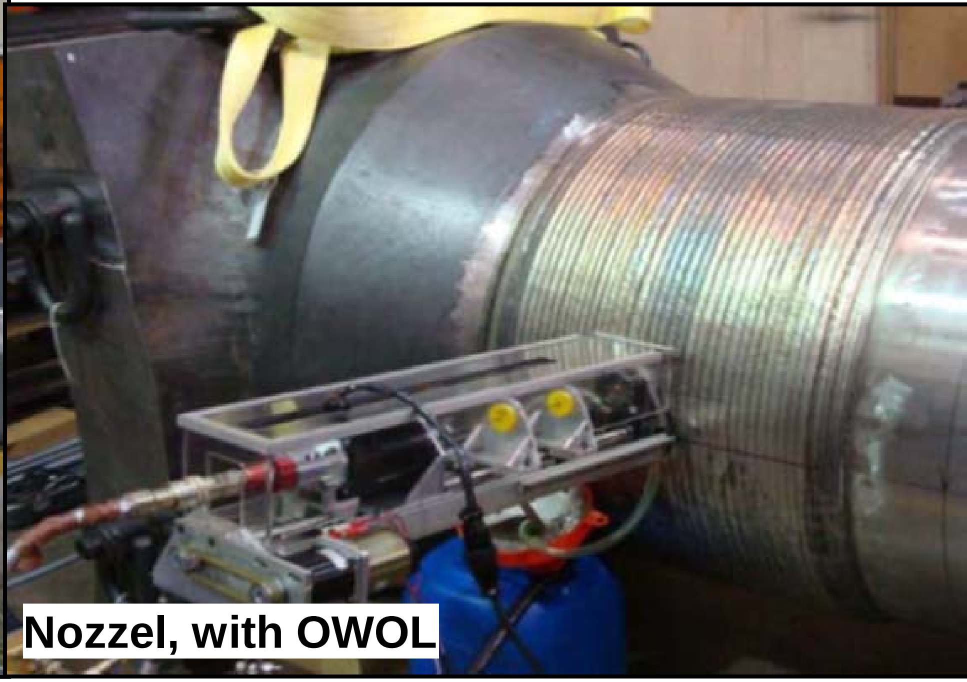
Phase 4 - EPRI

- 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

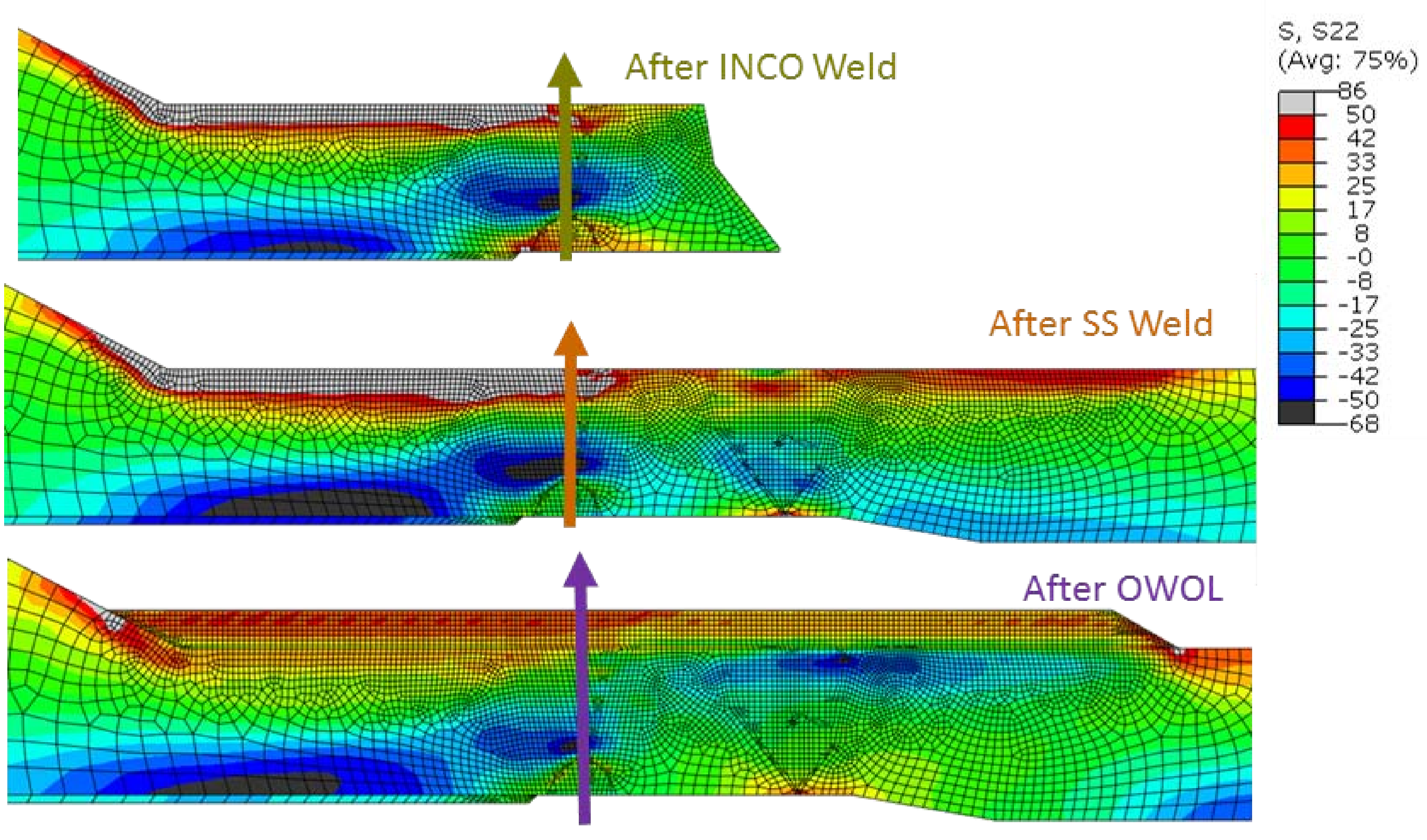

Nozzel, without OWOL


Nozzel, with OWOL

- Investigation of a mitigation technique: Optimized Weld Overlay (OWOL)

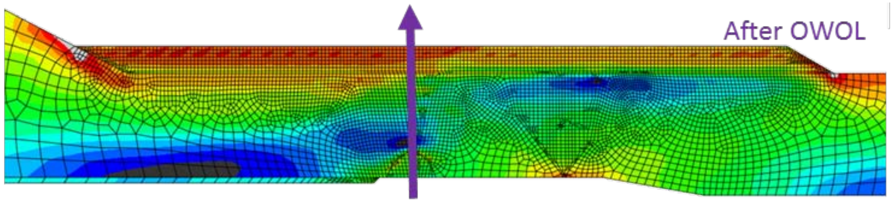
Phase IV: Cancelled Plant Nozzles

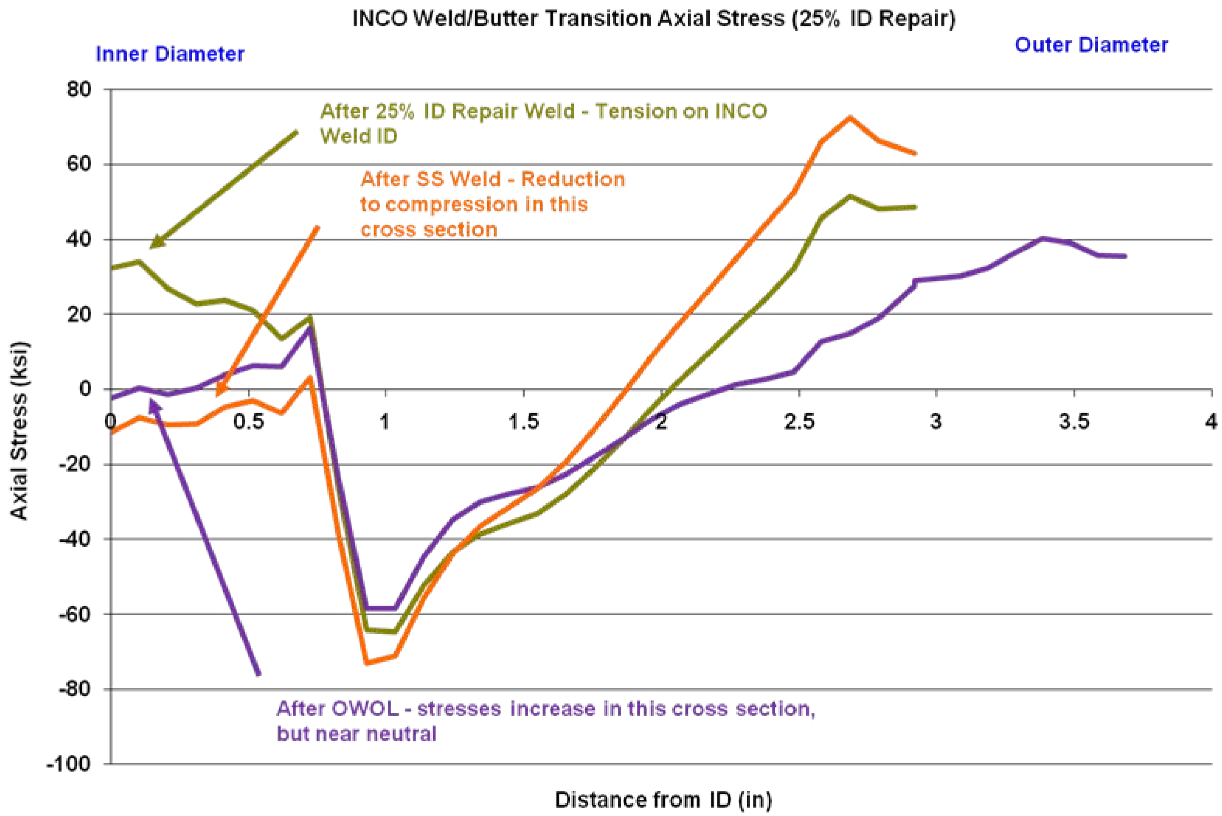
Results: Axial Stresses



Phase IV: Cancelled Plant Nozzles

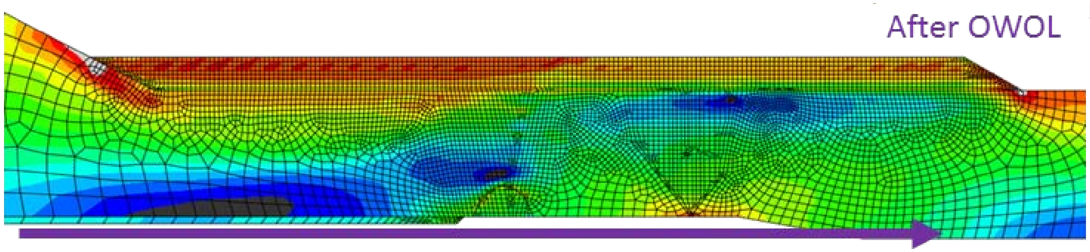
Results: Axial Stress, Midweld, Through Thickness

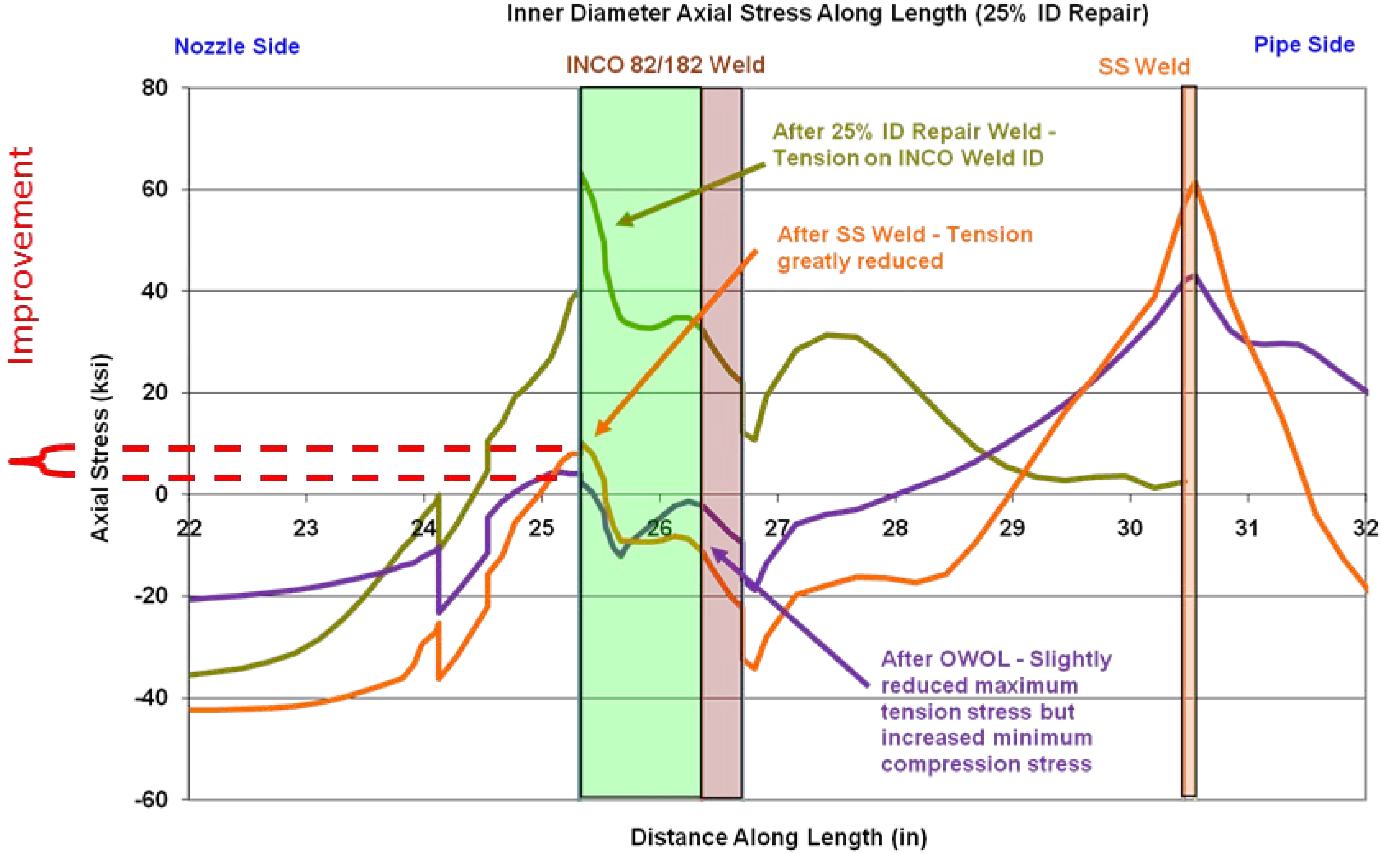




Phase IV: Cancelled Plant Nozzles

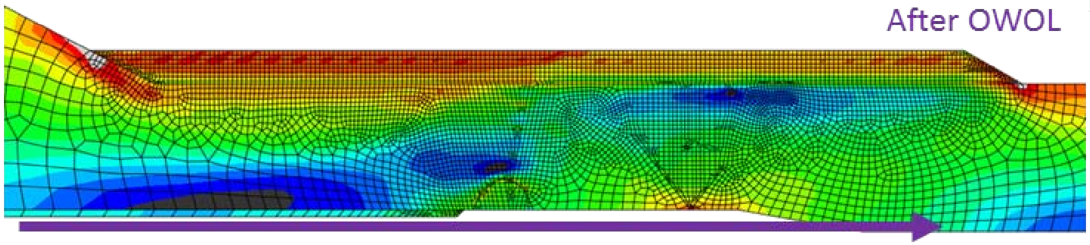
Results: Axial Stress, ID, Transverse to Weld

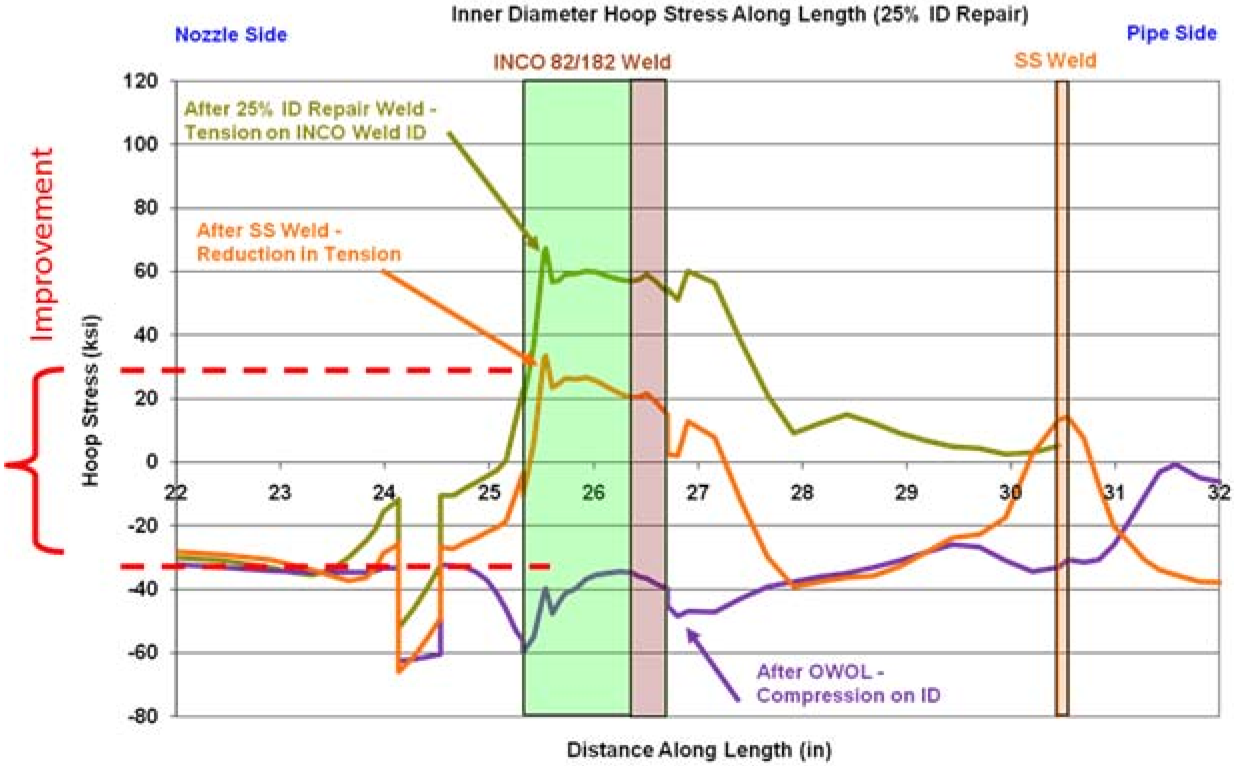




Phase IV: Cancelled Plant Nozzles

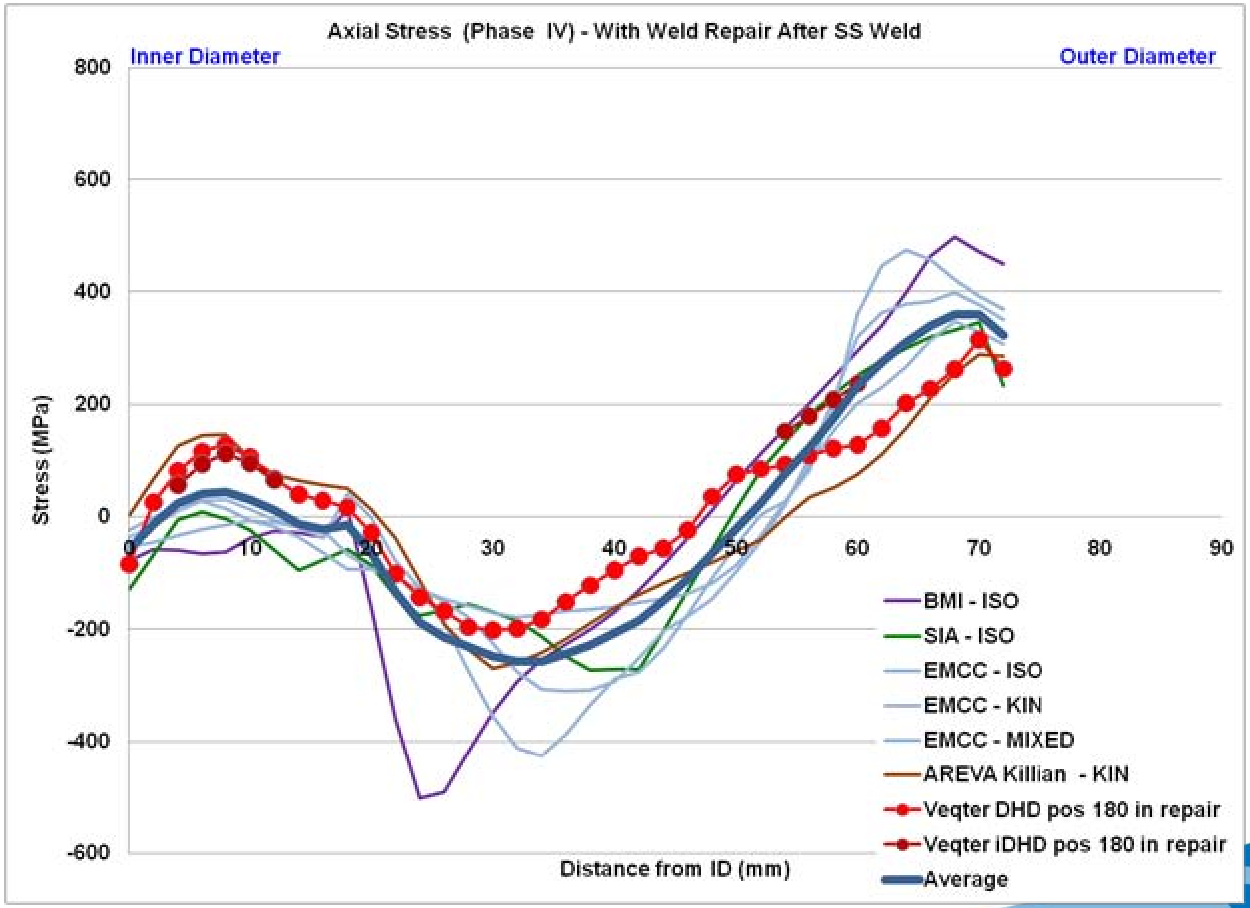
Results: Hoop Stress, ID, Transverse to Weld





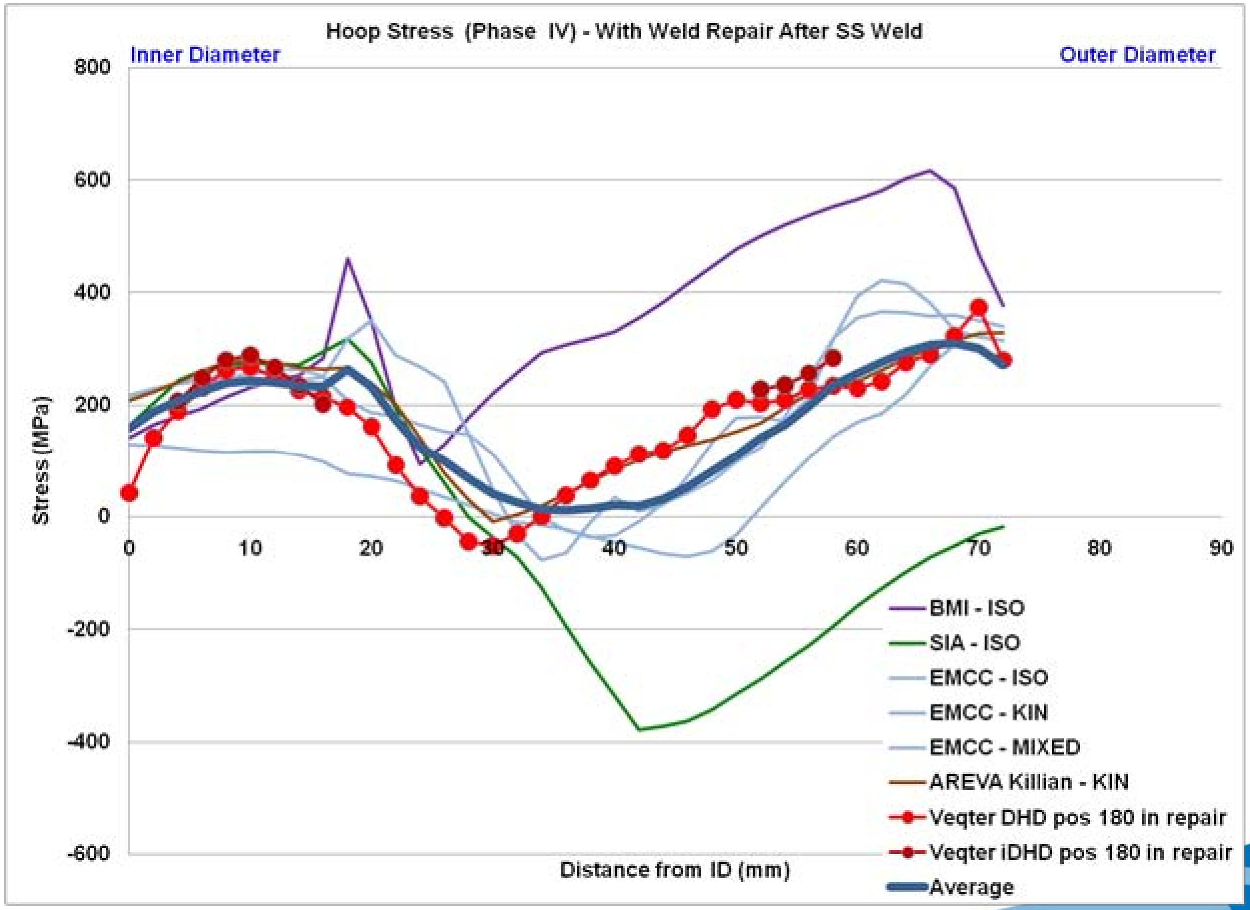
Phase IV: Cancelled Plant Nozzles

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

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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

U.S.NRC
United States Nuclear Regulatory Commission
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- 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

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

- 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